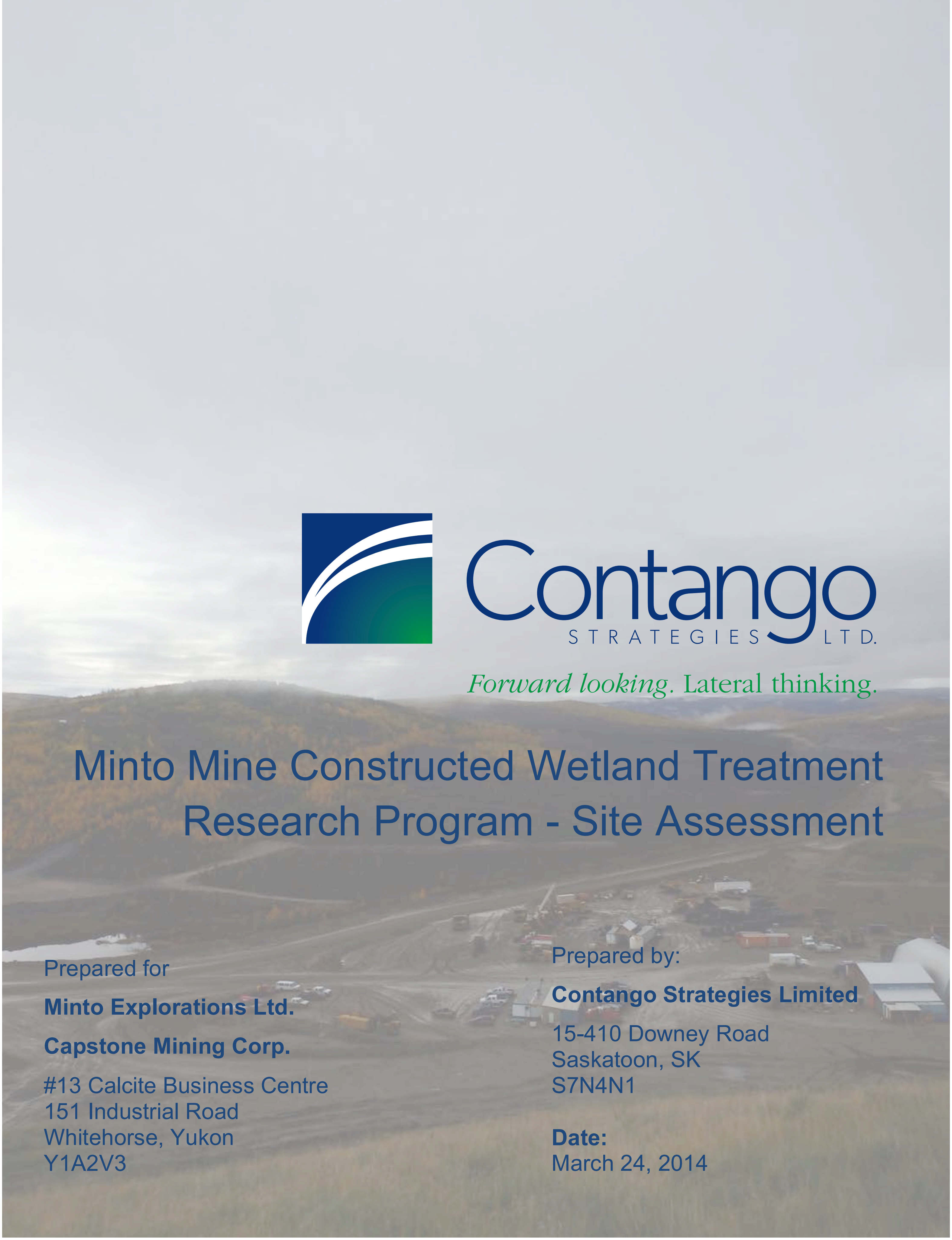
Appendix A1
Minto Mine Site Assessment



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Minto Mine Constructed Wetland Treatment Research Program - Site Assessment

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1. Abbreviations and Definitions

CWTS(s) – Constructed Wetland Treatment System(s)

DNA (deoxyribonucleic acid) – is the hereditary material in humans and almost all other organisms. This can be used to identify organisms.

DO – dissolved oxygen

DSTSF – Dry Stack Tailings Storage Facility

Heterotroph – an organism deriving its nutritional requirements from complex organic substances.

Metagenomics – the study of genetic material recovered directly from environmental samples, related to a community rather than an individual organism.

Microbes – microscopic organisms which may be uni- or multi-cellular. This includes algae, bacteria, fungi, viruses, and yeast.

MPN (Most Probable Number Method) – a statistical value representing the viable population of microbes in a sample through use of dilution and multiple inoculations.

MVFE – Mill Valley Fill Extension

Oxidation – is the loss of electrons or increase in oxidation state by a molecule, atom, or ion. Can be catalyzed by microbes.

Redox – Oxidation-reduction potential, measured in millivolts

Reduction (chemical) – is the gain of electrons or a decrease in oxidation state by a molecule, atom, or ion. Can be catalyzed by microbes.

SeIV broth or agar – laboratory growth medium that contains selenite (SeIV) and indicates reduction of selenite to elemental selenium through a visible colour change.

Species – one of the basic units of biological classification and a taxonomic rank. Rank in the classification of organisms below genus and above strain.

SWD – Southwest Waste Dump

Taxonomy – classification, identification, and naming of organisms.

TSS – total suspended solids

YTS250 (Yeast, Tryptone, Starch, 250g each) – a type of laboratory growth medium used for environmental microbes.

2. Introduction

Constructed Wetland Treatment Systems (CWTSs) have been identified as a contingency method for improvement of the quality of site runoff water in the post-closure period for the Minto Mine (Minto Phase V/VI Expansion Project, YOR Project Number 2013-0100). Once established, wetlands can become self-sustaining ecosystems with the plants providing yearly renewal of carbon to fuel microbial activity. As such, they possess the desirable potential to remediate contaminated mine drainage for as long as it is generated. In order for the CWTS to be effective, they must be designed, piloted, optimized, implemented, and maintained in a site-specific manner.

At the request of Minto Explorations Ltd, Contango Strategies has undertaken a site assessment to inform the design of site-specific passive treatment technologies for the Minto site during post-closure. The overriding goal of the study was to identify natural water treatment processes that are currently occurring at the Minto site in areas receiving impacted waters, and how these could be optimized for passive water treatment in closure. As such, the focus of the research program reported here was on areas that currently receive impacted waters (Figure 1), with emphasis on the W15 monitoring station and upstream creek and wetland area that receive seepage and runoff from the Southwest Waste Dump (SWD). Additionally, preliminary information was gathered for the W37 area receiving seepage and runoff from the Dry Stack Tailings Storage Facility (DSTSF) and Mill Valley Fill Extension (MVFE) toe area. As was outlined in Appendix W – Preliminary Reclamation and Closure Plan Phase V-VI of the Phase V-VI expansion plan, the focus of work at this point is on the W15 area and SWD. At a future date, additional work will occur in the future down gradient of the DSTSF and within the footprint of the current water storage pond. The site assessment included two visits to the Minto Mine to gather information and samples. Sampling consisted of in situ measurements, collection of samples for physiochemical, geochemical, and microbiological analyses. General feasibility of implementing passive treatment was also evaluated during the site visits.

It is our understanding that before this site assessment of the natural wetland area, there has been no monitoring of water quality along the creek between the W10 and W15 monitoring points, of the creek entering the W15 monitoring point, or the W15 runoff area entering the W15 monitoring point. Therefore, this study provides new information to inform decisions regarding the plausibility of water treatment by constructed wetlands at the Minto Site.

Copper is of greatest interest in this study, however, there are a number of other elements and parameters that can influence the biogeochemistry of a system and overall treatability of the copper. These include the presence of iron and sulphur, as well as the pH and oxygen content of the environment. Additionally, there are a few other elements (e.g., selenium) that will require some treatment in order to achieve discharge goals.

3. Site Visits

3.1. Information Gathering

Two site visits were conducted as part of the site assessment for the CWTS. Prior to the first site visit, preparations included gathering site-specific historical and predicted closure information including:

- Rates of seepage for known seeps (and interpretation as a function of dump area and catchments)
- References to analytical results about the site
- Rate of flow for W15 and W37 based on existing data
- Aerial photo interpretation or site personnel knowledge of areas with potentially acceptable granular soil materials, peat, limestone, and organic soils for subsequent on-site materials investigation, inspection and testing.
- Use of site-wide vegetation map to identify areas for possible vegetation borrow sources for the CWTS.
- Determine water quality parameters to be monitored and concentrations that will be used for pilot tests.

3.2. First Site Visit

The first site visit was conducted mid-August 2013 and had a primary goal of familiarizing Contango personnel with the site layout and water flows in order to properly design sampling plans for assessment of existing natural treatment mechanisms occurring on site. Specific information gathered in the first site visit included:

- Visual inspection along the toe of SWD, Main Dump, DSTSF, and area down-gradient of W37 to identify and document primary seeps that have the potential to be intercepted along with an assessment of current fate of seepage surface flows.
- Identify conceptual options for intercepting and routing seepage into the CWTS.
- Selection of a significant seep(s) for further test work based on initial site reconnaissance. Evaluate potential path of seepage interception trench in comparison to seep location(s).
- Identify probable locations for CWTS. Investigation and evaluation of natural remediation processes that may be occurring on site as identified by redox and pH changes between surface water and plant roots, and choice of plant types to be tested in Contango’s pilot CWTS tests.
- Identification of borrow sites for CWTS substrate (limestone, coarse sand/gravel, peat, plant sources for much, etc.)
- Identify ideal CWTS plant species based on site observations of vegetation.

Information collected prior to and during the first site investigation were reviewed and then used to refine the scope and direction of data collection in the follow up site visit. The refinement of scope and testing locations was conducted in consultation with ACG and staff from the Minto Mine.

3.3. Second Site Visit

A second site visit took place September 20-23, 2013 based on observations from the first site visit and historical and modeling data compiled to date. The purpose of the second site visit was to collect water, soil, plant, and microbiological samples from the natural wetland and creek area flowing between the W10 to W15 monitoring stations. This area begins with a creek that flows from off site through the W10 area and subsequently receives seepage and surface runoff from the SWD, surface runoff from the catchment area (including non-contact waters), and road runoff from a culvert entering the W15 collection pond. Samples were taken from potential borrow sources to assess suitability of the materials for constructing soils for the CWTS. Additionally, *Carex aquatilis* (Water Sedge) and *Sphagnum* (moss) plants were collected at the W10 site and transported back to Contango’s CWTS research facilities in Saskatoon for use in the pilot-scale systems to be built specifically for testing and optimization of designs for the Minto site.

4. Experimental Setup

4.1. Sample and Analytical Data Collection

During the second site visit, fourteen different locations were sampled at the Minto Mine Site (Table 1 and Figure 2). Samples were collected starting at the most downstream location (W15) and progressing upstream to the W10 area over a period of 2 days. In all cases, water samples were collected first, then soil and plant samples. Water and soil samples were collected by grab sample, with soil sampled to a maximum depth of 5-7 cm. Water, sediment, and plant samples were submitted to Maxxam Analytics and analyzed for parameters listed in Table 2. For plants, only the above water (or above ground) portion was analyzed. For *Carex aquatilis*, *Equisetum* sp. and *Sphagnum* sp., the entire above ground (or water) portion was analyzed. For *Salix* sp., only the recent year's growth was collected. All micro samples were processed according to Sections 4.2 and 4.3.

4.2. Growth-based analyses (MPN)

The most-probable number (MPN) of bacteria was determined for all micro samples (Table 1). The test allows for estimation of the number of bacteria that can grow in a specific laboratory medium. The mediums tested for in this project were specific for bacteria that can reduce nitrate, selenite, and sulfate, respectively, as well as the total number of heterotrophic bacteria for comparative purposes (i.e., a growth-permissive test for all bacteria capable of growing on organic carbon as an energy source). MPN tests for sulphate (Active Standard ASTM D4412) were performed under anaerobic conditions, whereas selenite (Siddique et al., 2006) and nitrate (Nitrate Reduction Test, supplied by Sigma-Aldrich) were tested under aerobic conditions. Total heterotrophs (grown with YTS250 medium; Lefrançois et al., 2010) were tested for in both aerobic and anaerobic conditions. In brief, sediment samples were diluted 1:10 with a 0.1% peptone solution. This dilution was then used to perform a serial dilution along a sterile 96-microwell round-bottom plate containing the respective growth media. Sediment dilutions tested in the MPN plate ranged from 1/400 to 1/419,430,400. At a minimum, all tests were performed in duplicate. Wells were incubated at +30°C in a dark incubator and assessed for visible growth (formation of a bacterial pellet) and/or colour change specific to the type of media after 16 (aerobic) or 28 (anaerobic) days. A colour change to black or red/orange indicated sulphate or selenite reduction, respectively. Nitrate reduction was tested as per the kit manufacturer's protocol by addition of reagents to differentiate between reduction to nitrite or nitrogen gas. The most probable number of bacteria capable of each metabolism was then calculated as described in the FDA Bacteriological Analytical Manual, Appendix 2: Most Probable Number from Serial Dilutions: (http://www.fda.gov/Food/FoodScienceResearch/LaboratoryMethods/ucm109656.htm).

4.3. DNA-based analyses

DNA was extracted from all samples using the MO BIO Powersoil Powerlyzer DNA extraction kit. To identify the bacteria present in each sample, we performed targeted sequencing. The gene that is targeted by polymerase chain reaction (PCR) for bacteria is the v4 region of the 16S ribosomal RNA gene (Caporaso et al., 2011). Because the same gene is sequenced for all targeted organisms in a community, the relatedness of different microbes can be inferred based on sequence similarity. As such, the first step in the analysis of targeted metagenomics is clustering similar sequences into groups which are called Operational Taxonomic Units (OTUs). An OTU can essentially be described as a "species cluster", where all sequences present in an OTU are similar and presumed to represent the same or very closely related organisms. The threshold for choosing what is or is not considered the same organism is dependent on the region that is being targeted for sequencing. For example, bacteria are clustered together at 97% identity, as the v4 16S rRNA region that is targeted is known to have ~3% intra-species variation. Once the sequences have been clustered together, each OTU is assigned a taxonomy based on similarity with sequences from known organisms (using databases specific for each targeted region). The taxonomy classification is very dependent on the presence of that organism in the databases that are being used. For example, if a novel bacterium is sequenced, no taxonomy is assigned because no representative would be present in the database. Furthermore, different levels of taxonomy can be assigned based on how confident or similar the sequence is to known organisms. An OTU can therefore sometimes be classified as "Bacteria", or a second OTU as "Bacteria;Proteobacteria" as the software pipeline is not confident in the assignment of lower taxonomy levels, while a third OTU may be classified as "Bacteria;Proteobacteria;Epsilonproteobacteria;Campylobacterales; Helicobacteraceae;Sulfurimonas" based on high similarity with other *Sulfurimonas* sequences found in the database. While we cannot always confidently assign names to each of these OTUs, we can be confident that they are different from one another, as we have already compared their sequences. Hence, even though in this example both the second and third OTUs belong to the *Proteobacteria* phylum, we are confident that they are in fact different organisms. Once taxonomy has been assigned, the abundance of each OTU in each sample is determined. To compare the community profile of different samples, a multitude of statistical analyses were performed.

5. Results and Discussion

5.1. Site Assessment

The sections below correspond to results and discussion specific to each of the objectives that are reiterated here for ease of reference.

- Visual inspection along the toe of SWD, Main Dump, DSTSF, and area down-gradient of W37 to identify and document primary seeps that have the potential to be intercepted along with an assessment of current fate of seepage surface flows.
- Selection of a significant seep(s) for further test work based on initial site reconnaissance. Evaluate potential path of seepage interception trench in comparison to seep location(s).

Fourteen sites at the area receiving water from the SWD were selected for further testing (Table 1, Figure 2) and assessed for the parameters listed in Table 2. These include 3 seeps that are part of Minto's routine monitoring program (W32, W38, W39) as well as areas of the creek parallel to the seep (W38 Creek, W39 Creek, W32 Creek). Additionally, the W32 area had visible seepage between the seep and creek, and there were two distinctly different branches of the creek itself. Therefore, a total of four samples were collected at the W32 location. These are the W32 Seep, W32 Creek, W32 Mid (further seep between the toe seep and creek), and W32 Creek Red. The W32 Creek Red sample is a distinct branch of the W32 creek that was covered in red foam in August, and red precipitate on the soil in September (Figure 3). It should be noted that due to the parallel selection of sites and the direction of flow in the area between the seeps and creek, the water from seep W38 would never be present in W38 creek. We realize it is not possible to know the exact areas of entry of the seeps into the creek unless detailed hydrological studies and use of tracers were used; however, the purpose of this site assessment was to determine overall trends in water chemistry through the site and not a thorough hydrological investigation. During the first site assessment to locate priority sampling areas, the weather was hot (>+30°C daytime temperature) and dry, and therefore the seeps marked for routine monitoring (including W32, W38 and W39) were mostly dry with no visible standing or flowing water. However, these sites are routinely monitored and have a wealth of historical data relating to toe seepage from the SWD, and so they were identified as high priority areas. During the second site visit, snowmelt was causing a greater volume of seepage than in the first visit. Water pools were present at all marked monitoring seepage points along the SWD toe, some with visible flows.

Runoff was observed directly from the road above via a culvert entering into the W15 collection pond, bypassing the creek and natural wetland area entirely (Figure 2). This "culvert runoff into W15" was sometimes clear, but at other times muddy, seemingly when the grader passed over the road on its routine schedule. While flow volumes and periodicity would need to be determined in order to calculate actual contribution to loading and concentrations, it is likely that water from the culvert (runoff into W15) is contributing to elevated concentrations of constituents of concern that have been observed to coincide with high total suspended solids (TSS) events at the W15 monitoring station at the far end of the pond (Figure 2).

Further geotechnical and hydrological assessments of the W15 area are planned to determine the depth of seepage, to ensure that the interception trench is adequately built such that seepage does not pass below it, and to delineate the extent of permafrost. This will be conducted under a separate scope of work.

The W37 area was inspected during the first site visit. However, as noted in the Phase V/VI project proposal, this area and the MVFE are likely to change with further development prior to closure. As such, they were not targeted as a key area for research at this time.

- Identify conceptual options for intercepting and routing seepage into the CWTS.

The W15 and W37 (Figure 1) areas are both in natural depressions and likely suitable for implementation of a CWTS, although this will also cause the depressions to receive non-contact runoff water from the general catchment area. Due to the multiple seeps along the toe of the SWD, an interception trench would be needed to collect the seepage and direct it towards the entry of the CWTS. Alternatively, it may be possible to construct several smaller CWTSs, each with their own entry point for seepage. These two options will be evaluated as information pertaining to flow rates and removal rates are refined through scientific testing and continued gathering of information from the site.

W37 area appeared to be amenable to future implementation of a CWTS. We recommend that studies be conducted on the sediments under the current water storage area behind the dam, in order to ensure there has been no accumulation of elements that might be released upon oxidation once the dam is breached upon closure.

- Identify probable locations for CWTSs. Investigation and evaluation of natural remediation processes that may be occurring on site as identified by redox and pH changes between surface water and plant roots, and choice of plant types to be tested in Contango's pilot CWTS tests.

The W15, W37, and Main Pit have been identified as probable locations for CWTS in closure (Figure 1). The natural remediation processes occurring at the W15 site were investigated and evaluated in the second site assessment, with results and findings detailed in this report. We were unable to measure soil redox, however, as the water temperature was too cold for the reference probe, causing its internal buffer solution to crystalize (+0.5°C).

- Identification of borrow sites for CWTS substrate (limestone, coarse sand/gravel, peat, plant sources for much, etc.)

Overburden piles of sand and peat were located and tested for parameters relevant to their use as a soil in the CWTS. The samples of borrow material are suitable for use in a future CWTS. A source of slow release carbon (e.g., wood chips) is still yet to be identified.

- Identify ideal CWTS plant species based on site observations of vegetation.

Plant species and associated findings are discussed in section 5.3 below.

5.2. Water and Sediment Geochemistry

Dissolved chloride concentrations in the water can be used as a proxy to determine if concentration decreases in other elements can be attributed to dilution or putative treatment mechanisms. Comparison of changes in concentrations of elements of interest along the creek indicates fluctuations are similar to those of chloride, indicating dilution rather than treatment is occurring within the free flowing areas of the creek itself (Table 3). However, comparison of the water exiting and entering the W32 Creek Red site shows substantial treatment of copper and also some treatment of selenium and sulphur (Table 4). Comparison of the seeps with the creek also indicates significant treatment of copper, selenium and sulphur (Table 5). Overall, this indicates that active treatment of elements is occurring in the vegetated areas between the seep and the creek, but little or no treatment occurs in the creek itself. In this case, averages were used for the creek as the actual flow of seeps, and entry points into the creek are not known. More refined calculations cannot be made without detailed hydrological information for the area. Figures 4 and 5 show only small changes in chloride concentration through the system, yet large fluctuations in concentrations of other elements occur, especially near the seeps. Moreover, the chemistry of each seep varies greatly from one another, while the concentrations of elements in the creek show more consistency (Figures 5-7), supporting the notion of treatment between the seep and creek, which evens out these fluctuations in chemistry by the time the water reaches the creek.

At the furthest upstream location sampled in this assessment, the W10 site has some of the highest copper concentrations in sediment (Figure 8), yet some of the lowest concentrations of copper in the water (Figure 6). This could reflect that the W10 site has been accumulating copper for a longer time span (i.e., in existence for more years, as it is a background location, upstream of the SWD), or perhaps the materials used to build the access road near the W10 contained copper and spread further than is currently visible due to overgrowth. This could also be caused by removal of copper from the water and into the sediment by binding to oxidized iron as suggested by the ratios of total vs. dissolved iron at that sampling area, with further stabilization (retention) of the copper promoted by conditions (redox, pH) in the sediment created by the combination of plants, microbes, and chemistry in the area.

The culvert runoff into W15 area has the highest copper concentrations in both sediment and water (Figures 6 and 8). The W15 runoff area has a separate and independent flow than the creek, entering the W15 collection pond via a culvert from the road above, bypassing the creek and natural wetland entirely (Figure 2). The culvert runoff into W15 appears to only flow during melt and rain events. This W15 runoff was sometimes clear (as in the time the sample for this study was taken), but at other times is muddy, seemingly when the grader passed over the road on its routine schedule. While flow volumes and periodicity would need to be determined in order to calculate actual contribution to loading and concentrations, it is likely that water from the culvert (W15 runoff) is contributing to elevated concentrations of constituents of concern that have been observed to coincide with high TSS events at the W15 monitoring station at the far end of the pond. This can be seen in Figure 9 as the W15 inflow (from creek) has a lower concentration of key elements (e.g., copper, selenium) than is routinely measured at the W15 monitoring point. The only visible source for this loading is the culvert runoff into W15. This is a key finding of this site assessment, as the routine sampling performed at the set W10 and W15 monitoring points would indicate that there is less treatment ongoing in the natural wetland area than is truly occurring. This is because of the extra loading of contaminants contributed by the culvert runoff into W15 mixing in the collection pond with the cleaner water exiting the natural wetland area before reaching the W15 monitoring point (Figures 6 and 7).

The W32 Creek Red site is a location between the W10 (upstream) and W15 (downstream) areas where the creek briefly splits into two steams at the W32 clearing. The W32 Creek Red sample has a high concentration of oxidized iron, indicated by a visible red precipitate (Figure 3). At the first site visit in August, the red substance was fluffy and floating in the water and also on the sediment. In September, the red substance was entirely at the sediment interface. Moreover, the water exiting the W32 Creek Red site has the lowest concentration of copper in the water (at 1.92 µg/L, the only site sampled in this study with copper concentration below CCME guidelines). This finding, paired with moderate concentrations of copper in the sediment at the W32 Creek Red site compared to other locations (Figure 8), suggests that copper removal may be occurring via binding to oxidized iron at the W32 Creek Red site. It would be useful in the future to monitor sediment redox at this and other sites; however, the water temperature (+0.5°C) was too cold for the reference probes to be used at the time of the September sampling event. There were several other smaller areas similar in appearance to the W32 Creek Red site found along the creek, always where water was shallow and *Equisetum* or *Carex* present.

The W32 Seep has low ammonia (9.4 µg/L) and high nitrate (39.9 mg/L) concentrations in the water relative to other samples (Figure 7). It appears that the ammonia is being oxidized to nitrate as it seeps through the waste rock pile, which is consistent with the peaks of sulphur and selenium concentrations in the water at the W32 site, both of which could be released from the waste rock under oxidizing conditions. In contrast, the W32 Creek and W32 Creek Red water samples have higher concentrations of ammonia and lower concentrations of nitrate than other samples (measured as N, 0.11 and 0.18 mg/L ammonia and 3.02 mg/L and below detection limit (<0.02 mg/L) for nitrate, respectively; Figure 7). It is possible that there are greater concentrations of ammonia seeping from the SWD between the W10 site and W32 creek sampling point, or that the ammonia is being produced within the creek from decaying organic material. It is also possible that the ammonia is being produced by the abundant *Geobacter* bacteria at the W32 Creek Red site (see section 5.4), as it is a known iron-reducing organism that feeds on electrons from oxidized iron and can also respire nitrate to ammonia (Lovley & Phillips, 1988; Senko & Stolz, 2001).

As would be supported by redox and biogeochemical theory, there is a strong correlation between ammonia and total iron concentrations in water (Figure 10), while iron and nitrate show a negative correlation. This makes sense from a theoretical oxidation-reduction chemistry perspective, as ammonia will oxidize into nitrate, increasing nitrate concentration while the same oxidizing environment will cause iron to oxidize and precipitate from solution. Conversely, the sulphur, selenium, and copper concentrations in water are positively correlated to the nitrate concentration in water (Figure 10), as would be expected since sulphur and selenium are normally present as soluble compounds in oxidizing environments. Likewise, at increasingly negative redox nitrate will be reduced to nitrogen gas, followed by selenate/selenite to elemental selenium and at an even lower redox, sulphate is reduced.

5.3. Plants

Sphagnum (Moss) was found to grow in nearly all areas of the site, except directly at the outlet of the creek to the W15 pond. *Salix sp.* (Willow) was found at all sites, except at sites in the W32 area, which appeared to have been cleared at some point. *Carex aquatilis* (Water Sedge) was dominant within the W32 area that was recently cleared (Figure 11), and also within the W10 area where the water was deeper. *C. aquatilis* was found to be spreading through the W10 area access road, being the first plant to colonize the road and even recent tire ruts (Figure 12), indicating that it will be a potentially good choice for quickly establishing the CWTS. However, at locations with shallower water, *C. aquatilis* and *Sphagnum* coexisted, and *Equisetum* was also present, growing through the *Sphagnum.* This suggests that if water depth is not maintained, *Sphagnum* and *Equisetum* will grow in succession.

Compared to the other plant species tested, *Sphagnum* showed significantly greater uptake of elements such as copper, uranium, and iron at all sites that *Sphagnum* was available (Figures 13 and 14). No detectable selenium was found in any of the plants except for *C. aquatilis* and *Sphagnum* at the W32 Seep site (0.7 mg/kg) and *Sphagnum* at the W32 Mid site (0.3 mg/kg). This is presumably due to higher amounts of selenium being present in water at the W32 Seep site (Figure 6). Uptake of copper and iron in all plants was negatively correlated with copper concentration (-0.904) or iron concentration (-0.994) in sediment at each location, respectively. These findings suggest varying bioavailability of copper at the different sites sampled, and when elements are being deposited into the soils, they are in forms (species) that are less bioavailable to the plants than when in aqueous form.

All cases of water channeling through the natural wetland area were in association with *Salix* plants (Figure 15). *Salix* species had the least uptake of elements compared to other plant species at most of the sites (Figure 13). The root structure of these plants appears to contribute to the creation of channelized creeks, which also corresponds with little or no treatment occurring in the creek area. *Salix* has not regrown in the W32 area that was previously cleared, and it is recommended that this area be surveyed yearly to assess whether they will begin to reestablish in this area. It should also be determined when the W32 area was cleared. This information will be used to establish a maintenance schedule for the wetlands, as young *Salix* plants should be removed before becoming well established.

Although a greater water depth is one parameter that can be used in CWTS to create an anaerobic redox and decrease dissolved oxygen concentration in the water, the research conducted here has shown that *Sphagnum* can be an effective means of removing elements from the seepage through uptake, a finding supported by literature. As such, this potential succession of plants may occur, but is not expected to significantly impact the performance of the CWTS, and may even improve the performance via plant uptake in the *Sphagnum*.

5.4. Microbiology

Genetic profiling of the microbial communities indicate great diversity with hundreds of species, but for the purpose of discussion in this section, the top ten most abundant organisms are focused upon (Appendix I). When assessing the microbial genetic profiles of all sites, most samples have a very similar distribution of organisms (Figure 16). The outflow of the W15 creek was sampled in triplicate as a control for microbial variability within a given sampled site. All of the creek samples receiving seepage (W32, W38, W39, and the three W15 sites) cluster together, which indicates similar microbial profiles. All three W15 sites show nearly identical microbial distributions (Appendix I and II), while strong similarities are found for all creek sites. One common trend in all creek sites is the presence of the *Intrasporangiaceae* organism group (yellow in Appendix I). This group appears to be closely related to *Tetrasphaera,* which are known to be involved in phosphorus removal from wastewater. Conversely, the W10 and W10 *Carex* Root samples show distributions more similar to one another than to the downstream creek locations. A large distribution of the organisms at W10 and W10 *Carex* Root locations represents the order *Bacteroidales*, which are ubiquitous colonizers of a wide range of environments (e.g., soil, activated sludge, decaying plant material, compost, fresh water and marine samples, dairy products). However, the W10 *Carex* Root had a denser population of organisms than the W10 sample taken away from plants in the area (i.e., # of organisms per gram of sample; Figure 17).

Laboratory growth-based assays also tested for total heterotrophic, selenite-, sulphate-, and nitrate-reducing organisms at different sites (Figures 17 and 18). The population of total heterotrophs grown under aerobic conditions was significantly greater than under anaerobic conditions (Figure 18). Interestingly, both the laboratory- and genetic profiling-based methods showed very few sulphate-reducing organisms at most of the sites, with the highest amounts found at the W10 *Carex* Root and W15 inflow sites (Figure 17). The W10 *Carex* Root sampling location also showed interesting sediment features with black color and smell at deeper depths, characteristic of sulphate-reducing organisms, but with red iron oxides visible at the water interface (Figure 19). Selenite-reducing organisms were found at all tested locations, while nitrate-reduction only occurred to completion at the W10 *Carex* Root, W10, W32 Creek Red, W38 Creek and W15 inflow locations (Figure 17). No correlation was found between the number of selenite-, sulphate-, or nitrate-reducing organisms and the water concentration of nitrate, selenium, and sulphate at each location. This is potentially due to the correlation analysis being performed on water concentrations instead of sediment concentrations for these compounds (which is where the reducing organisms would be found), as non-detectable selenium and nitrogen levels were found in most of the sediment samples. In the case of sulphur, the laboratory (Maxxam Analytics) did not perform the requested analysis on the soils, and discussions are ongoing to determine if new samples could be collected and analyzed at their cost to fill in this data gap.

In addition to the red precipitate at the W32 Creek Red site, this location has a unique microbiological profile (Figure 16 and Appendix I). A very dominant percentage of the microbial population at W32 Creek Red is a bacterium called *Geobacter*. This organism is known to seek out insoluble iron oxides, and establish direct contact and reduce them as part of its metabolism. As such, it is likely that the high abundance of *Geobacter* bacteria found at W32 Creek Red is actively reducing Fe(III) to Fe(II), which then reduces Cu(II) to Cu(I) through a coupled biogeochemical reaction. In addition to the interplay between iron-reduction and other elements, the W32 Creek Red site has much lower available phosphorus in the soil and total phosphorus in the water in comparison to the W32 Creek site which is water flowing just adjacent to the red precipitate area, also suggesting that increased microbial activity may be playing a role.

6. Summary and Conclusions

Collectively, these findings contribute greatly to the ability to design and operate a CWTS for effective treatment of waters at the site. The geochemical data indicate that substantial treatment of seepage is occurring on site within the natural wetland, validating the concept that a constructed wetland could be designed to function in the long-term closure condition at the site, but with optimized treatment performance. Mechanisms for treatment of copper and selenium were identified in the natural wetlands receiving seepage from the SWD, including dissimilatory sulfate reduction followed by sulfide precipitation, dissimilatory selenium reduction, and iron co-precipitation.

It is clear that there is greater and faster treatment occurring within the natural wetland than would have been evident if calculated only using data collected by previously existing routine sampling programs. The additional loading of elements at the runoff/culvert into the W15 collection pond is likely a significant contributor to loading during rainfall and melt events, masking the treatment that is occurring through the wetland for seepage that is originating from the SWD toe.

It is evident that the seepage chemistry varies greatly, both between seeps and over time (this study and historical data gathered). This will need to be taken into consideration when evaluating options of constructing a seepage diversion trench compared with building multiple smaller wetlands. The sources and amounts (frequency and range in flows) can be coalesced or treated as separate flows with individual specifically designed wetlands. Collection of seepage by a diversion trench would allow mixing of the various seepage chemistries and more uniform composition and volume of inflow water to the wetlands, but individual wetlands may be favoured in the W15 area due to topography and seepage locations.

There appears to be sufficient soil on site for both hydrosoil and berms for the CWTS. Analysis indicated that the chemistry of overburden soils is amenable to use as soil in the CWTS and to support plant growth, although slightly elevated in copper as is the entire background area. The overburden peat on site is also amenable to use in the soil as an amendment to the CWTS. However, additional sources of organic matter to create anaerobic conditions in the sediment and improve dissimilatory reduction pathways for sulfur and selenium will still need to be identified (such as wood chips, straw, and/or compost). Additionally, when an onsite demonstration-scale CWTS is built, there should be a mechanism developed to deliver seepage water to the CWTS rather than creek water, as substantial treatment is currently occurring between the seeps and the creek.

There is suitable vegetation present that is well adapted to the site conditions. The plants at site show a robust ability to grow in the range of water chemistries present in the area. Moreover, all sites sampled are host to a wide diversity of microbes with known capability of performing favourable biogeochemical reactions, which will contribute to water treatment in a CWTS. This confirms that even at sites where no chemical evidence of treatment was found, there are microbes present that would be capable of these reactions if encouraged with the right environment (e.g., plant roots, shift in dissolved oxygen or redox, availability of electron donors). While organisms capable of favorable geochemical reactions were ubiquitous at the site, they were found in elevated numbers associated with *Carex* roots, enforcing our selection of this plant species for the CWTS.

CWTS designs are currently being piloted at Contango's year-round pilot facilities. These systems are planted with *C. aquatilis* from site, and peat from the selected borrow site is incorporated into the soils. Replicate pilot-scale CWTS experiments are in progress with and without *Sphagnum* added in order to assess whether the *Sphagnum* contributes positively or negatively to the treatment, and also whether succession from *C. aquatilis* to *Sphagnum* as the dominant plant can be prevented or enhanced through modification of water depth.

The pilot study will continue to integrate information and design decisions, as well as provide supplementary soil and water redox measurements to validate hypotheses about biogeochemical pathways in the CWTS. Further to this, pilot CWTS sediments will be subjected to leachabilty testing for elements of concern to confirm suitability and longevity of the designs. CWTS designs will continue to be optimized as closure water chemistry and volumes are refined.

7. Closure

We trust the information herein satisfies your present requirements. Should you have any questions, please contact the persons listed below. We appreciate the opportunity to provide the services detailed in this report, and look forward to discussing any comments you may have.

Respectfully submitted,

Contango Strategies Ltd

8. References

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9. Tables

Table 1: Summary of samples taken at the Minto Mine site

Location	**Water Sample**	**Sediment Sample**	**Micro Sample**	**Plant Sample**
W10 *	Yes	Yes	Yes	Yes
W10 *Carex* Root	-	-	Yes	-
W32 Seep	Yes	-	-	Yes
W32 Mid	Yes	-	-	Yes
W32 Creek	Yes	Yes	Yes	Yes
W32 Creek Red	Yes	Yes	Yes	-
W39 Seep	Yes	-	-	-
W39 Creek	Yes	Yes	Yes	-
W38 Seep	Yes	-	-	-
W38 Creek	Yes	Yes	Yes	-
W15 Inflow 1	Yes	Yes	Yes	Yes
W15 Inflow 2	-	-	Yes	-
W15 Inflow 3	-	-	Yes	-
Culvert runoff into W15	Yes	Yes	Yes	-

* *Carex aquatilis* and *Sphagnum* for the Minto Pilot 1 CWTS at Contango Strategies were obtained from this location

Table 2: Summary of water, soil, and plant analyses

Water Analysis	**Soil Analysis**	**Plant Analysis**
Total Regulated Metals (Al, Sb, As, Ba, Be, Bi, B, Cd, Cr, Co, Cu, Fe, Pb, Li, Mn, Mo, Ni, P, Se, Si, Ag, Sr, Tl, Sn, Ti, U, V, Zn, Zr, Ca, Mg, K, Na, S, Hg)	Assessment ICP Metals (Al, Sb, As, Ba, Be, Bi, Cd, Ca, Cr, Co, Cu, Fe, Pb, Li, Mg, Mn, Hg, Mo, Ni, P, K, Se, S, Ag, Na, Sr, Tl, Sn, Ti, U, V, Zn, Zr)	Metals (Al, Sb, As, Ba, Be, Bi, B, Cd, Ca, Cr, Co, Cu, Fe, Pb, Mg, Mn, Mo, Ni, P, K, Se, Ag, Na, Sr, Tl, Sn, Ti, U, V, Zn)
Routine Water (Alkalinity, HCO_3, Ion Balance, Dissolved ions, Hardness)	Available Nitrogen, Phosphorous, and Potassium (NPK)	
Total Suspended Solids (TSS)	Cation Exchange Capacity (CEC)	
Chemical Oxygen Demand (COD)	Sodium Adsorption Ratio (SAR)	
Biological Oxygen Demand (BOD)	Total Organic Carbon (TOC)	
Total Kjeldahl Nitrogen (TKN)	Electrical Conductivity (EC)	
Total Organic Carbon (TOC)	Texture Analysis (Physical properties)	
Ammonia		

Table 3: Copper, selenium, sulphur, and chloride concentrations along the creek. The approximate fold change in concentration along the creek is provided in grey in parentheses.

	W10	W32 Creek	W38 Creek	W39 Creek	W15 Inflow
Total Copper (µg/L)	5.92	32.5 (5.5)	10.6 (0.3)	11.5 (1.1)	19.7 (1.7)
Total Selenium (µg/L)	<0.1	0.71 (7.1)	2.64 (3.7)	2.53 (1.0)	2.10 (0.8)
Total Sulphur (mg/L)	<3	9.7 (3.2)	24.7 (2.5)	23.0 (0.9)	23.1 (1.0)
Dissolved Chloride (mg/L)	1.2	1.8 (1.5)	3.0 (1.7)	3.1 (1.0)	2.9 (0.9)

Table 4: Copper, selenium, sulphur, and chloride concentrations at W32 Creek compared to W32 Creek Red location, and W32 Mid compared to W32 Seep. Approximate fold concentration difference between the two sites is provided in grey parentheses.

	W32 Creek	W32 Creek Red	W32 Seep	W32 Mid
Total Copper (µg/L)	32.5 (0.06)	1.93	10.1 (1.5)	15.1
Total Selenium (µg/L)	0.71 (0.3)	0.21	19.6 (0.01)	0.24
Total Sulphur (mg/L)	9.7 (0.3)	<3	110 (0.1)	11.9
Dissolved Chloride (mg/L)	1.8 (2)	3.5	5.5 (1.2)	6.8

Table 5: Average copper, selenium, sulphur, and chloride concentrations in the creek (W32, W38, W39, and W15; i.e., not including W10), compared to each seep. Approximate fold concentration difference between the seep and average creek is provided in grey parentheses.

	Avg. Creek	W32 Seep	W38 Seep	W39 Seep
Total Copper (µg/L)	18.6	10.1 (0.5)	102 (5.5)	71.4 (3.8)
Total Selenium (µg/L)	2.0	19.6 (9.8)	7.59 (3.8)	0.94 (0.5)
Total Sulphur (mg/L)	20.1	110 (5.5)	45.8 (2.3)	46.0 (2.3)
Dissolved Chloride (mg/L)	2.7	5.5 (2.0)	5.5 (2.0)	3.8 (1.4)

10. Figures

Aerial imagery obtained from Challenger Geomatics. Imagery acquired August 14th 2012. Site contours derived from 2012 aerial imagery obtained from Challenger Geomatics.

Datum: NAD 83 Projection: UTM Zone 8N

This drawing has been prepared for the use of Access Mining Consultants Ltd.'s client and may not be used, reproduced or relied upon by third parties, except as agreed by Access Mining Consultants Ltd. and its client, as

Figure 1: Conceptual closure diagram of Minto mine (Appendix A, Minto Phase V/VI Preliminary Reclamation and Closure Adaptive Management Plan), indicating potential wetland locations and routine monitoring sites.

Figure 2: Sampling locations at the Minto mine. All routine monitoring points are indicated in white, while sampling locations unique to this study are shown in yellow. The blue arrows indicate the direction of water flow. The W32 Creek label corresponds to the location of both the W32 Creek and W32 Creek Red.

Figure 3: Minto Site W32 Creek (bottom in A; left in B) and W32 Creek Red (top in A; right in B) in A) August 2013 and B) September 2013. The pictures show the same site at two different dates.

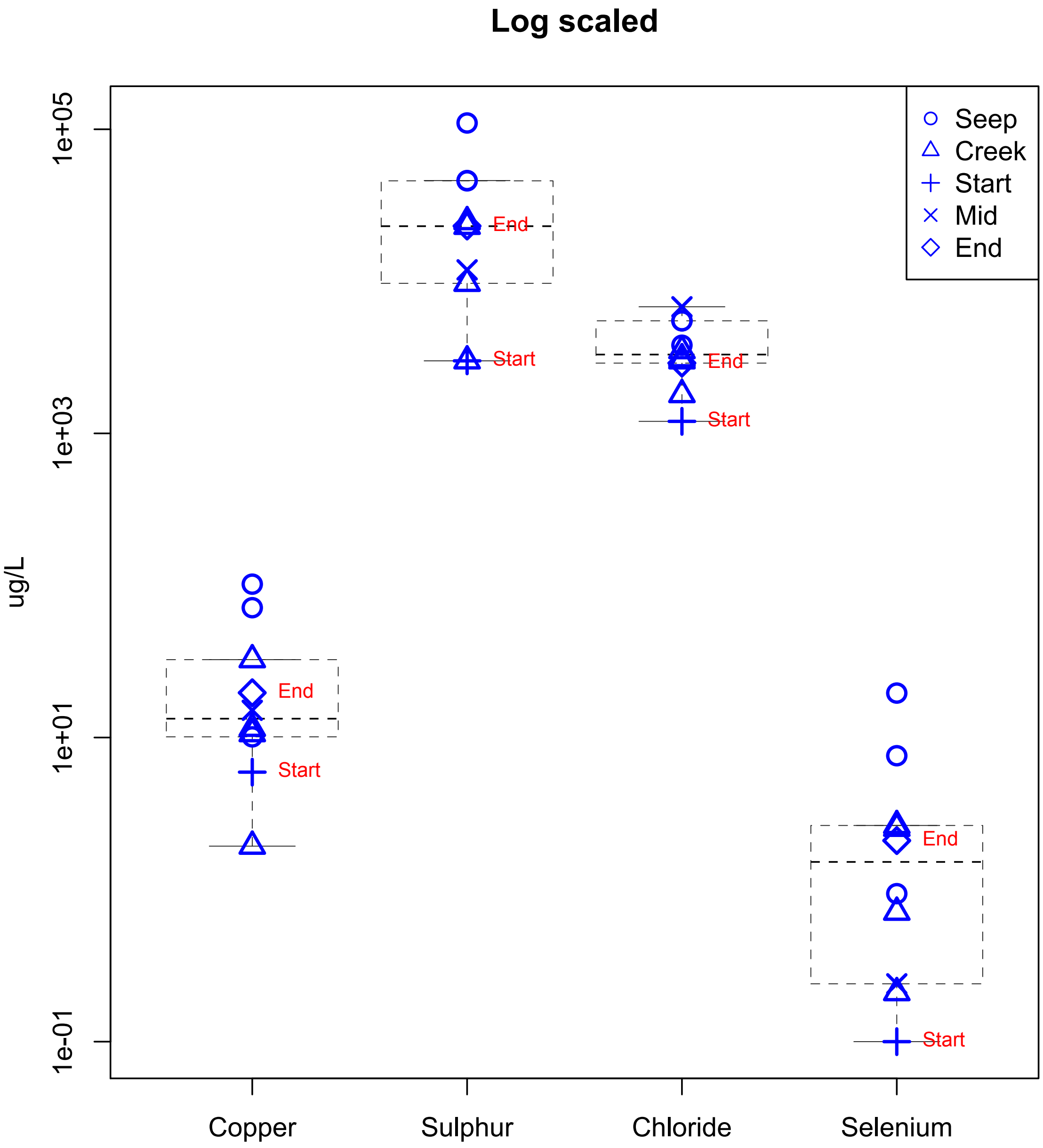


Figure 4: Comparison of copper, sulphur, chloride and selenium concentrations in the creek between the W10 and W15 areas, and seeps along the toe of the SWD. "Start" indicates the W10 location, while "End" indicates the W15 inflow. The W32, W38, and W39 Creek locations are shown as triangles, while all seeps are differentiated as circles. The W32 Mid site is depicted as a X. Note the spread of the copper, sulphur, and selenium plots is greater than that of chloride. The seeps demonstrate the highest concentration of copper, sulphur, and selenium, while chloride concentrations do not follow this trend.

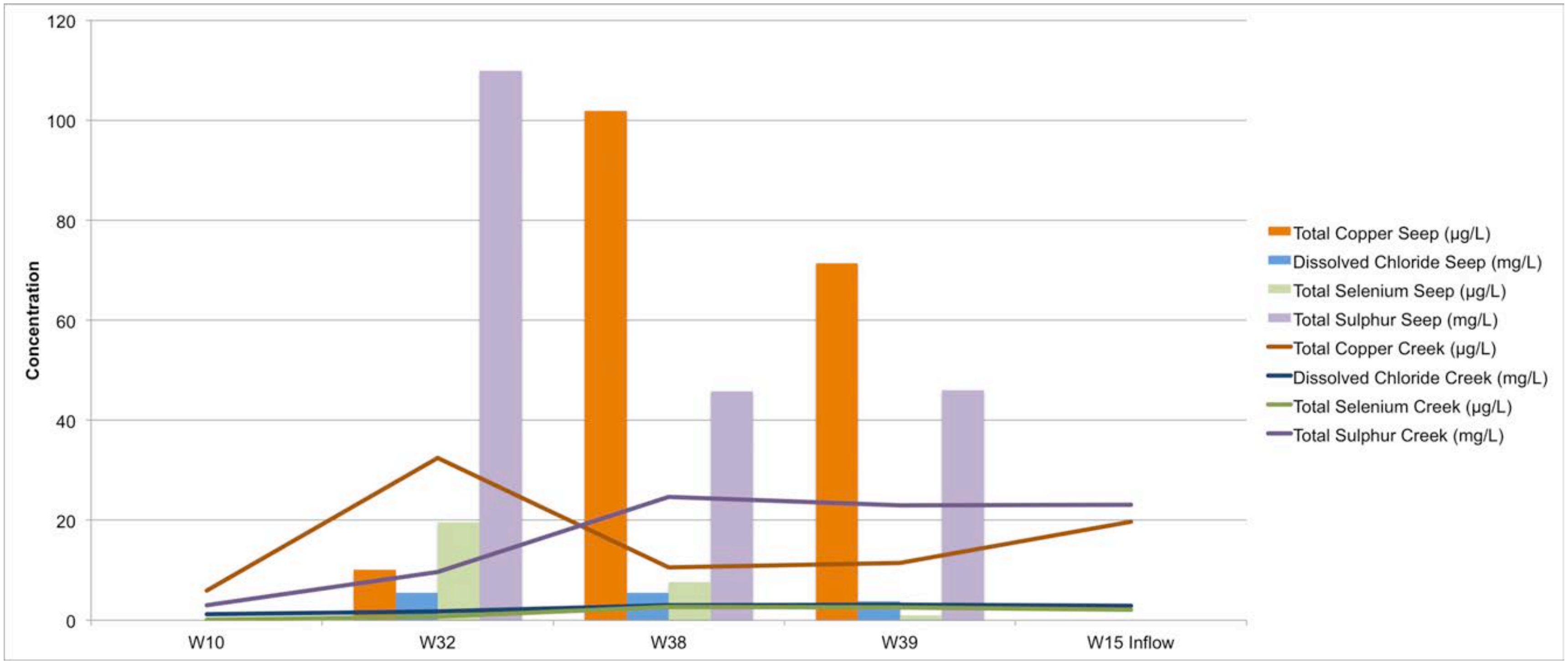


Figure 5: Copper, chloride, selenium, and sulphur concentrations in the creek and seep locations. Bars indicate seepage, while lines indicate the creek concentration of each element.

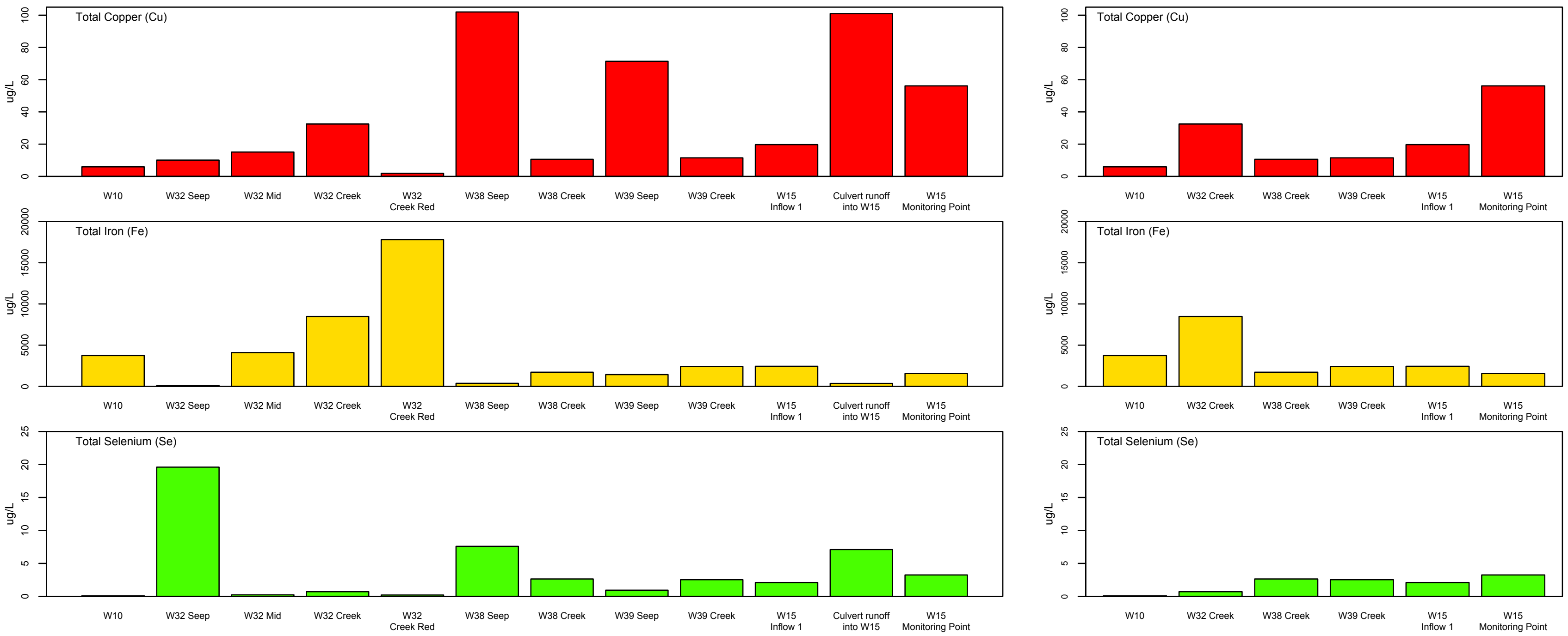


Figure 6: Copper, iron, and selenium concentration in water. The left plots show all sites, while the right plots show the distribution of elements along the creek. The W15 Monitoring Point represents the average of September 17th and September 28th, 2013, monitoring timepoints, which are the closest dates to the site visit when samples were obtained.

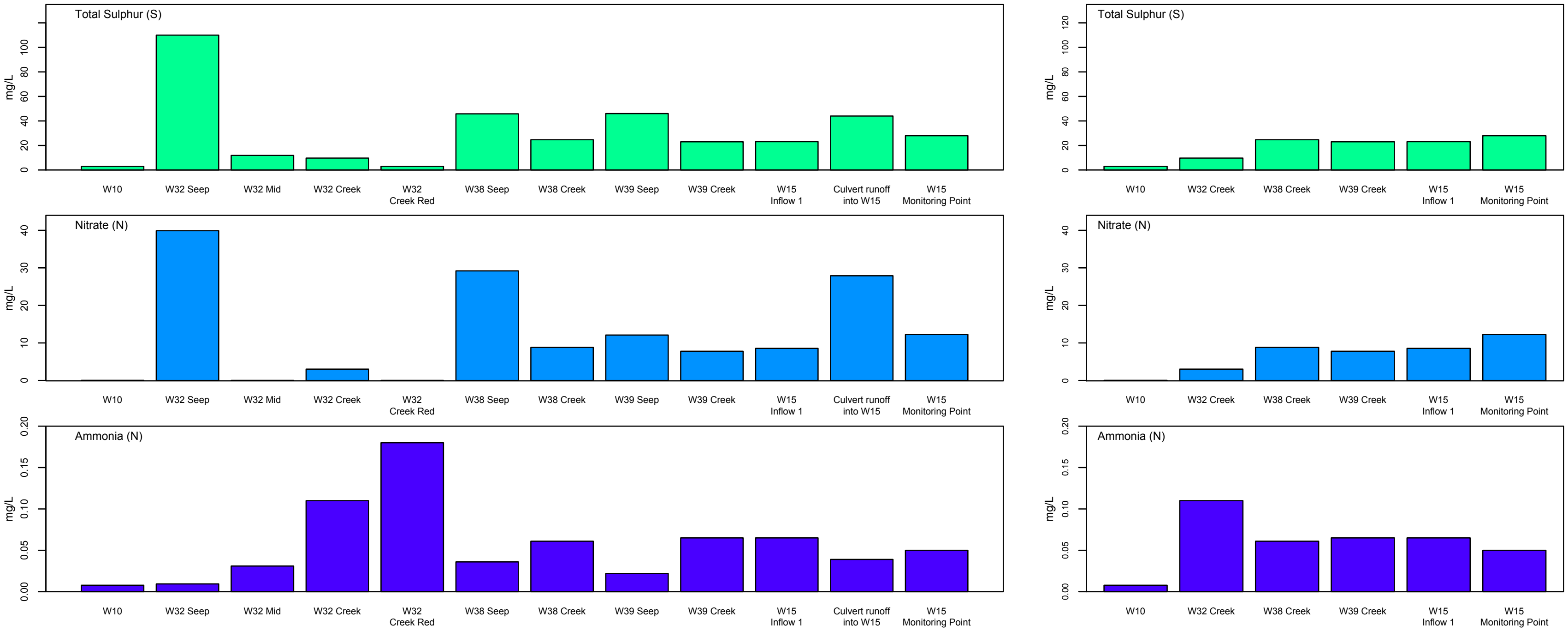


Figure 7: Sulphur, nitrate, and ammonia concentration in water. The left plots show all sites, while the right plots show the distribution of elements along the creek. The W15 Monitoring Point represents the average of September 17th and September 28th, 2013, monitoring timepoints, which are the closest dates to the site visit when samples were obtained.

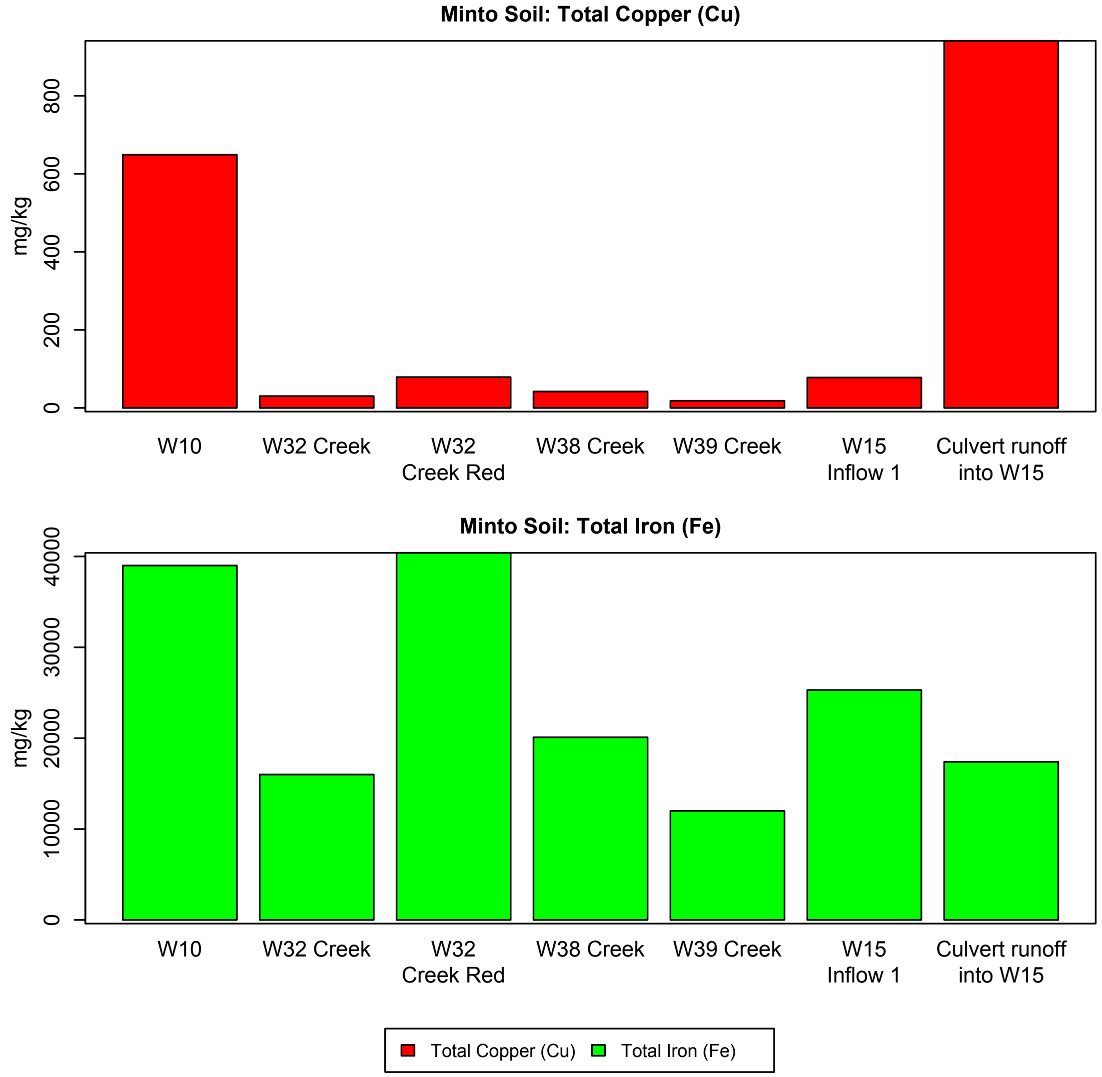


Figure 8: Copper and iron concentration in soil. Selenium was below the detection limit in sediment (<0.5 mg/kg), and is therefore not shown.

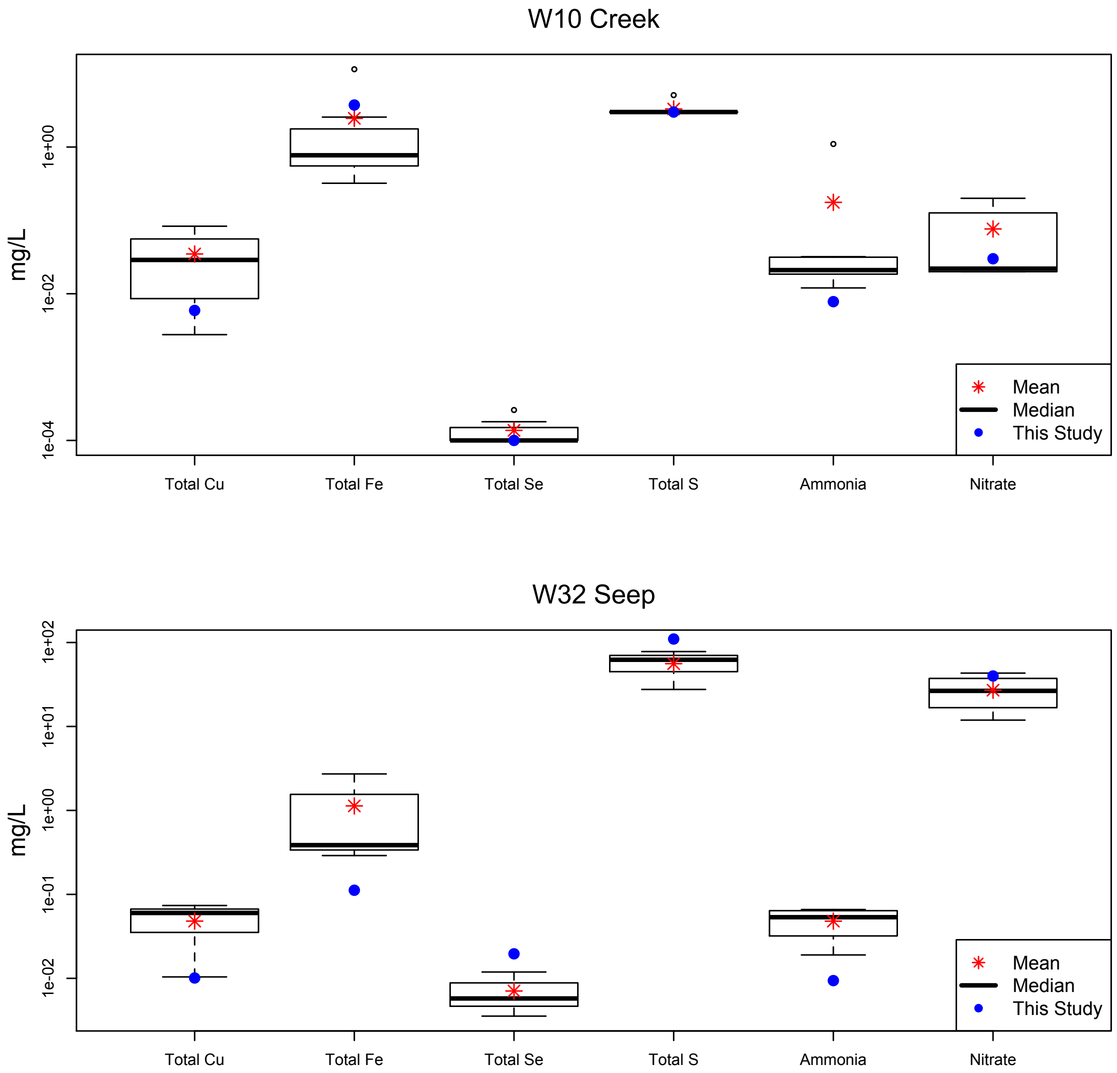


Figure 9: Concentration of select elements from all 2013 routine monitoring program measurements. Blue dot indicates concentration measured in samples collected as part of this study. Figure is continued on following page.

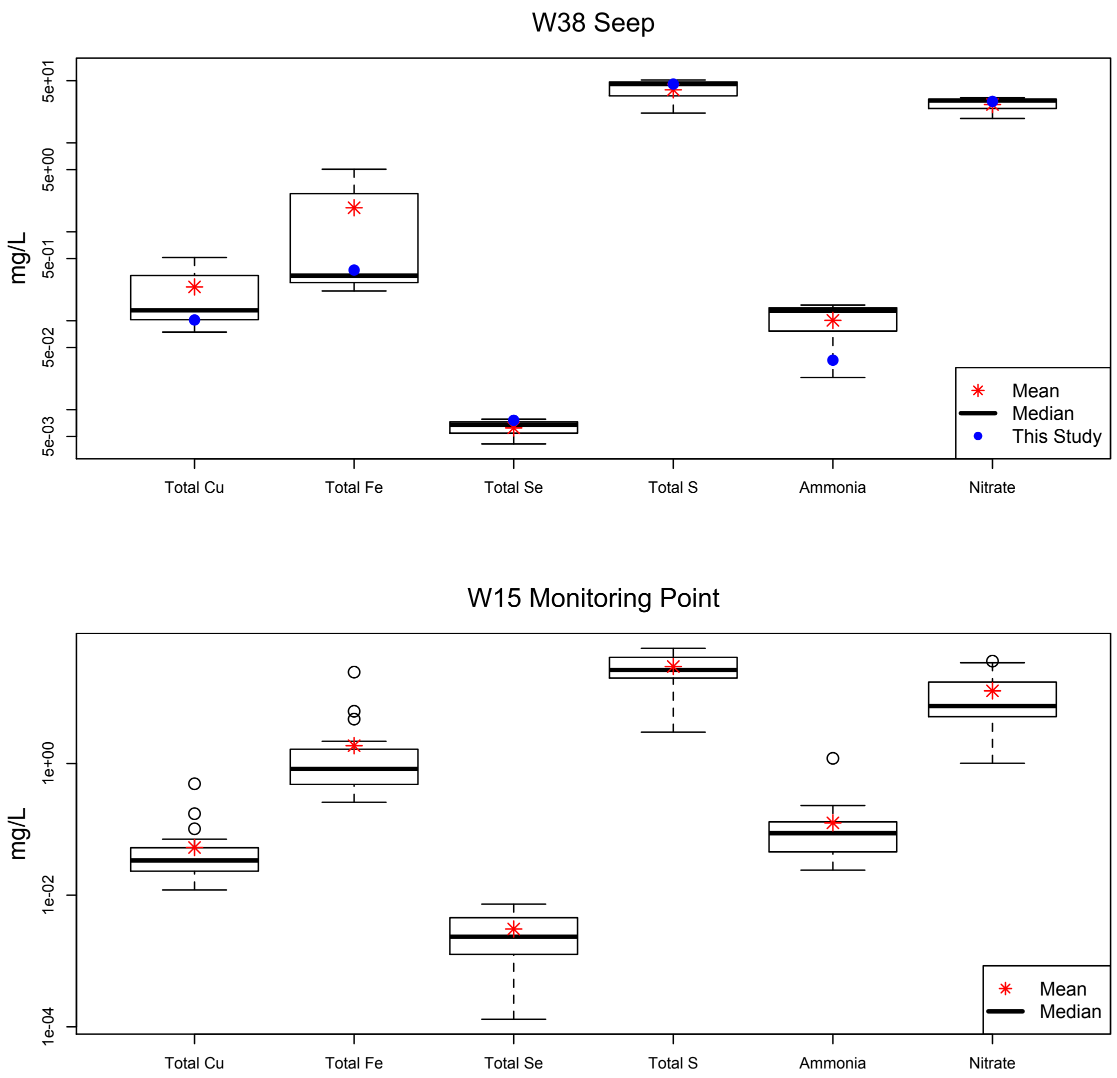


Figure 9: Concentration of select elements from all 2013 routine monitoring program measurements. Blue dot indicates concentration measured in samples collected as part of this study. Figure is continuation from previous page.

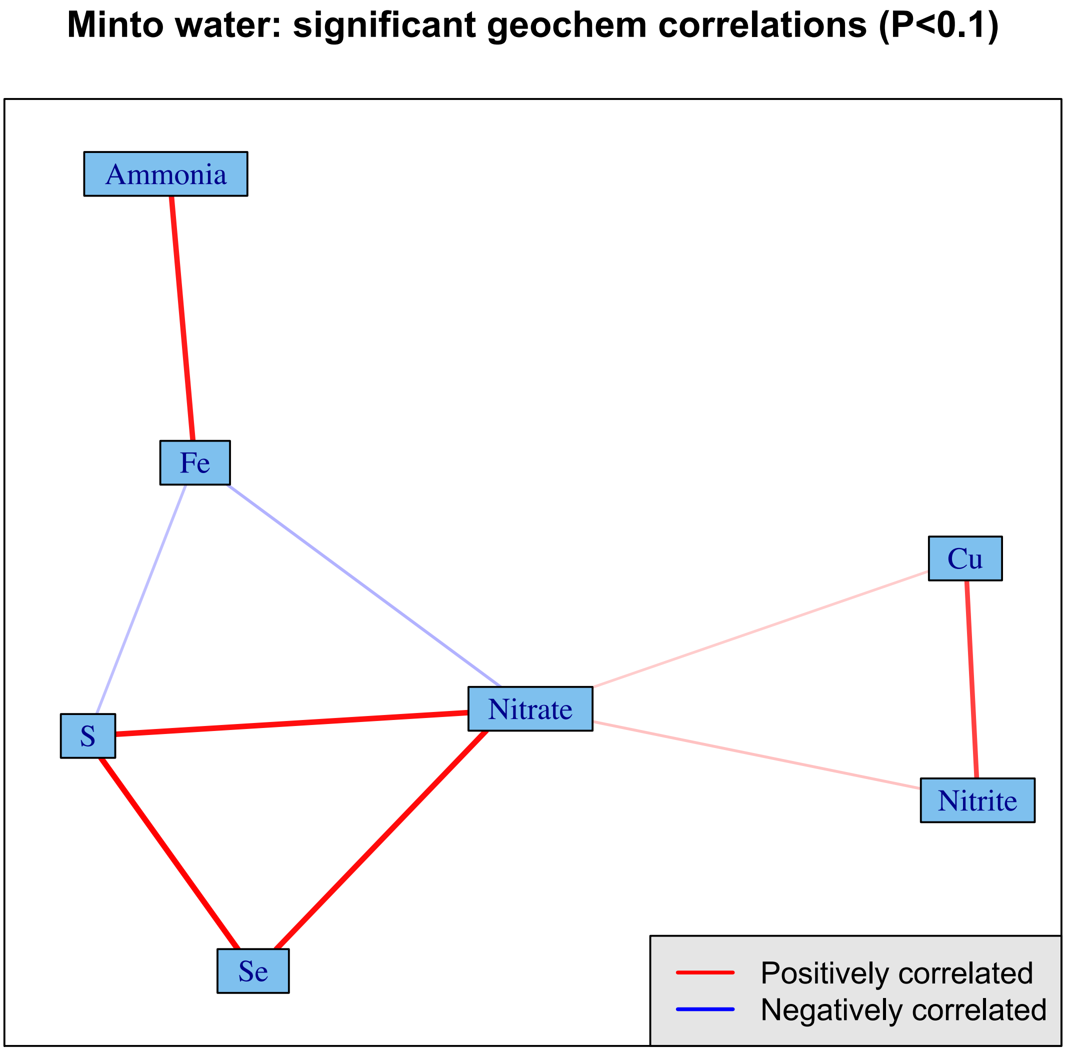


Figure 10: Correlation of various compounds in water. The strength of the line connecting different compounds indicates the strength of the correlation. For example, the thick line between Se and S corresponds to a Pearson correlation coefficient of 0.939, while the line connecting Cu, and Nitrate or Nitrite corresponds to a coefficient of 0.527 or 0.812, respectively. All Pearson correlations are significant at a level of $P<0.1$. Also of note, copper concentrations in soil were found to be significantly correlated with copper and nitrite concentrations in the water (not depicted in figure).

Figure 11: *C. aquatilis* and grasses are dominant at the W32 area that was recently cleared.

Figure 12: *C. aquatilis* spreading through the W10 area access road, being the first plant to colonize the road and recent tire ruts.

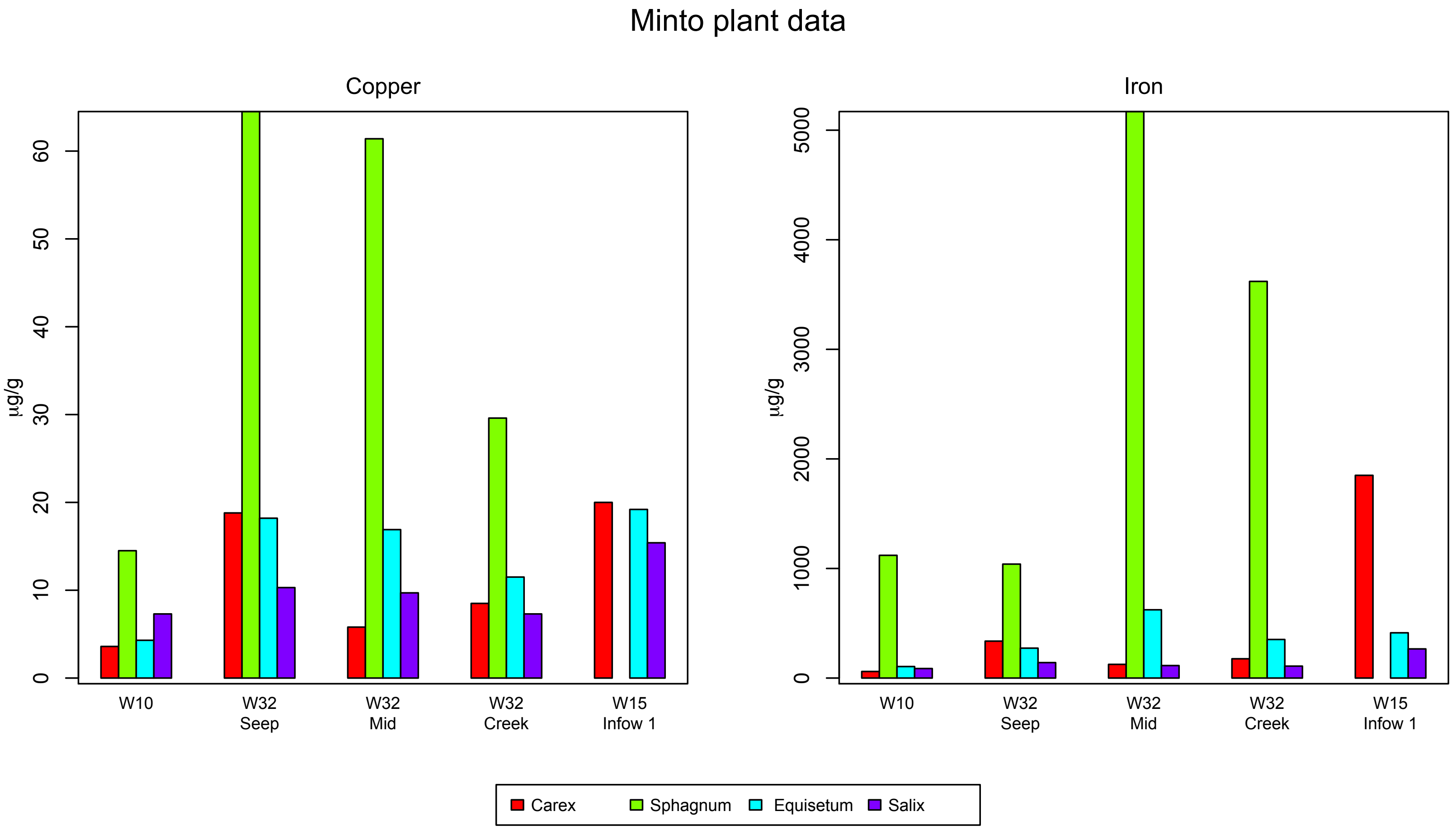


Figure 13: Concentration (µg/g) of dry plant matter for copper and iron in plants at the Minto Site. Note that there was no *Sphagnum* present at the W15 inflow site available for collection.

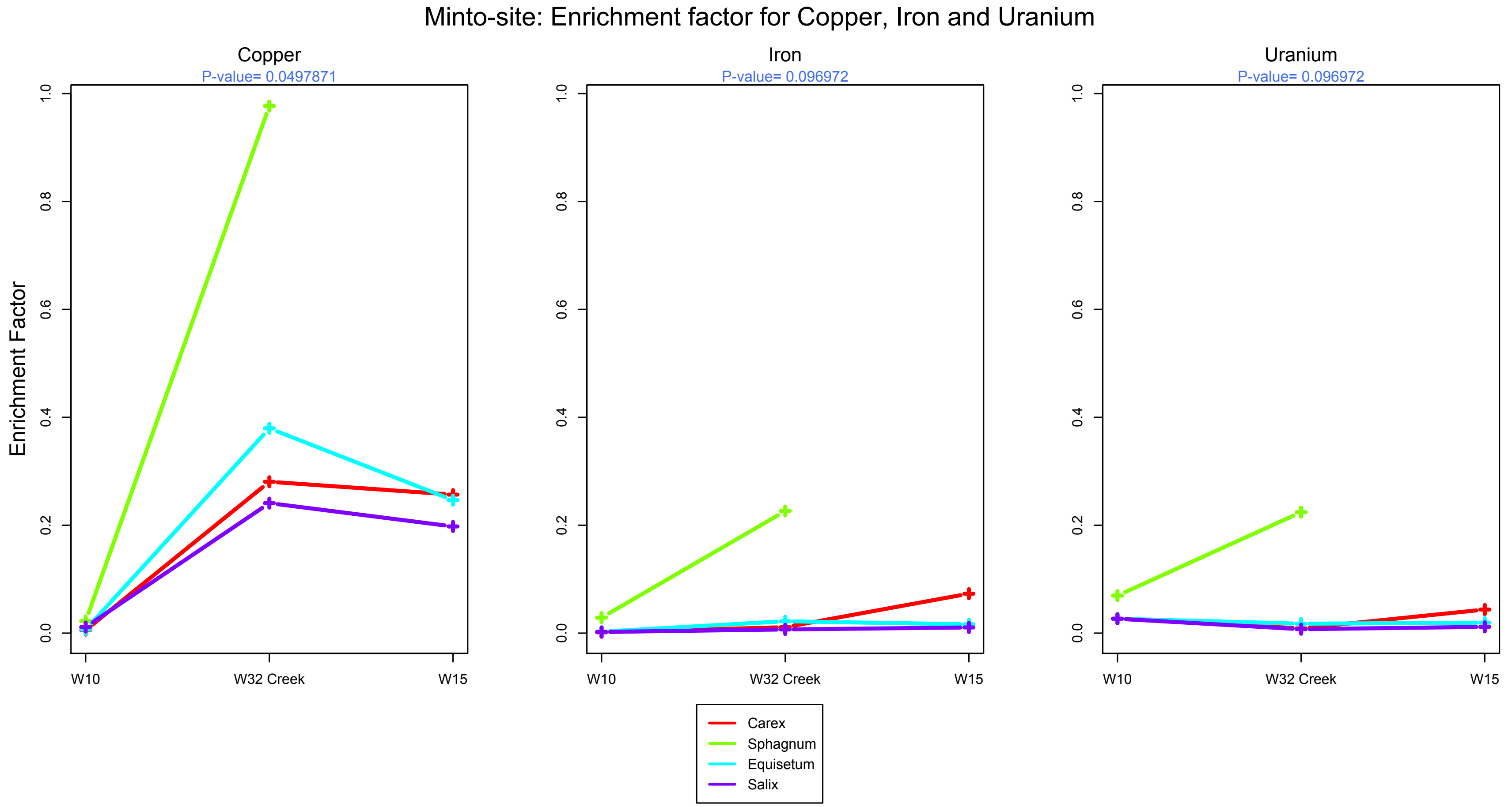


Figure 14: Enrichment factor for copper, iron, and uranium in *Carex, Sphagnum, Equisetum,* and *Salix.* A p-value <0.1 indicates there is a significant difference in the enrichment factor at different sites. Note that there was no *Sphagnum* present at the W15 inflow site available for collection.

Figure 15: Example of creek channeling through *Salix* plants.

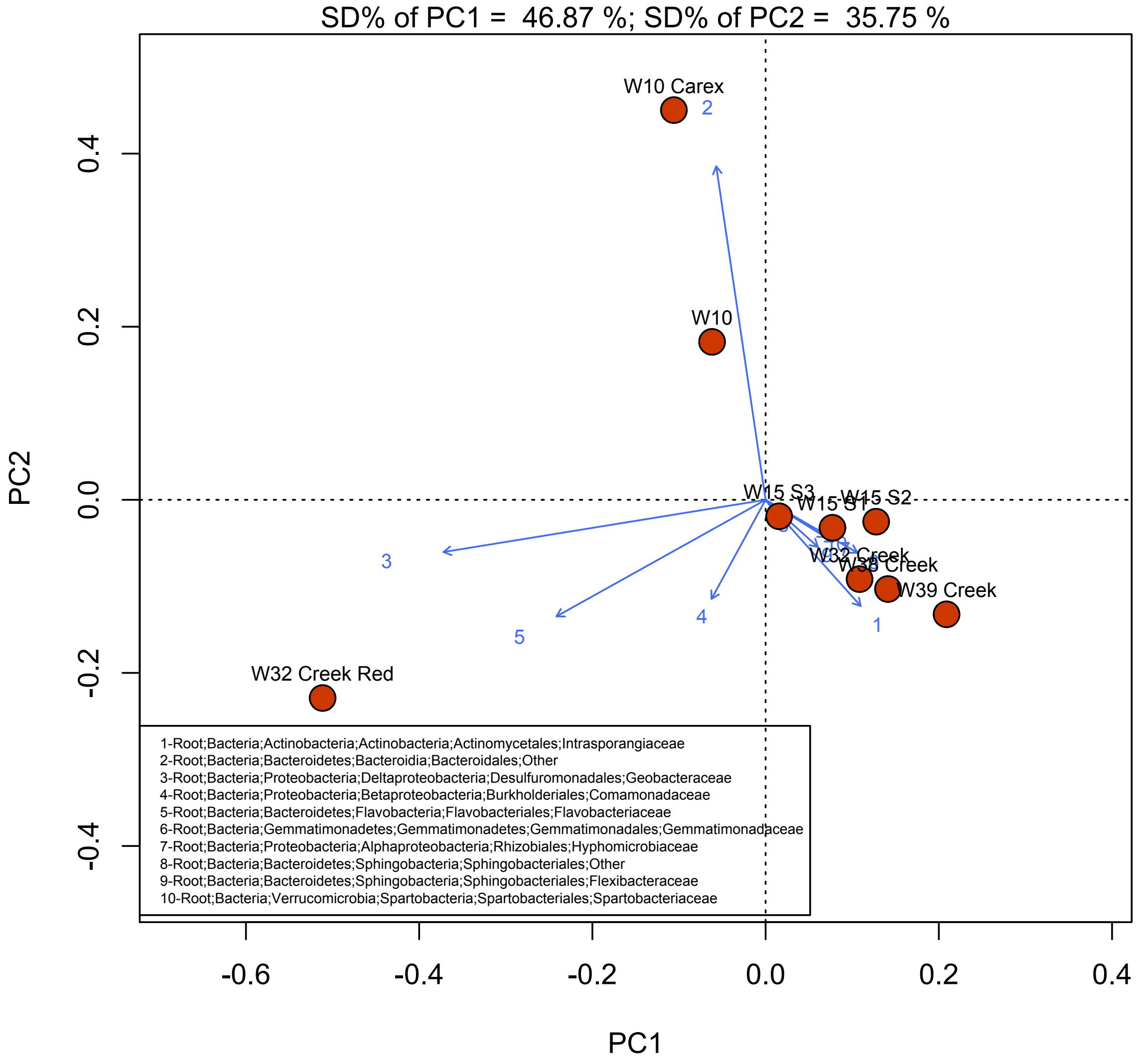


Figure 16: Principal component analysis of all sites based on microbial community profiles. All sites that cluster together have similar microbial profiles, while sites clustering on their own (e.g., W32 Creek Red) show a less similar profile. Each numbered arrow represents a group of microorganisms listed in the legend. Essentially, the direction and length of an arrow represents how abundant that group of microorganisms is in each sample. For example, W32 Creek Red would show a high abundance of *Geobacteraceae* (arrow #3) and *Flavobacteriaceae* (arrow #5), while W10 Carex shows a high abundance of *Bacteroidales* (arrow #2). All creek samples (W32, W38, W39, and W15) cluster together and show similar microbial profiles (high abundance of *Intrasporangiaceae,* arrow #1).

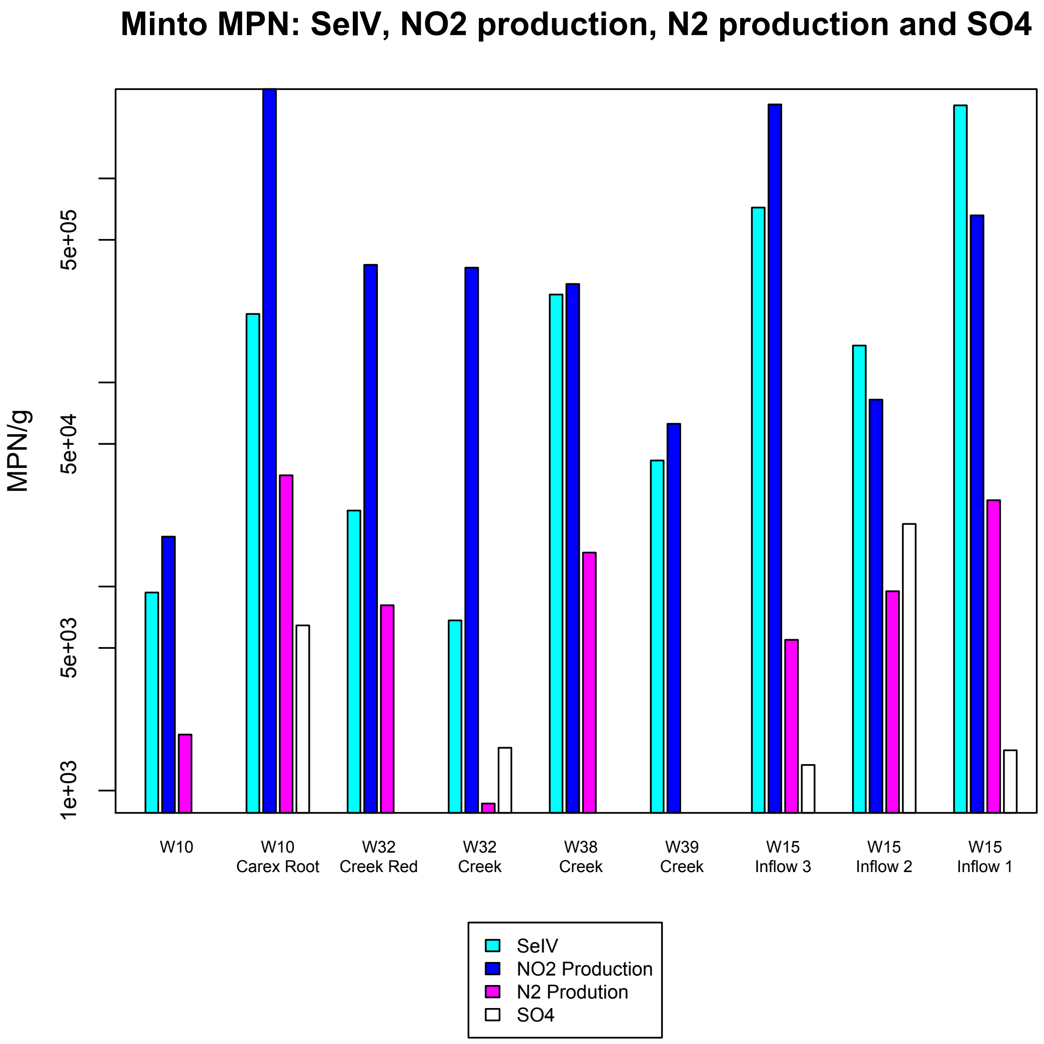


Figure 17: Predicted number of selenite, sulphate, and nitrate reducing bacteria found at various Minto sites, based on the most-probable number assay. The nitrate-reduction assay tests for microbes that can reduce nitrate to nitrite (i.e., NO_2 Production), as well as microbes that can further reduce nitrite to nitric oxide or nitrogen gas (i.e., N_2 Production).

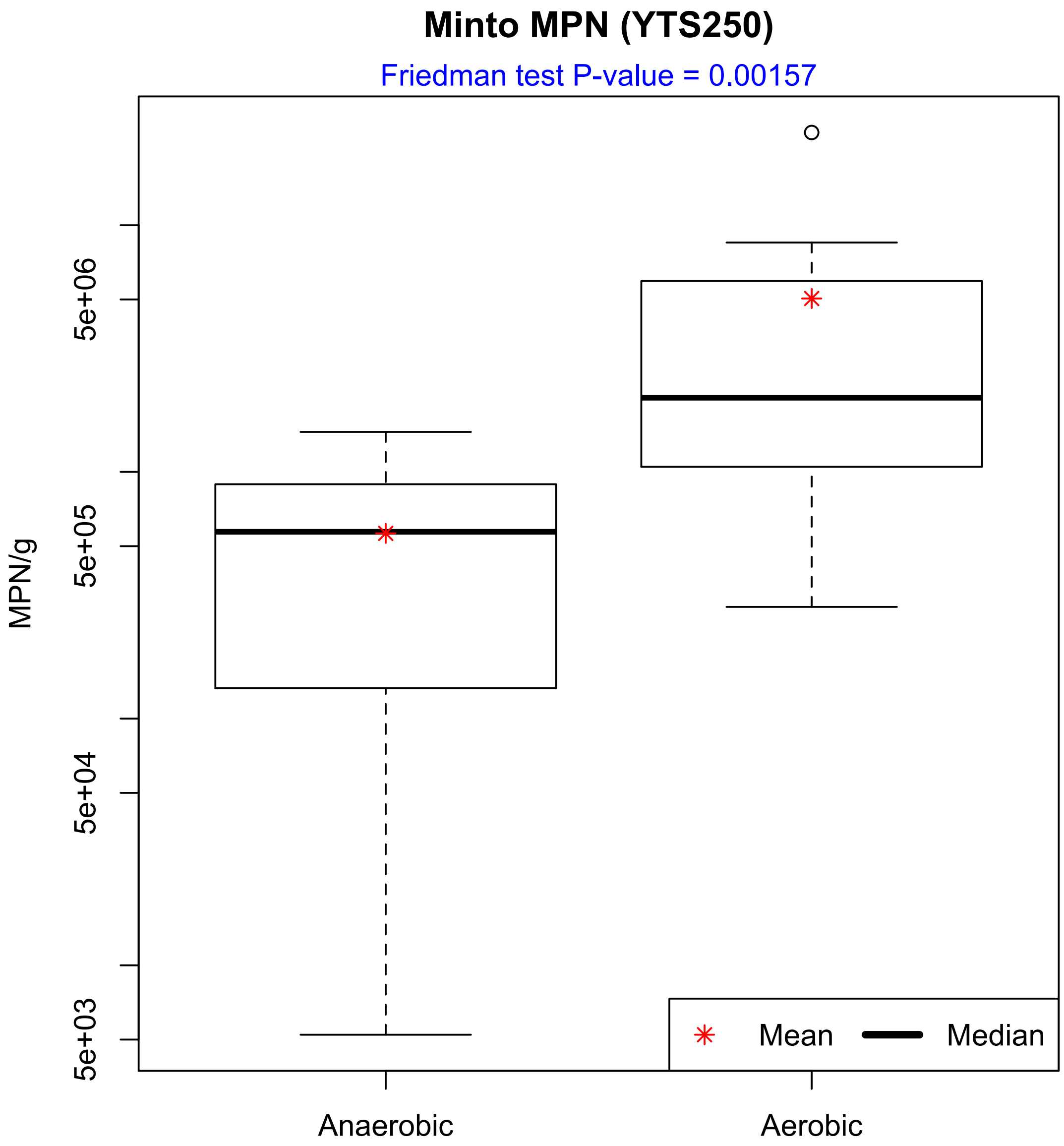
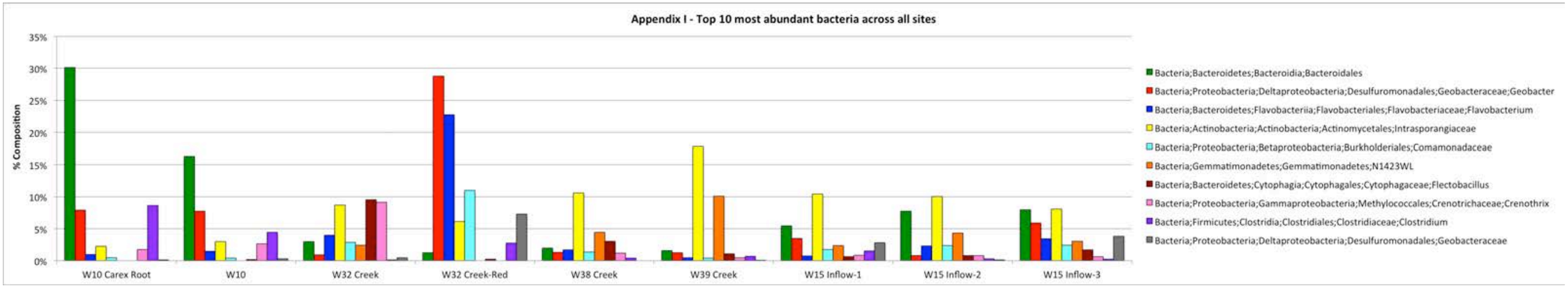


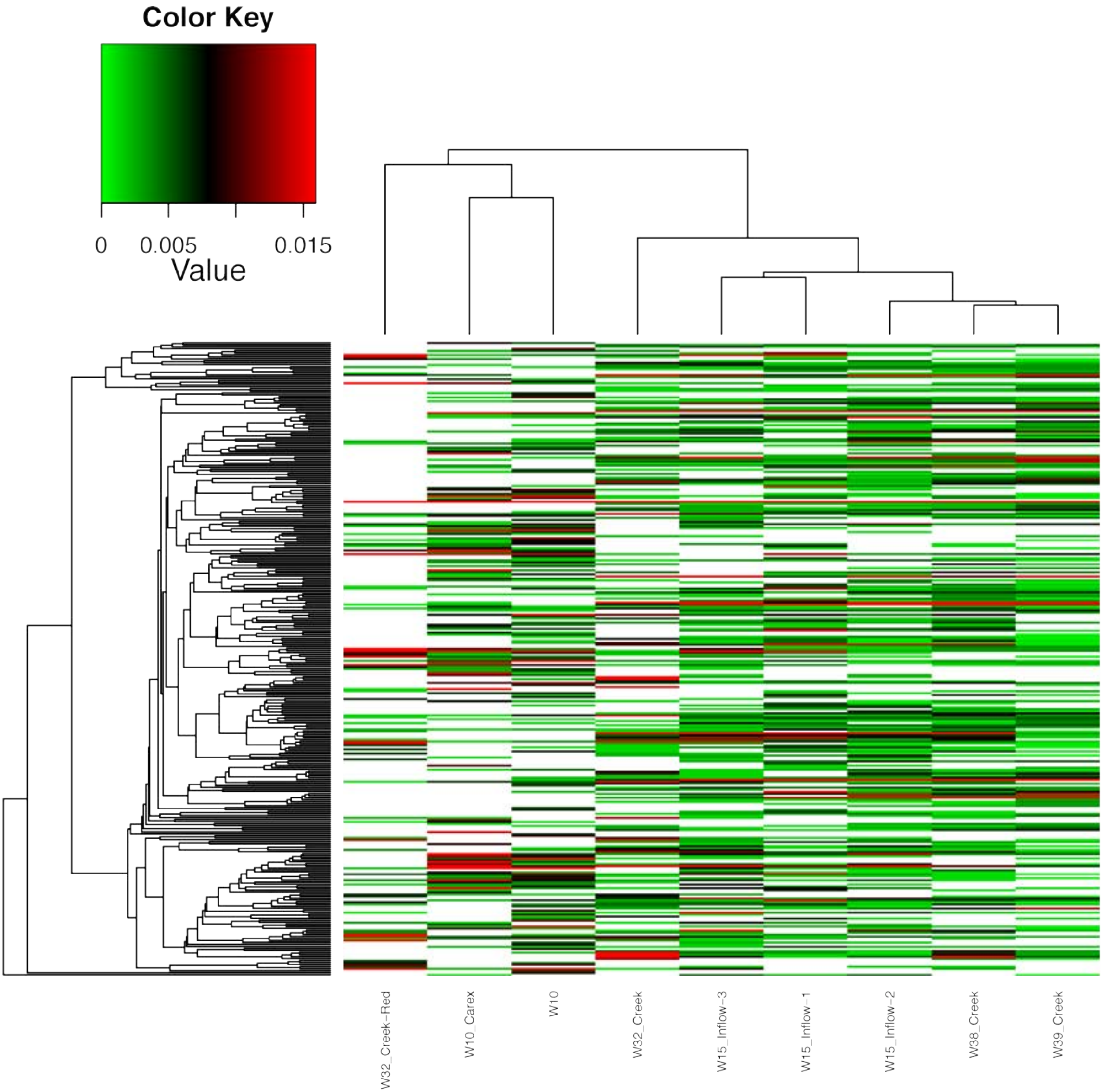
Figure 18: Most-probable number of total heterotrophic organisms at the Minto site. The number of heterotrophic organisms growing under aerobic (with oxygen) and anaerobic (no oxygen) conditions is shown. Significantly more total heterotrophs grew under aerobic conditions that under anaerobic, as demonstrated by a P-value < 0.05.

Figure 19: Color distribution of sediment surrounding *Carex* root at the W10 location.



Appendix I - Top 10 most abundant bacteria across all sites

Appendix II - Microbial Profile



Heatmap showing the distribution of bacteria at the Minto Mine. Each column represents a sampling location, while each row represents an OTU (group of bacteria). The abundance of each group of bacteria is depicted through a heatmap: white indicates absent, and green through red indicates increasing abundance. Samples are clustered together based on the similarity of microbial communities, and indicated by the dendrogram at the top of the heatmap. The dendrogram on the left represents a phylogenetic tree of all OTUs.

Appendix A2

Wetland Treatment Research Program - Pilot Scale

Forward looking. Lateral thinking.

Minto Mine Constructed Wetland Treatment Research Program – Pilot Scale

Prepared for

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Date:
November 3, 2014

Table of Contents

1. Abbreviations and Definitions

CWTS(s) – Constructed Wetland Treatment System(s).

Dissimilatory reduction – is a process utilized by specific types of bacteria where an electron donor material (e.g. organic carbon) is oxidized, producing energy for the bacteria and reducing another material (e.g. sulphate, or selenium) as part of the microbial metabolism.

DNA (deoxyribonucleic acid) – is the hereditary material in almost all living organisms. This can be used to identify organisms.

DO – Dissolved Oxygen.

Heterotroph – an organism deriving its nutritional requirements from complex organic substances.

Metagenomics – the study of genetic material recovered directly from environmental samples, related to a community rather than an individual organism.

Microbes – microscopic organisms which may be uni- or multi-cellular. This includes algae, bacteria, fungi, viruses, and yeast.

MPN (Most Probable Number) – a statistical value representing the viable population of microbes in a sample through use of dilution and multiple inoculations.

Oxidation – is the loss of electrons or increase in oxidation state by a molecule, atom, or ion. Can be driven by microbes. Process is complementary to chemical reduction.

Redox – Oxidation-reduction potential, measured in millivolts.

Reduction (chemical) – is the gain of electrons or a decrease in oxidation state by a molecule, atom, or ion. Can be catalyzed by microbes. Process is complementary to chemical oxidation.

RRC (Removal Rate Coefficient) - a numerical value, expressed as the variable *k,* representing a first order rate of removal, considering removal extent and the time required for removal.

SeIV broth or agar – laboratory growth medium that contains selenite (SeIV) and indicates reduction of selenite to elemental selenium through a visible colour change.

Species – one of the basic units of biological classification and a taxonomic rank. Rank in the classification of organisms below genus and above strain.

Taxonomy – classification, identification, and naming of organisms.

TSS – Total Suspended Solids.

YTS250 (Yeast, Tryptone, Starch, 250g each) – a type of laboratory growth medium used for environmental microbes.

2. Introduction

Constructed Wetland Treatment Systems (CWTSs) have been proposed as a method for improving the quality of site runoff water in the post-closure period for the Minto Mine (Minto Phase V/VI Expansion Project, YOR Project Number 2013-0100). Once established, wetlands can become self-sustaining ecosystems with the plants providing yearly renewal of carbon to fuel microbial activity. As such, they possess the desirable potential to remediate contaminated mine drainage for as long as it is generated. In order for CWTSs to be effective, however, they must be designed, piloted, optimized, implemented, and maintained in a site-specific manner.

Wetlands provide a natural environment in which unique biogeochemical reactions can occur. CWTSs can be designed to have desirable conditions similar to those in natural wetlands, and should be designed specifically for each site. Having a site-specific approach allows for the appropriate set of operational conditions to be achieved, where complex coupled reactions can take place for treatment of targeted constituents. This can be done with complex and challenging waters, where problematic constituents are transferred or transformed to less bioavailable forms. The benefits of CWTSs include:

- low operational cost,
- low maintenance,
- effective and robust treatment,
- increased effectiveness over time,
- aesthetically pleasing,
- tolerance to changes in flow rate and contaminant load, and
- simultaneous treatment of multiple constituents more effectively than chemical or physical treatment processes.

CWTSs have been used to mitigate risks to aquatic receiving environments from a variety of aqueous contaminants, including copper (Cu) and selenium (Se). The biogeochemical reactions that take place in a wetland environment are many, but there are specific reactions that may decrease the aqueous and more bioavailable concentrations of some contaminants (e.g. Cu, Se), thus lowering risk to the receiving environmental systems by decreasing exposure to contaminants. A process called dissimilatory sulphate reduction can chemically reduce available aqueous sulphate to sulphide through the metabolism of specific bacteria. Once dissimilatory sulphate reduction has occurred, it provides a mechanism to remove dissolved cations such as Cu from water by complexation with the sulphide ion to produce copper sulphide, an insoluble precipitate. Selenium treatment in a CWTS is a similar process, but with slightly different results. The mechanism for Se treatment is more direct, through dissimilatory selenium reduction that is also microbially mediated, often by some of the same bacteria that undergo dissimilatory sulphate reduction. The most common forms of aqueous Se are selenite and selenate, with valence states of IV and VI, respectively. When these are reduced in a wetland to an insoluble state, Se precipitates as elemental Se(0).

In both cases, the Cu and Se precipitates are removed from the water through filtration mechanisms inherent in wetlands and are sequestered into the sediments over time as an accretive process. Accretion is the naturally occurring process of accumulation of wetland sedimentary material (soil, minerals, decaying plant material, etc.) over time. Once an accreting CWTS is established and mature, targeted constituents are sequestered into the sediment and covered over time by newly generated sediments and detritus. This essentially seals away the treated constituents under layers of sediment, rendering them less bioavailable and less susceptible to re-entry into the water column. There is therefore no need to dredge or harvest wetland plants for the Minto site; in fact, this type of activity would disrupt the treatment functions and re-expose the previously sequestered constituents. This process mimics what occurs in naturally created wetlands; therefore, this process is often the best option for long-term, low-maintenance and effective treatment.

3. Background

At the request of Minto Explorations Ltd, Contango Strategies has undertaken a pilot-scale study to inform the design of site-specific passive treatment technologies for the Minto site during post-closure. These pilot-scale trials build upon a site assessment that was conducted and reported on in 2013. The overriding goal of this pilot study is to develop, optimize, and test site-specific pilot-scale CWTSs for post-closure water treatment at the Minto site.

4. Pilot System Operations

4.1. Design and assembly

In October 2013 three pilot CWTSs were constructed, each in duplicate, to evaluate the performances of different designs for selenium and copper treatment (Figures 1 and 2). These were planted with either Sedge (*Carex aquatilis*), or Sedge and aquatic moss as follows:

- System 1 and 2: *Carex aquatilis*
- System 3 and 4: *Carex aquatilis* + Moss
- System 5 and 6: *Carex aquatilis* + Moss, with biochar amendment in soil

The pilot CWTS systems were built with two cells per series, each cell having a 41 cm diameter and a height of 57 cm. To establish the plants, soil was filled to a depth of 20 cm at the bottom of each cell, and submerged under 10 cm of tap water. The water depth was changed throughout the pilot testing to evaluate effects on performance, and develop strategies for optimization.

4.1.1. Hydrosoil

Hydrosoil is a specially selected soil blend to aid in achieving the targeted hydraulic conductivity required to meet the CWTS objectives. In this case, the hydrosoil mixture was the same for all pilots; sand amended with 2% woodchips (v/v) and 5% peat, except that the third system design (system 5 and 6) also included a 5% pine biochar amendment. The sand and amendments were tested for initial metal and nutrient contents (Table 5). This specific type of biochar was chosen as an amendment as previous studies conducted by Contango have demonstrated that addition of biochar to the hydrosoil can result in faster establishment and growth of newly planted wetland plants (SETAC Presentation #593, Haakensen 2013). The biochar selected was low in soluble salts, had a high surface area, low metals content, and moderate available organic carbon and phosphorous (Appendix 1). The peat borrow site at the Minto Mine was selected as it provided a sufficient quantity for a full-scale wetland. It was tested for metals content and other relevant parameters such as nutrients (N, P, K), and total organic carbon before use in the pilot CWTS system.

4.1.2. Plants

Two plant species were of interest for the pilot CWTS based on data collected during the August/September 2013 site assessments (reports 2013-0100-256 and 2013-0100-257 on the YESAB registry). *Carex aquatilis* (sedge) was chosen, as it is readily available at the Minto site and was one of the first plants to colonize cleared areas, indicating that it may be a good candidate for quickly establishing the CWTS. Moss was also used in the second and third pilot CWTS designs (systems 3-6), as locations at Minto with shallower water had *Carex* and Moss coexisting. As such, we wanted to assess whether the Moss contributes positively or negatively to treatment, and also whether succession from *Carex* to Moss as the dominant plant can be prevented or enhanced through modification of water depth.

It is well known that Moss has a high uptake rate of cations (such as copper and selenium) and is also a relatively benign sink for these elements (i.e., is not a food source for invertebrates or higher animals and as such does not contribute greatly to bioaccumulation (Haines & Renwick, 2009; Longton, 1997; Suren & Winterbourn, 1991)). This was also confirmed in the site assessment in 2013, which produced data indicating that Moss at the Minto site has a high uptake of elements such as copper, and could therefore be an effective means of removing elements from seepage through uptake. During the September 2013 site visit, Moss and *Carex* were collected from the Minto site and these were subsequently used to vegetate all pilot CWTS in this study. A total of 10-12 *Carex* were planted per cell, with approximately a 250ml volume of Moss (compressed) added to systems 3-6.

4.1.3. Water and Testing Periods

The CWTS(s) were designed for treatment of water that would be present at the Minto site after closure. As such, this water does not yet exist and had to be synthesized as an approximation based on water quality modeling. The worst-case post-closure water chemistry was used based on the month of October, as it had the highest concentrations of key elements for any month with free-flowing water. The synthetic water underwent five iterations of design, testing, and optimization to ensure the composition and method of formulating the water resulted in analytical chemistry that matched the water quality predicted to exist after closure and reclamation of the Minto mine. The final recipe and resultant water chemistry is provided in Tables 1 and 2.

Design of the synthetic water chemistry focused on constituents requiring treatment and elements/compounds that are expected to affect treatment rates or capacity based on previous experience and scientific literature. For the first period (High N) of the pilot-phase work, the predicted maximum worst-case ammonia and nitrate concentrations were used, which reflected residuals of these compounds from blasting. The ammonia concentrations measured on site are lower than would be expected based on the chemical composition of ammonia nitrate used for blasting, suggesting that the ammonia has already undergone oxidation to nitrate prior to the seepage exiting the waste rock pile. Nitrate can affect compounds such as selenium that are removed from water through coupled biogeochemical reactions and dissimilatory reduction, as nitrate has a high affinity for available electrons and is preferentially reduced before other compounds. However, it is known that over time in closure, the concentrations of ammonia and nitrate will decrease dramatically, and this may affect removal rates of other compounds. As such, the pilot-scale CWTSs were subjected to a 6-week trial of synthetic water of the same max worst-case post-closure water quality, but with depleted ammonia and nitrate concentrations to simulate the chemistry expected in long-term closure (Low N period).

It is possible to shift the functionality of a CWTS to stimulate additional microbial dissimilatory selenium reduction and enhance overall treatment of this element. The resultant CWTS would be a hybrid bioreactor-CWTS and is a “passive care” option. This means that the hybrid-CWTS would require more maintenance and operational intervention than a normal CWTS, with periodic dosing of an organic amendment needed (once or a few times annually) in order to achieve the targeted decreased dissolved oxygen and redox levels. However, depending on actual inflow and target outflow concentrations, this approach may be a necessary compromise.

The third and final stage of pilot testing therefore included the addition of an organic carbon amendment (alfalfa hay and straw) to stimulate reducing conditions for improved selenium treatment. Alfalfa hay and straw were chosen as they would provide both short and long-term carbon sources compared to a metered dosing of more available electron donors such as ethanol. This hybrid bioreactor-CWTS period was conducted as an 8-week trial to test how the CWTS functions once converted from conventional CWTS operation to the hybrid configuration. A total of 1.4 g of alfalfa pellets were added per liter of water in each A cell. Straw was added at 10 cm^3 per L to A cells, and 5 cm^3 per L to B cells. The alfalfa pellets and oat straw were tested to ensure suitability for use (Appendix 1). A summary of the periods and timelines is provided in Table 3.

Over the course of the study, a total of 45,000 L of synthetic water (influent) was received by the pilot CWTS (in 41 batches), approximately 1,200 L of synthetic water per week in a pilot CWTS footprint of 1.56 m^2. The system operated with a flow rate of 20 mL/min, resulting in a hydraulic retention time (HRT) ranging from 34 to 94.3 hours, depending on the period of testing and water depth (Table 3).

4.1.4. Routine Monitoring of Explanatory Parameters

Explanatory parameters are characteristics of a specific environment that describe conditions in the context of how these parameters can affect the chemical reactions taking place. These parameters, when within specific ranges of values, can be used to predict and/or promote certain reactions in the aforementioned environment. Accordingly, dissolved oxygen (DO; mg/L and %), temperature (°C), pH, conductivity (µS/cm), specific conductivity (SPC; µS/cm), and oxidation-reduction potential (ORP; mV) were measured on a routine schedule with a YSI Professional Plus handheld unit.

Hydrosoil reduction-oxidation (redox) potential was measured using inert electrodes (copper wire probes with platinum tips) that were permanently installed in the hydrosoil of the cells and remained there for the duration of the project to ensure accurate readings (Faulkner et al., 1989). On testing days, a reference electrode (Accumet Calomel) was suspended in the water column above the inert electrode. The redox potential was then measured in millivolts by a voltmeter.

4.1.5. Flow Rates

Constant flow metering pumps were used to set the flow rate of water into the system. To confirm flow rates, the influent to cell A was collected into a graduated cylinder over a timed period of several minutes allowing a flow rate to be calculated in milliliters per minute (mL/min). Flow rates were measured regularly (at minimum weekly) and adjusted as necessary to within +/-10% of the desired flow, to achieve the desired HRT. The rate of water outflow from a CWTS cell was measured using the same procedure. Outflow rates for a series were typically measured every 2 weeks.

4.1.6. Water sampling

Water samples were collected from the outflow port of each CWTS cell. Care was taken to avoid collecting plant matter, invertebrates, or other debris in the sample. Samples were collected from downstream to upstream to ensure the water sampling did not affect sample collection from the next cell (e.g., disrupting flow rates or suspending solids). All samples were collected according to the schedule in Table 4, with parameters outlined in Table 5.

4.1.7. Stem Counts and Height Measurements

Carex aquatilis stems were counted in each CWTS cell, and 10 stems were randomly chosen in each cell for height measurement. The height of the tallest leaf of each stem was measured to the nearest 0.5 cm from the soil surface to the tip of the leaf. Stem counts and heights were taken monthly during the High N period, as well at the end of the Low N and hybrid bioreactor-CWTS periods (Table 4).

4.1.8. Sediment Sampling

Sediment/hydrosoil samples were collected at key intervals as per Table 4. Sediment was collected by carefully taking a grab sample of a small section of the top 6 cm of hydrosoil in each CWTS cell into a 50 mL centrifuge tube, pouring off any excess water after collection. In addition to the analyses listed in Table 5, sediment was also collected for microbial profiling according to the schedule in Table 4 and as described in Section 4.3.

4.1.9. Plant Sampling

Both *Carex* and Moss were collected for metals analysis at the beginning of the study, as well as at end of the Low N period. This schedule was chosen as it was uncertain if the Moss would survive through the hybrid bioreactor-CWTS period. For sample collection at the end of the Low N period, 4 stems of *Carex* (~15% of total stems) were randomly selected from each cell and trimmed at the surface of the water. An approximate 250 ml volume of compressed Moss was also collected from each cell in series 3-6. Plants from replicate series (e.g., series 1&2, 3&4, 5&6) were combined and sent for metals analysis as a representative sample for each system type. For the final sampling point (i.e., at pilot system takedown) all remaining *Carex* plants in each cell were trimmed at the soil level and rinsed with water prior to sending for metals analysis.

4.1.10. Freeze-Thaw Trial

In addition to routine analysis for metals in plants, a replicate of each plant sample collected at the end of the low N period was used in a freeze-thaw trial to determine if the plants will leach constituents of concern such as Cu and Se after freezing. In this trial, 200 mL of water from the corresponding CWTS cell was added to the plant sample to completely cover the plant material. The samples were frozen at -20°C for 5 days, and then thawed at room temperature (~22°C) overnight. The plant samples were removed and lightly squeezed to return residual water to the container, and the plant tissue was sent for metals analysis to compare with pre-freeze concentrations.

4.1.11. Organic Carbon Leach Test

To determine the constituents that could leach from the alfalfa and straw that were added for organic carbon during the hybrid bioreactor-CWTS period, a leach test was performed. In this test, 2 L of outflow from system 1 was collected and alfalfa and straw were added to mimic the concentrations that were added to the system. The water was tested for total metals 3 weeks after the organic carbon addition to determine if any metals had leached from the alfalfa and straw into the water.

4.2. **Methods for microbial analyses**

4.2.1. Growth-based analyses (MPN)

The most-probable number (MPN) of bacteria was determined for all micro samples. The MPN test allows for an estimation of the number of bacteria that can grow in a specific laboratory medium. The media tested in this project were specific for bacteria that can reduce nitrate, selenite, and sulfate, respectively, as well as the total number of heterotrophic bacteria for comparative purposes (i.e., a growth-permissive test for all bacteria capable of growing on organic carbon as an energy source). MPN tests for sulphate (Active Standard ASTM D4412) were conducted under anaerobic conditions, whereas selenite (Siddique et al., 2006) and nitrate (Nitrate Reduction Test, supplied by Sigma-Aldrich) were tested under aerobic conditions. Total heterotrophs (grown with YTS250 medium; (Lefrançois et al., 2010) were quantified in both aerobic and anaerobic conditions.

In brief, sediment samples were diluted 1:100 with a 0.1% peptone solution. This starting dilution was then used for a serial dilution along a sterile 96-microwell round-bottom plate containing the respective growth media. Sediment dilutions tested in the MPN plate ranged from 1/400 to 1/419,430,400. At minimum, all tests were conducted in duplicate. Wells were incubated at +30°C without light and assessed for visible growth (formation of a bacterial pellet) and/or colour change specific to the type of media after 27 days. A colour change to black or red/orange indicated sulphate or selenite reduction, respectively. Nitrate reduction was tested as per the kit manufacturer's protocol by addition of reagents to differentiate between reduction to nitrite or nitrogen gas. The most probable number of bacteria capable of each metabolism was then calculated as described in the FDA Bacteriological Analytical Manual, Appendix 2: Most Probable Number from Serial Dilutions: (http://www.fda.gov/Food/FoodScienceResearch/LaboratoryMethods/ucm109656.htm). The MPN of organisms in each pilot system was compared over time using the non-parametric Kruskal-Wallis test.

4.2.2. DNA-based analyses

DNA was extracted from all samples using the MO BIO Powersoil Powerlyzer DNA extraction kit, with the addition of phenol during cell lysis as per the manufacturer's alternative protocol. Targeted sequencing was used to identify bacteria present in each sample via polymerase chain reaction (PCR) amplification of the v3/v4 region of the 16S ribosomal RNA gene (Klindworth et al., 2013). Library preparation and sequencing was performed as per the manufacturer's instructions for MiSeq v3 paired-end 300 bp sequencing (Illumina). All raw sequences were filtered to remove low quality reads, and the forward and reverse primers were truncated. Bioinformatics pipelines consisting of internal scripts and selected QIIME scripts (Caporaso et al., 2010; Edgar, 2010) were used to process the reads. Similar sequences were clustered into groups called Operational Taxonomic Units (OTUs) using a 97% identity threshold. Taxonomic classification of the OTU's was performed according to the Greengenes database (DeSantis et al., 2006; McDonald et al., 2012). Non-metric multidimensional-scaling was used to compare microbial communities across samples using the Bray-Curtis dissimilarity metric. The percentage of the microbial community classified as organisms of interest (e.g., sulphate-reducing bacteria) was also compared across samples. The most abundant OTU's were compared to the Cu, Se, and S concentrations in the sediment to calculate the Spearman correlation coefficient and associated p-value.

5. Results and Discussion

5.1.1. Outflow concentrations of copper and selenium

The pilot systems were operated for 37 weeks with three distinct trial periods of High Nitrogen, Low Nitrogen, and Hybrid Bioreactor-CWTS, with the average influent and outflow water chemistry provided in Tables 6, 7, and 8, respectively. The minimum, maximum, and average measurements of selected parameters and copper and selenium concentrations are summarized in Table 9. While copper treatment was relatively stable through both the High N and Low N periods, selenium treatment improved during the High N period (Figure 3), and then stabilized through the Low N period. For both the High N and Low N periods, the systems that were planted with Moss and *Carex* had significantly better copper treatment than Moss only. There was no statistically significant difference found among the three pilot system designs for selenium removal (i.e., Moss or biochar did not show a significant effect on selenium treatment during these periods).

The hybrid bioreactor-CWTS configuration was effective for both copper and selenium treatment. The purpose of the bioreactor-CWTS configuration is to serve as a contingency in case greater treatment is needed than is being achieved by the CWTS at a given point in time (e.g., the influent water quality or outflow objectives change). The tests here show that the CWTS can be repurposed as a hybrid bioreactor-CWTS with improved selenium and copper treatment within the same footprint, and without need for added construction. However, operating the system as a hybrid bioreactor-CWTS would require greater operational maintenance than it would in its original CWTS configuration.

In the case of selenium, the reconfiguration resulted in a statistically significant decrease in outflow concentration compared to that prior to the reconfiguration (Figure 3). This result for selenium was expected based on the design targeting more favourable conditions for selenium reduction, such as lower dissolved oxygen and ORP resulting from the additional electron donors from the microbial decomposition of the alfalfa and straw. In terms of copper, the lowest outflow concentration of the study was measured during the hybrid bioreactor-CWTS phase (7.5µg/L); however, prior to this there was a brief decrease in treatment effectiveness in all systems (Figure 3, June 19th data point). However, even during this brief disruption, 86% of the total copper entering the system was treated.

It is not known whether this brief change in treatment effectiveness was due to a short-term loss of treatment capacity during the transition, or if it might have been caused by a release of copper and other constituents that were sorbed to the moss or other organic matter during the transition. This decrease in treatment effectiveness coincided with low dissolved oxygen and moderately reducing conditions in the water column being attained in all cells (DO < 0.5 mg/L, ORP < -80 mV); however, it was not clear if the additional copper in the outflow was released from the alfalfa and straw that were added, or if constituents were briefly released from the sediment or moss and detritus after the system transitioned into more reducing conditions. As a result, a leach test was conducted on the alfalfa and straw and determined that there was no discernible release of copper from these organic materials. The origins of the decrease in treatment effectiveness could not be determined definitively, with the disturbance being registered during a single sampling point, with a maximum potential disturbance period of 4 weeks.

While the hybrid bioreactor-CWTS configuration improved selenium treatment, and demonstrated the lowest outflow concentration of copper of the entire trial, the short upset of treatment performance during the transition is meaningful in terms of monitoring during site implementation. It should be emphasized that if a transition from a typical CWTS design to a hybrid bioreactor-CWTS style is performed, careful monitoring of the CWTS is required as some elements may have decreased treatment effectiveness for a brief period. During this timeframe, if concentrations of elements exceed regulatory guidelines, water may need to be recycled through the wetland, or a contingency water treatment plan should be put in place for the outflow over the period of treatment disturbance.

5.1.2. Removal Rate Coefficients

An important factor for wetland design is the rate of treatment, also known as the removal rate coefficient (RRC). The RRC is based on treatability of a specific compound and the hydraulic retention time of the system. Once the RRC is known, the equation is rearranged and the RRC can be used to calculate the HRT needed to meet outflow objectives (and accordingly, the size of the wetland). It can also be used to predict the expected outflow concentrations of a specific element in a wetland of the same design based on inflow rates, concentrations, and footprint. RRCs vary with the concentrations of an element, and therefore, a sequential cell approach was used in this pilot study to allow for the RRC to be calculated over a broader range of inflow and outflow concentrations than if the system were only considered as a single treatment unit. Together these can then be used to estimate the size needed for a full-scale CWTS to meet outflow concentration performance objectives for a given influent concentration and flow rate. It should be noted that a RRC is specific to each given constituent respective to a particular wetland design, and can change based on the water chemistry and/or system design. The RRCs presented in this paper are a representative approximation of the Minto Mine site in a closure scenario and accounts for High N, Low N, and the use of a hybrid bioreactor-CWTS operational period (Figure 4, Table 10). When comparing the RRC of different designs of pilot systems in which the retention time and inflow concentrations are the same, a higher RRC indicates increased removal of the constituent. In the equation below, the first order RRC has been reconfigured to calculate *t* (hydraulic retention time), allowing the use of *Ci* (initial concentration), *Cf* (final, desired concentration), and *k* (removal rate constant, RRC) to be used to size the wetlands accordingly.

$$k = \frac{-ln(C_f/C_i)}{t}$$

$$t = \frac{-ln(C_f/C_i)}{k}$$

Equation: Removal rate coefficient (RRC) calculation, and rearranged to solve for HRT

When comparing the copper RRC of cells A and B within a series during the High N period, the RRC of the first cell is very high, while the RRC of the second cell is negligible (Figures 5 and 6). This phenomenon is frequently observed in treatment wetlands, where the treatment rate is faster at higher concentrations than at lower concentrations (Horner et al., 2012; Murray-Gulde et al., 2008; Spacil et al., 2011). As such, increasing the HRT of these systems by adding additional cells to the series would not result in a linear decrease in the final copper outflow concentration.

In contrast, the Low N and hybrid bioreactor-CWTS periods do not have this same degree of difference between copper RRC between cells A and B within a series (Figure 5). This change in cell-to-cell difference of RRC still results in similar or improved outflow concentrations. Generally speaking, the RRC of the first cell in the system has decreased, while that in the second cell has improved. This observation can be attributed to a variety of factors. Based on previous experience, the most likely explanation is that there was an abundance of sorption sites available in all cells at pilot initiation. As the study progressed, the sorption sites became occupied and removal via this mechanism was no longer available. This same phenomenon is also often seen when setting up an on-site demonstration-scale or full-scale treatment wetland. As such, both pilot and demonstration scale studies should be conducted for a sufficiently long period of time so as to realize the actual treatment capacity of the system beyond this initial sorption phase. This phenomenon must also be taken in the context of the duration over which the system must operate within a year, and the knowledge that the reaction front will move downstream within a wetland through this time. Therefore, an increased wetland size might not significantly improve outflow concentrations, but will aid in maintaining treatment performance through the year, so long as the added size does not result in concentration of the elements due to evaporation of the water caused by increased size.

A second possibility is that since the High N conditions coincided with an algal bloom (both visible, but also confirmed by community profiling that there was an abundance of cyanobacteria; Figure 7), the greater concentrations of cyanobacteria and algae during the High N period could have also been responsible for increased sorption and uptake of copper in the A cells. In either case, it is not to say that the B cells were not capable of a high removal rate, but rather that the concentration of copper in the A cell effluent left very little copper available for treatment in the B cell, regardless of capacity for treatment.

It is important to note that the RRCs for copper decreased during the hybrid bioreactor-CWTS period (Figure 4). This can be attributed to the longer HRT created by the increased water depth in this period despite similar outflow concentrations. Through all periods, the outflow concentration of copper for any given system did not vary significantly, indicating that regardless of the cause of the difference in RRC at different points in the system operations (e.g., sorption, algal uptake, increased water depth), the thermodynamic minimum for copper removal has likely been approached within the system, with an average outflow concentration of 18 ± 5 µg/L (Figure 6). That is to say, making the wetland bigger using any of the tested designs would not result in a further significant decrease in outflow copper concentration, but rather, design alterations would need to be made in order to attempt to achieve lower outflow concentrations. During the High and Low N periods when the Moss was actively growing, copper removal rates were greater in systems containing Moss than in systems with only *Carex*. It is likely that as the Moss continues to grow over time and increase in total mass, the RRC would also improve in these systems. Finally, the addition of biochar did not have any significant effect on performance.

Selenium tells a different story than copper in regards to the RRC. Selenium had a fairly similar removal rate in both the A and B cells during the Low N period (Figures 5 and 6). This could be because the selenium treatment is microbially mediated, or because the inflow concentrations are already so low that both the inflow and outflow concentrations of all cells still fall within the same RRC range. A test of the metals composition in the plants and subsequent mass balance of the systems confirmed that the system was operating as designed to target selenium mineralization to the sediment, as plant uptake was responsible for only 1-3% of the total selenium that was removed from the water during the entire course of the study (Figure 10). Based on the RRCs for selenium in the Low and High N periods, an increased HRT is expected to result in a lower outflow concentration of selenium (Figure 6). This could be achieved by increased footprint, or water depth, so long as the depth does not exceed that in which the *Carex* and Moss will grow.

Conversely, the hybrid bioreactor-CWTS time period had a significantly higher RRC for selenium in the A cells compared to the B cells (Figure 5). It should be noted that while the HRT is longer during the hybrid bioreactor-CWTS period than it was during the Low or High N periods due to an increase in water depth, it can be calculated using the RRC from the previous periods that this alone does not account for the degree of improvement in outflow concentration of the bioreactor-CWTS design. If the improvement in outflow concentration could be attributed solely to the increased HRT, the RRC would remain the same. Instead, we observe an improvement of not just the outflow concentration, but also in improvement in the RRC for selenium in all systems when converted to the bioreactor-CWTS configuration. This higher RRC is presumably due to the more favourable conditions that have been targeted for selenium reduction, including lower dissolved oxygen and a lower ORP resulting from the additional electron donors available through the microbial decomposition of alfalfa and straw. Through all time periods, there was no discernible benefit measured by the addition of biochar into the soils of the systems; rather, the systems that were planted with *Carex* and Moss performed similarly regardless of whether biochar had been included in the soil or not.

As would be expected based on the RRC data for systems containing *Carex* and Moss, the final sediment concentrations of copper are higher in the A cells than the B cells, with the B cells being only slightly higher in concentration than the starting levels (Figure 8). The same trend is evident for selenium; however, the starting concentration and concentrations in most of the B cells are below detection limits. It is of note that the copper and selenium sediment concentrations are positively correlated to an increase of sulphur in the sediment, while no discernible change was found in iron concentrations (Figure 8). This correlation is important to understand the long-term stability of copper within the system, as copper is highly stable when mineralized in a sulphide form and maintained under reducing conditions such as those in the wetland soils. In this case, the sulphides are being formed by microbes living in the soil and associated with the plant roots (see black areas in soil and around roots in Figures 14 and 15). This is supported by the finding of an initial increase of sulphate-reducing bacteria in the sediment, followed by stability over time at a most probable number of approximately 10,000-100,000 microbes per gram of sediment that are capable of reducing sulphate to sulphide (Figure 17). In the case of selenium, the correlation with sulphur in sediment is presumably due to the ranges of explanatory parameters found within the system (dissolved oxygen, ORP, soil redox, pH) which are favorable to both microbially-mediated selenium and sulphur reduction, suggesting the sedimentary selenium is likely in an elemental form, or sorbed to organic materials such as biofilms. While, the stability of the copper and selenium mineralizations were not tested in this study, it is planned for testing to be performed during the upcoming on-site demonstration-scale trial by using sequential extractions on the sediment paired with ICP analysis.

5.1.3. *Fate and distribution of copper and selenium*

Mass balances were calculated for each pilot system to assess the fate and distribution of elements removed from the water during the course of testing (i.e., the full 37 week period). For systems that were planted with *Carex* and Moss, 64-75% of the copper removed from the water was sequestered into the top 6 cm of sediment (Figure 9). In contrast, systems with only *Carex* planted and no Moss had only 33% of the copper ending up in this top sediment fraction (Figure 9). For systems planted with both *Carex* and Moss, 68-83% of the treated selenium was sequestered to this top portion of the sediment, but less than 52% was in the sediment of the system planted with only *Carex* (actual percentage cannot be calculated as the selenium was below the sediment detection level; Figure 10). For both elements, only 1-3% of the total load removed from the water was found in the above water vegetation (*Carex*) at the end of pilot testing.

It was not possible to determine the concentrations of elements in Moss, as the majority did not survive in the hybrid bioreactor-CWTS period conditions. However, in anticipation of this potential issue, samples of Moss were sent for analysis prior to the start of the hybrid bioreactor-CWTS period, allowing for a bioconcentration factor (BCF) to be calculated.

5.1.4. *Plant uptake and overall performance*

The bioconcentration factor (BCF) is the ratio of the amount of an element taken up into or sorbed onto the surface of a plant, compared to the amount of the element in the water, and is expressed as the ratio of mg of chemical per kg of organism to mg of chemical per liter of water. The amount of an element sorbed onto the surface of a plant was included in the BCF calculation to give a better representation of the amount that would be present in and on a plant in the wetland (i.e., for plant death/degradation as well as consumption perspectives). As would be expected based on samples collected during the site visit in 2013 and supported by scientific literature, we found in this study, and also in the site visit that *Carex* had a much lower BCF than Moss for both selenium and copper (Table 11). This finding is expected, as moss is known to have a high sorption capacity and therefore, high BCF (Aldrich & Feng, 2000; Gstoettner & Fisher, 1997). For some elements, bioconcentration factors within a plant species are higher when the element itself is at a lower concentration. This held true in the pilot systems when comparing cells A and B in a series, as the BCF for copper in *Carex* was significantly higher in B cells (which had lower aqueous concentrations) than in A cells (with higher influent concentrations) for all three pilot system designs tested (Figure 11). However, for selenium, the A cells had a similar BCF as B cells planted with both *Carex* and Moss (not statistically different), but a significantly higher BCF in the A cells planted with only *Carex* (Figure 11).

Selenium bioconcentration in *Carex* in the pilot systems was very low, resulting in average final tissue concentrations of only ~1.9 mg/kg wet weight. The BCF of selenium was greater in the Moss than the *Carex* in the pilot systems (Table 11). However the Moss BCF recorded here is still relatively low overall based on the United States Environmental Protection Agency Toxic Substances Control Act which considers BCF less than 1000 as non-bioaccumulative. It should also be noted that although selenium is generally known to bioaccumulate, Moss is not a food source for higher animals or invertebrates; as such, the selenium in the Moss should not be contributing to bioaccumulating pathways (Haines & Renwick, 2009; Longton, 1997; Suren & Winterbourn, 1991).

It is important to the overall treatment system design to determine if elements may be released by the plants by freezing and thawing in the water, as would occur through natural seasonal progression. A freeze-thaw trial was conducted in which *Carex* and Moss were collected and sent for metals analysis both before and after being submerged in water from the wetland and freezing to -20°C followed by thawing to room temperature. It was promising to find that *Carex* released only a small percentage of the selenium (18-38%) and copper (0-13%) as noted by the decrease in tissue concentrations after freezing and thawing (Figure 12). Moreover, Moss was found to have a significant increase in concentration of these elements after being frozen and thawed (Figure 13). It appears that through the freeze-thaw process, the Moss has an enhanced sorption of these compounds, removing an additional amount from the water.

Based on the pilot system design and plant densities, *Carex* would theoretically release on average 0.14 mg of copper and 0.27 mg of selenium per square meter of wetland area, while Moss would theoretically bind 511 and 11.8 mg/m^2, respectively. This finding is important, as it demonstrates that despite some release of constituents by *Carex* through freeze-thaw, the Moss will provide uptake in excess of what is released by the *Carex* and also assist with treatment during initial spring thaw before biogeochemical processes are at full capacity.

During the pilot CWTS takedown, it was noted that the *Carex* had an extensive root structure throughout the entire hydrosoil (Figures 14 and 15), making it an ideal candidate for construction of stable wetlands on site. Additionally, it should be noted that no significant difference in plant health or growth (i.e., number of stems, plant height, weight, and percent moisture at end of pilot) was found for systems with or without biochar or Moss (Figure 16). Based on the data collected during the pilot-phase testing, we can conclude that the combination of *Carex* and Moss is the ideal CWTS design for long-term and sustainable copper and selenium treatment. In this design the *Carex* provides structure to soil and sediment of the wetland with extensive root structure, additional treatment capacity based on the roots drawing water down into the sediment, renews organic carbon in the sediment and contributes to accretion through detritus decomposition, and aids in the production of sulphate reducing zones (as indicated by black areas in Figure 15). Meanwhile, the Moss provides sorption and uptake of elements even through freeze-thaw events.

5.1.5. Microbially-mediated treatment

In order to fully understand the function of biogeochemical processes such as the mineralization of copper and selenium, it is critical that the microbial populations performing these functions are well characterized and understood. Therefore, the microbial communities populating the sediment of each pilot CWTS cell were analyzed by both genetic and growth-based methods. The genetic method identifies and comparatively quantifies all of the bacteria in a sample without requiring growth, which is very important because a large proportion of environmental organisms will not grow in a laboratory setting. The genetic-based profiling is therefore used to assess which microbes are present and at what abundance, giving an idea of the robustness of the community and allowing for potential function to be inferred. The second method is called the most-probable number (MPN) assay, which is a dilution-based growth method that can determine the number of selenite-reducing, sulphate-reducing, and nitrate-reducing organisms per gram of sediment. The MPN method is therefore a means to evaluate the biogeochemical cycling potential of a sample; however, because the analysis is based on growth in laboratory media, it is presumed that not all organisms are able to grow and that only a partial profile of the microbial community is provided. Both methods allow for comparisons to be made of the microbial populations across samples, treatments, or time series.

With the microbial analyses, we were interested in three key questions:

- How does the microbial community adapt and change with different influent water chemistries and system designs?
- Are microbes that contribute to selenium, copper, or nitrate treatment present in the pilot wetland cells, and if so, are these same organisms present at the Minto site?
- Is selenium or copper treatment mediated by microbes present in the sediment?

As Figure 7 shows, the microbial population adapted rapidly and consistently to the changes in influent chemistry (i.e., High N, Low N), as well as the addition of organic matter. The nMDS plot of Figure 7 can be interpreted simply as samples that cluster together have more similar microbial communities, while those that are farther apart have distinct differences in their populations (such as identity or relative abundance). At the beginning of the pilot system operation, the microbial community had a proportionately high number of *Actinobacteria*, which then transitioned to *Cyanobacteria* during the High N period corresponding to a visible algal bloom. The Low N and hybrid bioreactor-CWTS phases had similar microbial populations, indicating that either the microbes present in the Low N phases were also well suited to the bioreactor-CWTS conditions, or that the community was still in flux at the final sampling, and treatment would have continued to improve over time in the hybrid system as more anaerobic organisms flourished. Overall, Figure 7 shows that as expected, the microbial populations were both adaptive and robust, shifting to respond to changes in the water chemistry and explanatory parameters such as dissolved oxygen and redox.

The results of the MPN testing indicate that the High N period had an abundance of organisms capable of denitrification including the reduction of nitrate to nitrite, and nitrate to N_2 gas (Figure 17). As expected based on the elevated water concentrations of nitrate, the High N period had a large number of organisms present that could reduce nitrate to N_2 gas. Although in decreased abundance, denitrifying bacteria were present through the Low N period and the hybrid bioreactor-CWTS period, despite having much lower nitrogen concentrations during this timeframe. As such, it is anticipated that fluctuations in ammonia and nitrate concentrations over time would be rapidly met with millions of microbes per gram of soil that are able to perform denitrification reactions.

Sulphate-reducing bacteria consistently increased in abundance over time in all system designs, starting out with a most probable number of approximately a thousand per gram of sediment and increasing by two orders of magnitude through the study (Figure 17). This increase is consistent with trends observed in the soil redox measurements becoming more negative over time in this study. The presence and abundance of sulphate-reducing bacteria were positively correlated with final sulphur concentrations in sediment, according to both the genetic and growth-based profiling methods. Several groups of known sulphate-reducing bacteria (e.g., *Desulfobacterium, Desulfosarcina, Desulfotomaculum)* were found to also correlate with copper concentrations in the sediment, suggesting that their presence leads to reduction of sulphate to sulphide, which then binds to copper and precipitates into the sediment. This can also be demonstrated by the black areas surrounding the *Carex* roots and black precipitates on the sediment surface observed during system takedown (Figures 14 and 15). This copper-sulphide mineralization mechanism is ideal for treatment as it provides a non-bioavailable and stable form of copper in the sediment.

We can tell from the genetic sequencing that these same types of sulphate-reducing bacteria were found in samples that were collected during the August 2013 site visit, specifically associated with *Carex* roots and sediment at the W10 location, as well as in the sediment at W15. It is likely that these were brought to the pilot system along with the plant roots as these *Carex* were harvested from the Minto W10 area. This indicates that despite having different sediment and environmental conditions at the site in comparison to the pilot CWTS, these microbes are robust and can be further encouraged to thrive and perform beneficial functions by having the ecological niches that they prefer (e.g., *Carex* roots, low ORP and DO).

The most probable number of selenite-reducing bacteria ranged from hundreds of thousands to tens of millions per gram of soil and was similar between the different system designs, having similar variance through the three testing periods (Figure 17). There was a general increase in selenite-reducing bacteria during the High N and Low N periods, followed by a decrease in their numbers during the hybrid bioreactor-CWTS period similar to denitrifying organisms discussed above. It was not possible to calculate a correlation between the number of selenite-reducing bacteria and the selenium concentration in the sediment due to the generally low levels (i.e., non-detectable) of selenium in the sediment of most cells. An abundance of selenite-reducing organisms in the pilot systems as well as at the Minto site indicates that these organisms are a robust and diverse group, and are present with a latent capacity to perform microbially-mediated selenium treatment given the proper conditions (e.g., electron donors, targeted ORP and DO levels).

The importance of these microbial results is two-fold: first, the treatment of selenium, copper, or nitrate can be mediated and sustained in a very passive manner by microbes if provided the right environment. Second, this necessary environment can be targeted through system design and adjustments in operation as have been done through this study, resulting in stimulation of these microbes in abundance, diversity, and activity.

5.1.6. Range of operational parameters

In order to be able to effectively implement a full-scale passive treatment system such as a CWTS, the targeted explanatory parameters must be predefined. As such, one of the goals of this pilot-scale work was to confirm or optimize the ranges of these parameters from what can be derived from publications and previous experience. These explanatory parameters can then be used to predict the functionality of a wetland and efficacy of treatment. Moreover, well-defined explanatory parameters allow for adaptive management plans to be developed in order to maintain optimal treatment effectiveness and predictability. The pilot systems tested here performed well not only across a variety of water chemistries and induced conditions, but also over a wide range of water pH, DO, ORP and soil redox. Table 9 includes the minimum, maximum and average recorded values of some selected explanatory parameters for the different periods of testing. Most importantly, this table shows that the range of conditions needed for effective copper and selenium treatment were achieved for this site-specific CWTS design, highlighting the robustness and adaptability of the design and providing a range of conditions under which the system will function.

6. Conclusions and Recommendations

When designed and implemented in a strategic and scientifically guided manner, CWTSs can mitigate risks posed by many contaminants. A treatment plan that includes processes that precipitate insoluble species of these constituents for sequestration into the sediments of the wetland are very desirable, as this mechanism captures the contaminant and stores it with stability in the sediments, rather than transferring the contaminant to an indeterminate fate (e.g., plant uptake or volatilization). This study has addressed several important design considerations regarding implementation of a CWTS at the full scale for the treatment of copper and selenium at the Minto Mine. A synopsis of the conclusions and recommendations are:

- An effective and robust pilot-scale CWTS design was demonstrated and optimized using plants from the Minto site and predicted closure water chemistries.

- The pilot-scale CWTSs provided much of the information needed to effectively size full-scale CWTS for treatment at the Minto site, but sizing will also be dependent on other factors (hydrology, available area, and constructability considerations).

- The recommended CWTS design for long-term passive treatment of copper and selenium at the Minto site is a combination of *Carex* and Moss planted in a sand substrate supplemented with woodchips and peat.

- The selected design achieved average outflow concentration of 12 µg Cu/L (average influent 146 µg Cu/L), and 6 µg Se/L (influent 10.2 µg Se/L).

- Conversion of the CWTS to a hybrid bioreactor-CWTS design resulted in the lowest copper (7.5 µg/L) and selenium (1.9 µg/L) concentrations of the study, but was preceded by a brief disruption of treatment capacity. This configuration would require greater maintenance than the basic CWTS, but could be implemented if any changes in influent water quality are predicted or if outflow objectives change.

- If transitioning from the CWTS design to hybrid bioreactor-CWTS, close monitoring of CWTS and potential consideration of contingency treatment is recommended during the transition period, as there may be a brief and temporary disruption in treatment effectiveness.

- The majority of the copper and selenium treated by the system was sequestered to the top 6 cm of sediment, with only a small portion (1-3%) being taken up into the *Carex* (commonly known as sedge).
- After undergoing a freeze-thaw cycle, the *Carex* used in this study released only a small amount of copper and selenium; however, under the same trial the binding and sorption capacity of the Moss increased, resulting in a net removal of copper and selenium from the water through a freeze-thaw cycle.
- Fluctuations in nitrogen levels (as would be expected in early closure due to residue from blasting activities) are responded to by a diverse microbial community with a robust capacity to treat nitrate, but also continue to treat Cu and Se through this transition;
- There were thousands to billions of nitrate, sulphate, and selenium reducing bacteria present per gram of soil in the pilot CWTS, many of which were confirmed through genetic testing to be the same groups of organisms as found at the Minto site.
- It is recommended that the design be tested on-site at Minto with a demonstration-scale CWTS receiving seepage water.

7. Closure

We trust the information herein satisfies your present requirements. Should you have any questions, please contact the persons listed below. We appreciate the opportunity to provide the services detailed in this report, and look forward to discussing any comments you may have.

Respectfully submitted,

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9. Tables

Table 1: Synthetic water formulation.

Element	Compound	Concentration (mg/L)
Aluminum	$Al_2(SO_4)_3 \cdot 18H2O$	0.929
Ammonium	NH_4HCO_3	1.00[1]
Arsenic	$Na_2HAsO_4 \cdot 7H_2O$	0.012
Barium	$BaCl_2 \cdot 2H_2O$	0.817
Cadmium	$CdCl_2$	0.0005
Calcium	$CaCl_2$	11.68
	$Ca(NO_3)_2 \cdot 4H_2O$	197.59[1]
Chromium	CrO_3	0.013
Cobalt	$CoCl_2 \cdot 6H_2O$	0.017
Copper	$CuCl_2 \cdot 2H_2O$	0.239
Iron	$FeSO_4 \cdot 7H_2O$	15.29
Lead	$Pb(NO_3)_2$	0.0007
Magnesium	$MgSO_4 \cdot 7H_2O$	324.77
Manganese	$MnSO_4 \cdot H_2O$	8.10
Molybdenum	$Na_2MoO_4 \cdot 2H_2O$	0.026
Nickel	$NiCl_2 \cdot 6H_2O$	0.023
Potassium	KNO_3	28.34[1]
	KH_2PO_4	0.298
Selenium	$Na_2SeO_3 \cdot 5H_2O$	0.032
Silver	$AgNO_3$	0.0005
Sodium	Na_2SO_4	54.14
Strontium	$SrCl_2 \cdot 6H_2O$	8.73
Vanadium	V_2O_5	0.026
Zinc	$ZnCl_2$	0.056

[1] During Low N and hybrid bioreactor-CWTS periods of testing, NH_4HCO_3 and KNO_3 were not added, and the $Ca(NO_3)_2 \cdot 4H_2O$ was decreased to 1.976 mg/L

Table 2: Influent chemistry for pilot CWTS.

Element (total)	**unit**	**Influent**				
		Targeted	Acclimation Period	High N	Low N	Hybrid bioreactor-CWTS
Aluminum (Al)	mg/L	0.100	0.089	0.085	0.080	0.098
Antimony (Sb)	mg/L	0.00160	0.00060	0.00065	0.00061	0.0006
Arsenic (As)	mg/L	0.0030	0.0031	0.0033	0.0033	0.0037
Barium (Ba)	mg/L	0.500	0.153	0.284	0.192	0.224
Beryllium (Be)	mg/L	0.00078	<0.001	<0.001	<0.001	<0.001
Boron (B)	mg/L	0.315	0.0243	0.0262	0.0239	0.0243
Cadmium (Cd)	µg/L	0.3340	0.011	0.236	0.336	0.392
Calcium (Ca)	mg/L	82	70.33	73.90	40.73	48.22
Chromium (Cr)	mg/L	0.0065	0.0058	0.0064	0.0071	0.0075
Cobalt (Co)	mg/L	0.0039	0.0039	0.0042	0.0043	0.0044
Copper (Cu)	mg/L	0.13	0.14	0.15	0.15	0.18
Iron (Fe)	mg/L	3.1	3.1	3.1	3.2	3.5
Lead (Pb)	mg/L	0.00070	0.00044	0.00067	0.00059	0.00071
Magnesium (Mg)	mg/L	50	49	49	51	53
Manganese (Mn)	mg/L	2.6	2.5	2.5	2.6	2.7
Molybdenum (Mo)	mg/L	0.012	0.013	0.015	0.013	0.013
Nickel (Ni)	mg/L	0.0072	0.0077	0.0087	0.0076	0.0080
Phosphorus (P)	mg/L	0.082-0.27 [1]	0.333	0.236	0.082	0.082
Potassium (K)	mg/L	14	14.3	14.6	3	3
Selenium (Se)	mg/L	0.010	0.010	0.011	0.010	0.011
Sodium (Na)	mg/L	44	40	41	42	43
Strontium (Sr)	mg/L	2.9	2.5	2.5	2.5	2.6
Sulphur (S)	mg/L	85	85	84	86	88
Uranium (U)	mg/L	0.0051	0.0012	0.0012	0.0012	0.0014
Vanadium (V)	mg/L	0.016	0.015	0.013	0.014	0.018
Zinc (Zn)	mg/L	0.032	0.0517	0.037	0.040	0.042
Nutrients						
Total Ammonia (N)	mg/L	0.2-0.5 [2]	0.61	0.50	0.29	0.05
Dissolved Nitrate (N)	mg/L	0.8-28 [2]	29.33	29.67	0.86	0.84
Misc. Inorganics						
pH	pH	7.5-8.0	7.89	8.16	7.96	8.01
Anions						
Alkalinity (Total as CaCO3)	mg/L		107.33	107.00	100	100
Bicarbonate (HCO3)	mg/L		133.33	130.00	122	130

[1] Phosphorous was not modeled for closure, so the maximum concentration from W15 (2007-2012) was used (0.27mg/L), this was later decreased to 0.082mg/L (95th percentile).

[2] Ammonia and nitrate were not added to the synthetic water for the Low N and hybrid bioreactor-CWTS periods.

Table 3: Pilot CWTS testing periods.

Period	Timeline	# Weeks	Water Depth	HRT (hr) ± Std. Dev.	Description/Purpose
Pre-Influent	Nov 4, 2013 – Dec 12, 2013	6	10 cm	N.D.	Plant establishment
Acclimation	Dec 13, 2013 – Feb 26, 2014	10	10cm	37± 3	Acclimation of system to influent
High N	Feb 27, 2014 – Apr 12, 2014	7	10 cm, 17 cm[1]	37 ± 3 53 ± 3[1]	High ammonia and nitrate in influent (early closure)
Low N	Apr 13, 2014 – May 28, 2014	7	17 cm	53 ± 2.5	Low ammonia and nitrate (long-term closure)
hybrid bioreactor-CWTS	May 29, 2014 – Jul 16, 2014	7	30 cm	87 ± 3	Post alfalfa and straw addition (hybrid bioreactor-CWTS)

[1] 17 cm from March 13 to Apr 12, 2014 to test higher water depth during High N Period. This therefore results in a longer HRT for this timeframe.

Table 4: Monitoring schedule.

Water	
Temperature	Weekly
pH	
Dissolved oxygen	
Regulated metals water package [1]	Bi-weekly
Phosphorus	
Ammonia [2]	
Nitrate	
Flow rate	
Alkalinity [3]	Monthly
Hardness [3]	
Conductivity [3]	
Chemical oxygen demand (COD) [4]	
Total organic carbon [4]	
Total Kjeldahl Nitrogen (TKN) [4]	
Sulphate [3]	
Biological oxygen demand (BOD) [3]	Monthly (outflow only)
Total suspended solids [2]	
Soil	
Eh (redox)	weekly
Available NPK	Initial soil, beginning of influent, end of study
Regulated metals package	
Total organic carbon	Initial soil, end of study
Particle size analysis	
Conductivity	
Cation exchange capacity (CEC)	
Sodium adsorption ratio	
Plant	
Regulated metals	Start and end; Freeze-thaw trial
Stem counts and heights [4]	Monthly
Microbial	
Most probable number (growth-based)	Initial soil; beginning High N period; end Low N period; end of study
Genetic microbial community profiles	

[1] Dissolved metals was tested in addition to total metals for the Low N and hybrid bioreactor-CWTS periods
[2] Not performed during hybrid bioreactor-CWTS period, except at takedown of pilot
[3] Bi-weekly during hybrid bioreactor-CWTS period
[4] Not performed during Low N and hybrid bioreactor-CWTS periods, except at takedown of pilot

Table 5: Summary of water, soil, and plant analyses.

Water	Soil	Plant
ICP-MS Total or Dissolved (Al, Sb, As, Ba, Be, B, Cd, Cr, Co, Cu, Fe, Pb, Li, Mn, Mo, Ni, P, Se, Si, Ag, Sr, Tl, Sn, Ti, U, V, Zn, Ca, Mg, K, Na, S)	ICP-MS (Al, B，Sb, As, Ba, Be, Cd, Ca, Cr, Co, Cu, Fe, Pb, Li, Mg, Mn, Mo, Ni, P, K, Se, S, Ag, Na, Sr, Tl, Sn, U, V, Zn,)	ICP-MS (Al, Sb, As, Ba, Be, Bi, B, Cd, Ca, Cr, Co, Cu, Fe, Pb, Mg, Mn, Mo, Ni, P, K, Se, Ag, Na, Sr, Tl, Sn, Ti, U, V, Zn)
Routine Water (Alkalinity, HCO_3, Ion Balance, Dissolved ions, Hardness, Nitrate/Nitrite)	Available Nitrogen, Phosphorous, and Potassium (NPK)	
Total Suspended Solids (TSS)	Cation Exchange Capacity (CEC)	
Chemical Oxygen Demand (COD)	Sodium Adsorption Ratio (SAR)	
Biological Oxygen Demand (BOD)	Total Organic Carbon (TOC)	
Total Kjeldahl Nitrogen (TKN)	Electrical Conductivity (EC)	
Total Organic Carbon (TOC)	Texture Analysis (Physical properties)	
Ammonia		

Table 6: Performance of pilot CWTS during High N period.

Elements (Total)	**Unit**	**Influent**	**Outflow Average**		
		Average	*Carex* only	*Carex* + *Sphagnum*	*Carex* + *Sphagnum* + Biochar
Aluminum (Al)	mg/L	0.085	0.012	0.008	0.009
Arsenic (As)	mg/L	0.0033	0.0010	0.0008	0.0007
Barium (Ba)	mg/L	0.284	0.039	0.036	0.040
Boron (B)	mg/L	0.0262	0.025	0.027	0.055
Cadmium (Cd)	µg/L	0.236	0.038	0.023	0.017
Calcium (Ca)	mg/L	73.9	78	78	77
Chromium (Cr)	mg/L	0.0064	0.0024	0.0023	0.0024
Cobalt (Co)	mg/L	0.0042	0.0008	0.0004	0.0003
Copper (Cu)	mg/L	0.150	0.018	0.013	0.012
Iron (Fe)	mg/L	3.10	0.08	0.08	0.08
Magnesium (Mg)	mg/L	49	50	51	51
Manganese (Mn)	mg/L	2.5	1.1	0.37	0.2
Molybdenum (Mo)	mg/L	0.0150	0.0139	0.0130	0.0128
Nickel (Ni)	mg/L	0.0087	0.0042	0.0027	0.0020
Phosphorus (P)	mg/L	0.236	<0.1	<0.1	<0.1
Potassium (K)	mg/L	14.6	14.9	15.3	15.1
Selenium (Se)	mg/L	0.0110	0.0076	0.0073	0.0067
Sodium (Na)	mg/L	41	43	45	42
Strontium (Sr)	mg/L	2.5	2.7	2.7	2.6
Sulphur (S)	mg/L	84	86	87	86
Uranium (U)	mg/L	0.0012	0.0011	0.0011	0.0011
Vanadium (V)	mg/L	0.0130	0.0023	0.0019	0.0017
Zinc (Zn)	mg/L	0.0370	0.0042	0.0044	0.0034
Nutrients					
Total Ammonia (N)	mg/L	0.50	0.05	0.05	0.05
Dissolved Nitrate (N)	mg/L	29.67	29.4	29.4	29.5
Explanatory Parameters					
pH	pH	8.16	7.47	7.61	7.80
DO (mg/L)			5.33	5.16	5.52
Water redox (mV)			154.5	144.2	136.0
Soil Redox (mV)			-148	-191	-220

Table 7: Performance of pilot CWTS during Low N period.

Elements (Total)	Unit	Influent	Outflow Average		
		Average	*Carex* only	*Carex* + Moss	*Carex* + Moss + Biochar
Aluminum (Al)	mg/L	0.080	0.008	0.006	0.007
Arsenic (As)	mg/L	0.0033	0.0007	0.0006	0.0006
Barium (Ba)	mg/L	0.192	0.028	0.027	0.030
Boron (B)	mg/L	0.024	0.023	0.024	0.022
Cadmium (Cd)	µg/L	0.336	0.070	0.027	0.023
Calcium (Ca)	mg/L	41	47	47	47
Chromium (Cr)	mg/L	0.0071	0.0034	0.0029	0.0030
Cobalt (Co)	mg/L	0.0043	0.0006	<0.0003	<0.0003
Copper (Cu)	mg/L	0.150	0.0210	0.0113	0.0125
Copper (Cu) Dissolved	mg/L	0.037	0.0123	0.0086	0.0086
Iron (Fe)	mg/L	3.20	0.16	0.06	0.09
Magnesium (Mg)	mg/L	51	55	55	55
Manganese (Mn)	mg/L	2.6	0.9	0.2	0.2
Molybdenum (Mo)	mg/L	0.0130	0.0110	0.0104	0.0105
Nickel (Ni)	mg/L	0.0076	0.0035	0.0018	0.0015
Phosphorus (P)	mg/L	0.11	<0.10	<0.10	<0.10
Potassium (K)	mg/L	3.0	3.2	3.4	3.4
Selenium (Se)	mg/L	0.0100	0.0061	0.0060	0.0063
Selenium (Se) Dissolved	mg/L	0.0080	0.0052	0.0053	0.0052
Sodium (Na)	mg/L	42	44	44	45
Strontium (Sr)	mg/L	2.5	2.7	2.7	2.7
Sulphur (S)	mg/L	86	93	94	93
Uranium (U)	mg/L	0.0012	0.0009	0.0010	0.0010
Vanadium (V)	mg/L	0.0140	0.0023	0.0016	0.0022
Zinc (Zn)	mg/L	0.0400	0.0082	0.0032	0.0031
Nutrients					
Total Ammonia (N)	mg/L	0.29	<0.05	<0.05	<0.05
Dissolved Nitrate (N)	mg/L	0.86	0.26	0.25	0.25
Explanatory Parameters					
pH	pH	7.96	7.58	7.76	7.61
DO (mg/L)			5.69	6.05	5.42
Water redox (mV)			179	170	205
Soil Redox (mV)			-148	-183	-209

Table 8: Performance of pilot CWTS during hybrid bioreactor-CWTS period.

Elements (Total)	**Unit**	**Influent**	**Outflow Average** [1]		
		Average	*Carex* only	*Carex* + Moss	*Carex* + Moss + Biochar
Aluminum (Al)	mg/L	0.098	0.010	0.013	0.009
Arsenic (As)	mg/L	0.0037	0.001	0.001	0.001
Barium (Ba)	mg/L	0.224	0.061	0.061	0.058
Boron (B)	mg/L	0.024	0.026	0.026	0.025
Cadmium (Cd)	µg/L	0.392	0.057	0.067	0.067
Calcium (Ca)	mg/L	48	49	48	48
Chromium (Cr)	mg/L	0.0075	<0.001	<0.001	<0.001
Cobalt (Co)	mg/L	0.0044	0.003	0.002	0.002
Copper (Cu)	mg/L	0.180	0.021	0.023	0.026
Copper (Cu) Dissolved	mg/L	0.0350	0.0122	0.0134	0.0168
Iron (Fe)	mg/L	3.50	0.41	0.33	0.22
Magnesium (Mg)	mg/L	53	54	54	55
Manganese (Mn)	mg/L	2.7	5.2	5.1	5.7
Molybdenum (Mo)	mg/L	0.013	0.015	0.020	0.021
Nickel (Ni)	mg/L	0.008	0.006	0.006	0.007
Phosphorus (P)	mg/L	0.12	0.11	0.11	0.10
Potassium (K)	mg/L	3.0	6.4	6.1	6.3
Selenium (Se)	mg/L	0.0100	0.0040	0.0040	0.0040
Selenium (Se)	mg/L	0.0119	0.0038	0.0039	0.0041
Sodium (Na)	mg/L	43	44	44	44
Strontium (Sr)	mg/L	2.6	2.6	2.6	2.6
Sulphur (S)	mg/L	88	87	87	87
Uranium (U)	mg/L	0.0014	0.0010	0.0010	0.0010
Vanadium (V)	mg/L	0.018	0.002	0.002	<0.001
Zinc (Zn)	mg/L	0.042	0.007	0.005	0.006
Nutrients					
Total Ammonia (N)	mg/L	0.05	0.06	0.05	0.05
Dissolved Nitrate (N)	mg/L	0.84	0.08	0.06	0.03
Explanatory Parameters					
pH	pH	8.01	7.16	7.20	7.19
DO (mg/L)			1.52	1.73	1.86
Water redox (mV)			-34	-91	-134
Soil Redox (mV)			-197	-218	-226

[1] The average outflow for the hybrid bioreactor-CWTS period includes data from June 19th, when there was a spike in several constituents when the system reached low dissolved oxygen and moderately reducing conditions in the water column.

Table 9: Summary of explanatory parameters and outflow concentrations of copper and selenium

Period	Parameter	Influent	System								
			Carex			*Carex* + Moss			*Carex* + Moss + Biochar		
		Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg
High Nitrogen	Copper (µg/L)	146.4	16	20	18	11	16	13	9	14	12
	Selenium (µg/L)	10.2	5.8	9.7	7.6	6.0	9.5	7.3	5.8	8.5	6.7
	pH	8.00	6.99	7.94	7.49	7.19	8.29	7.64	7.39	8.28	7.84
	DO (mg/L)	-	4.08	6.69	5.36	2.59	7.55	5.35	3.50	8.70	5.75
	ORP (mV)	-	82	215	157	104	215	247	84	205	140
	Redox (soil,mV)	-	-229	-51	-144	-273	-177	-190	-301	-135	-218
Low Nitrogen	Copper (µg/L)	145.5	17	32	21	10	13	11.3	11	15	12.5
	Selenium (µg/L)	10.2	5.3	6.7	6.1	5.6	6.5	6.0	5.8	6.9	6.3
	pH	7.96	7.16	8.05	7.54	7.26	8.32	7.71	7.15	8.25	7.60
	DO (mg/L)	-	3.99	7.72	5.61	3.02	9.78	5.73	2.57	9.04	5.21
	ORP (mV)	-	126	220	168	113	188	159	106	374	182
	Redox (soil,mV)	-	-249	-39.5	-150	-246	-88	-185	-264	-123	-211
Hybrid Bioreactor-CWTS	Copper (µg/L)	175.6	7.5	45	21	8.3	44	23	8.3	64	26
	Selenium (µg/L)	11.9	1.9	5.6	4.0	2.5	5.4	4.0	2.8	5.4	4.0
	pH	8.01	6.91	7.62	7.16	6.95	7.82	7.20	6.96	7.71	7.19
	DO (mg/L)	-	0.02	3.23	1.52	0.11	5.61	1.73	0.03	4.71	1.86
	ORP (mV)	-	-175	-79	-129	-212	-101	-150	-195	-30	-134
	Redox (soil,mV)	-	-232	-170	-197	-268	-159	-218	-290	-150	-226

Table 10: Removal rate coefficients for each system and period of testing.

Element	System	Period RRC (hr^{-1})		
		High N	Low N	hybrid bioreactor-CWTS [1]
Copper	*Carex*	0.0465	0.0390	0.0250
	Carex + Moss	0.0519	0.0497	0.0236
	Carex + Moss + Biochar	0.0543	0.0462	0.0242
Selenium	*Carex*	0.0069	0.0103	0.0130
	Carex + Moss	0.0078	0.0102	0.0128
	Carex + Moss + Biochar	0.0095	0.0090	0.0123

[1] The calculation of RRC for the hybrid bioreactor-CWTS period included data from June 19th, when there was a spike in several constituents when the system reached low dissolved oxygen and moderately reducing conditions in the water column.

Table 11: Bioconcentration factor for each plant species at the end of the Low N period.

Plant Species	Copper (L/kg)	Selenium (L/kg)
Carex	23	113
Moss	1390	593

10. Figures

Figure 1: Pilot CWTS layout

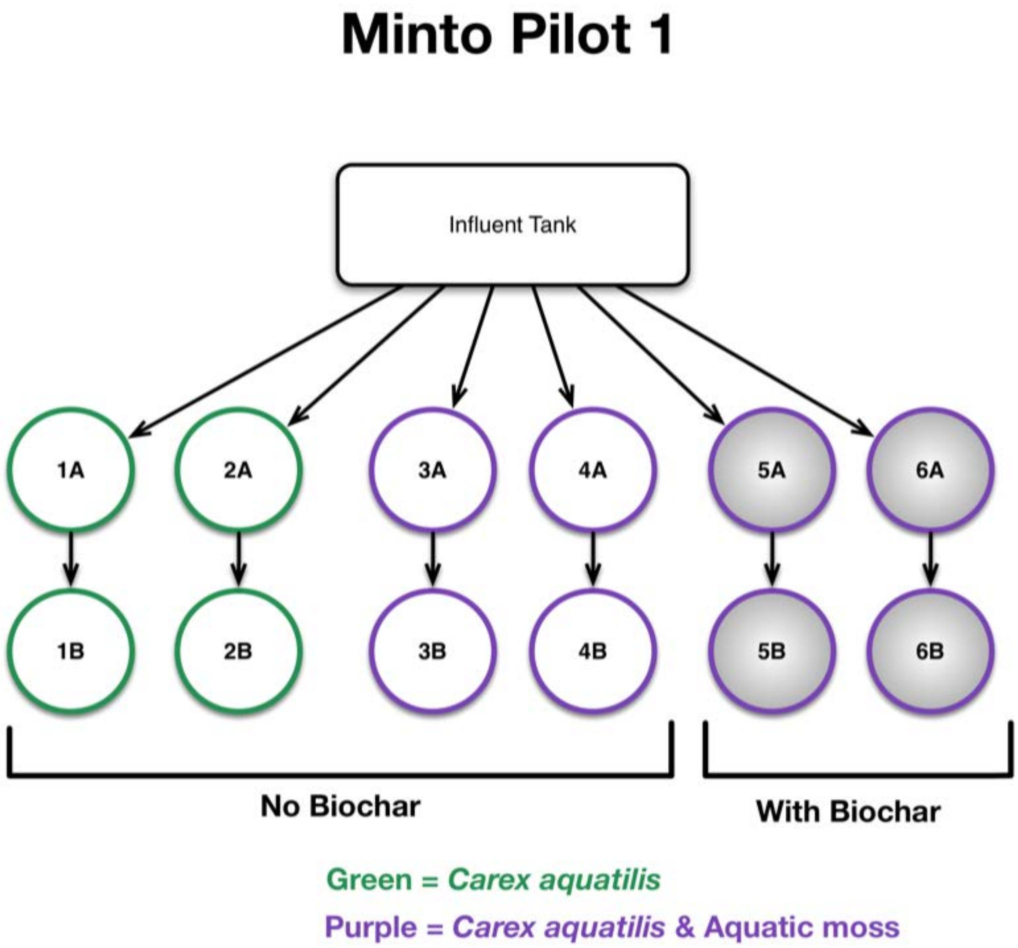


Figure 2: Photographs of pilot CWTS set up. Top is entire system, with 6 series of two cells; bottom is one cell.

Figure 3: Outflow copper and selenium water concentrations over time compared to influent.

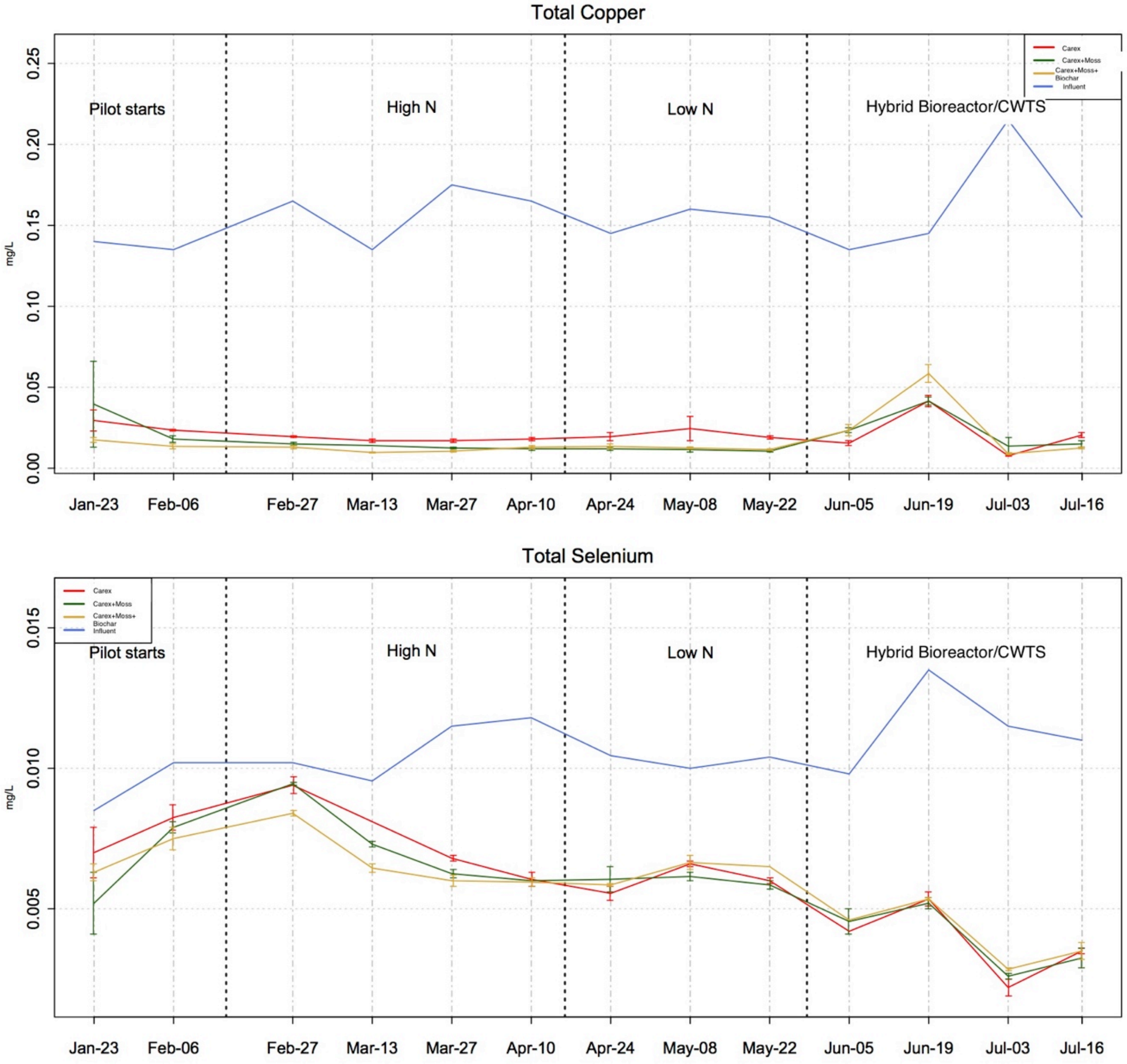


Figure 4: Copper and selenium removal rate coefficients during all periods of testing for the three system designs.

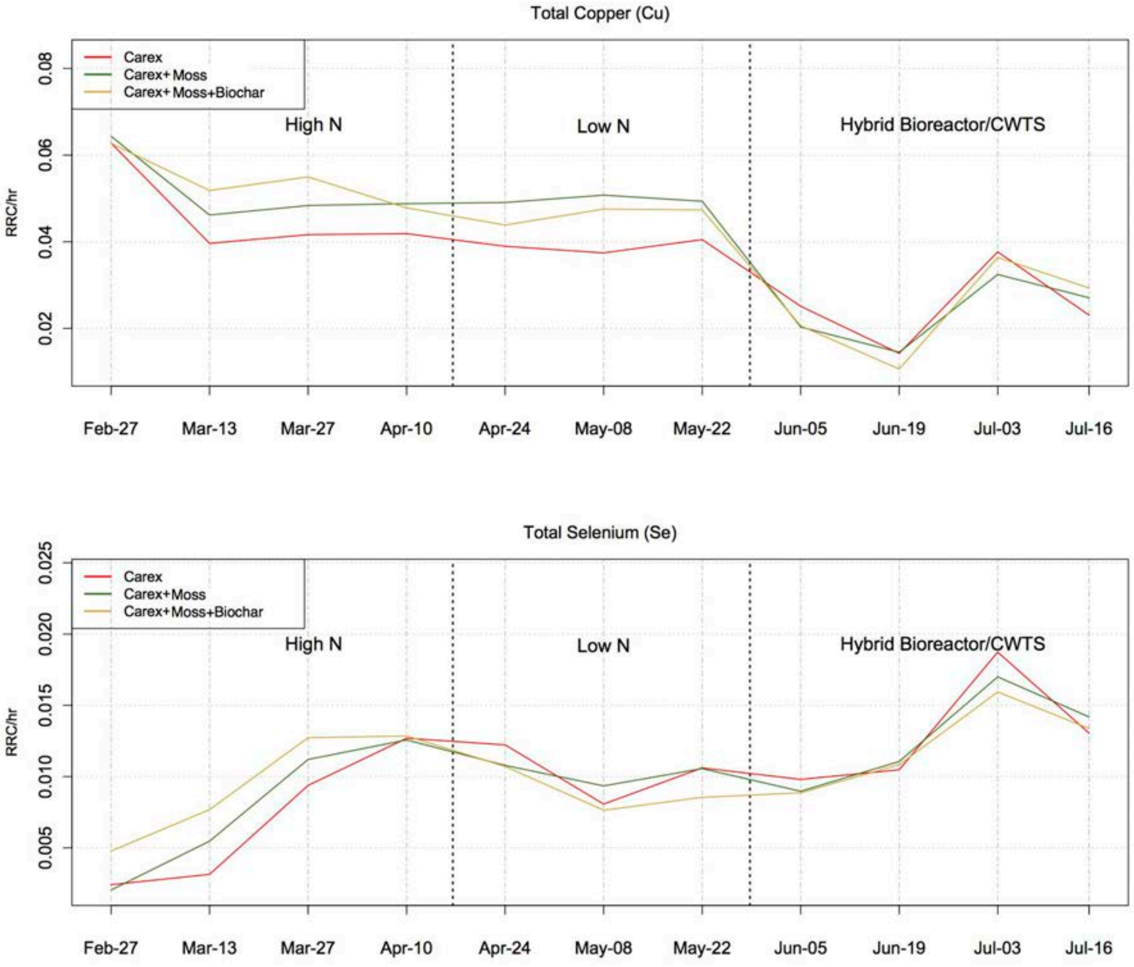


Figure 5: Copper (top) and selenium (bottom) removal rate coefficients for cells A and B in each system design. All three periods of testing are plotted separately (High N = Feb 27-April 12; Low N = April 13-May 28; hybrid bioreactor/CWTS = May 29-July 16). The average RRC is indicated with the bar chart, and error bars show the range. Note that the water depth was changed during the hybrid bioreactor/CWTS phase, which impacts the RRC.

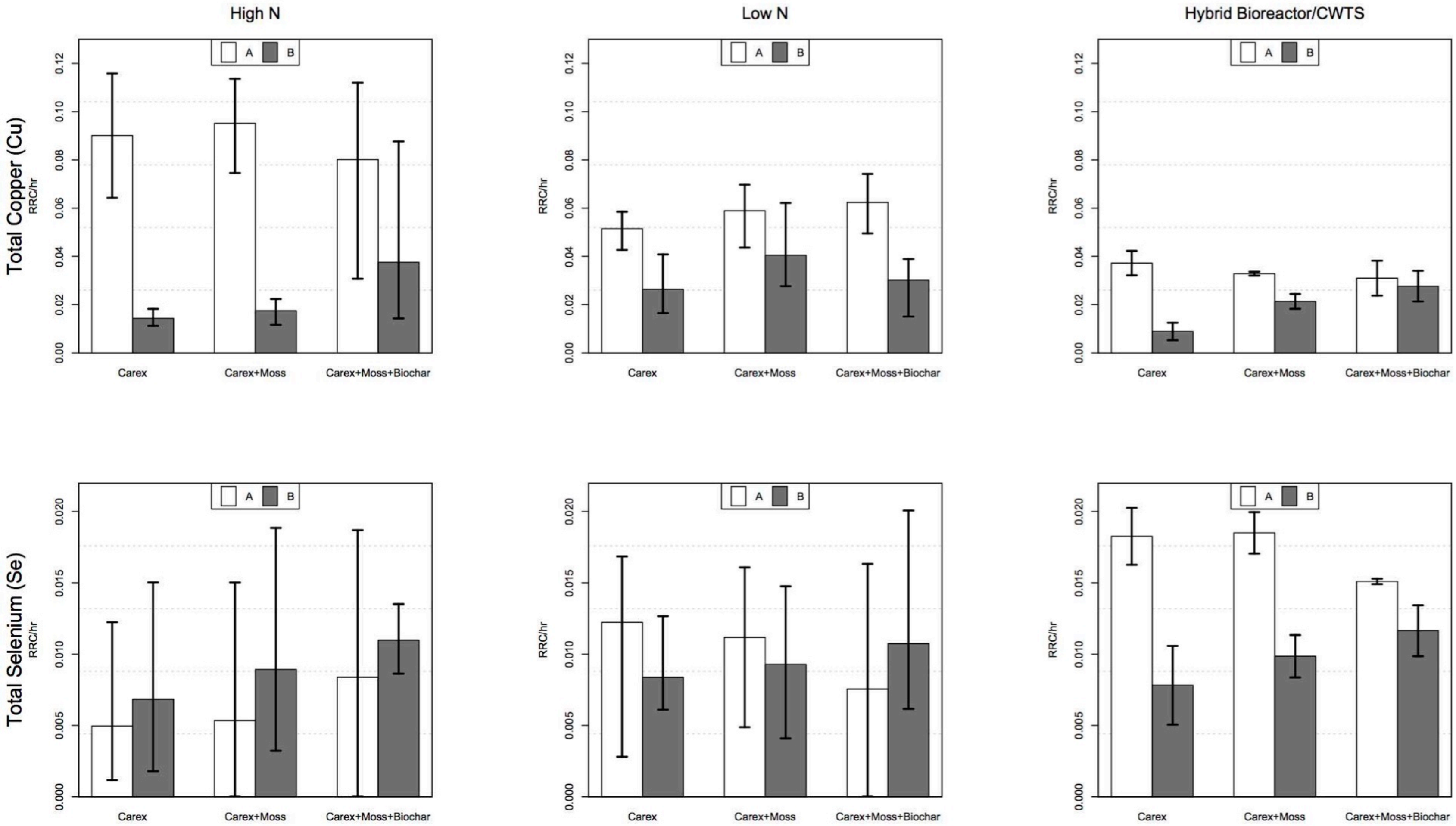


Figure 6: Outflow copper and selenium water concentrations from A and B cells over time compared to influent.

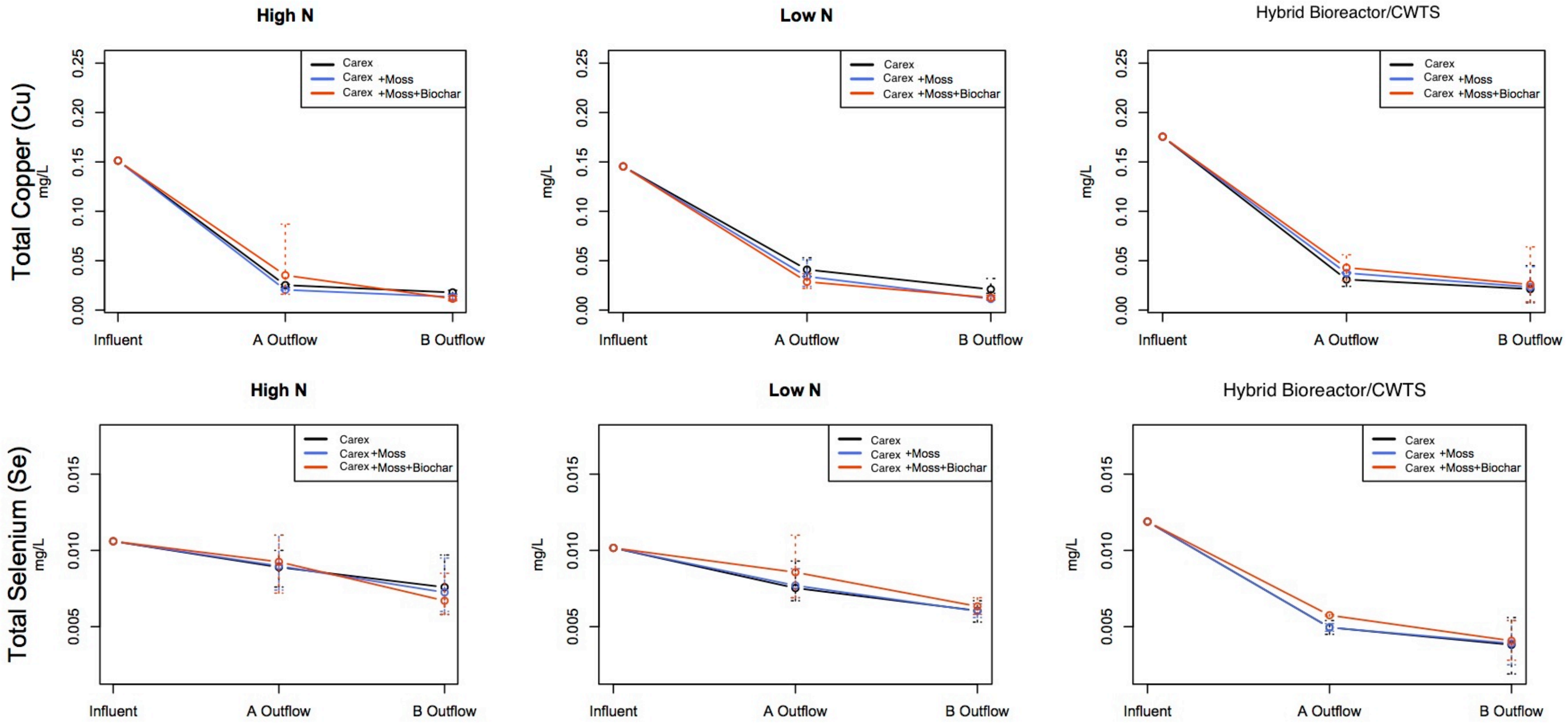


Figure 7: Non-metric multidimensional scaling (nMDS) analysis plot for bacterial community profiles of each pilot system design over time. Results are based on the genetic profiling method. Each time point during testing is shown with a different color, while the system design is indicated with shapes. All points that cluster together indicate similar bacterial communities. At the end of the pilot testing, we also determined the microbial population of the top root mass (orange outline), which was very similar to the microbial population in the sediment. The top 10 bacterial groups are indicated on the plot with dark blue numbers. The distance between a bacterial group label and a sample point depicts how high that group is in that sample.

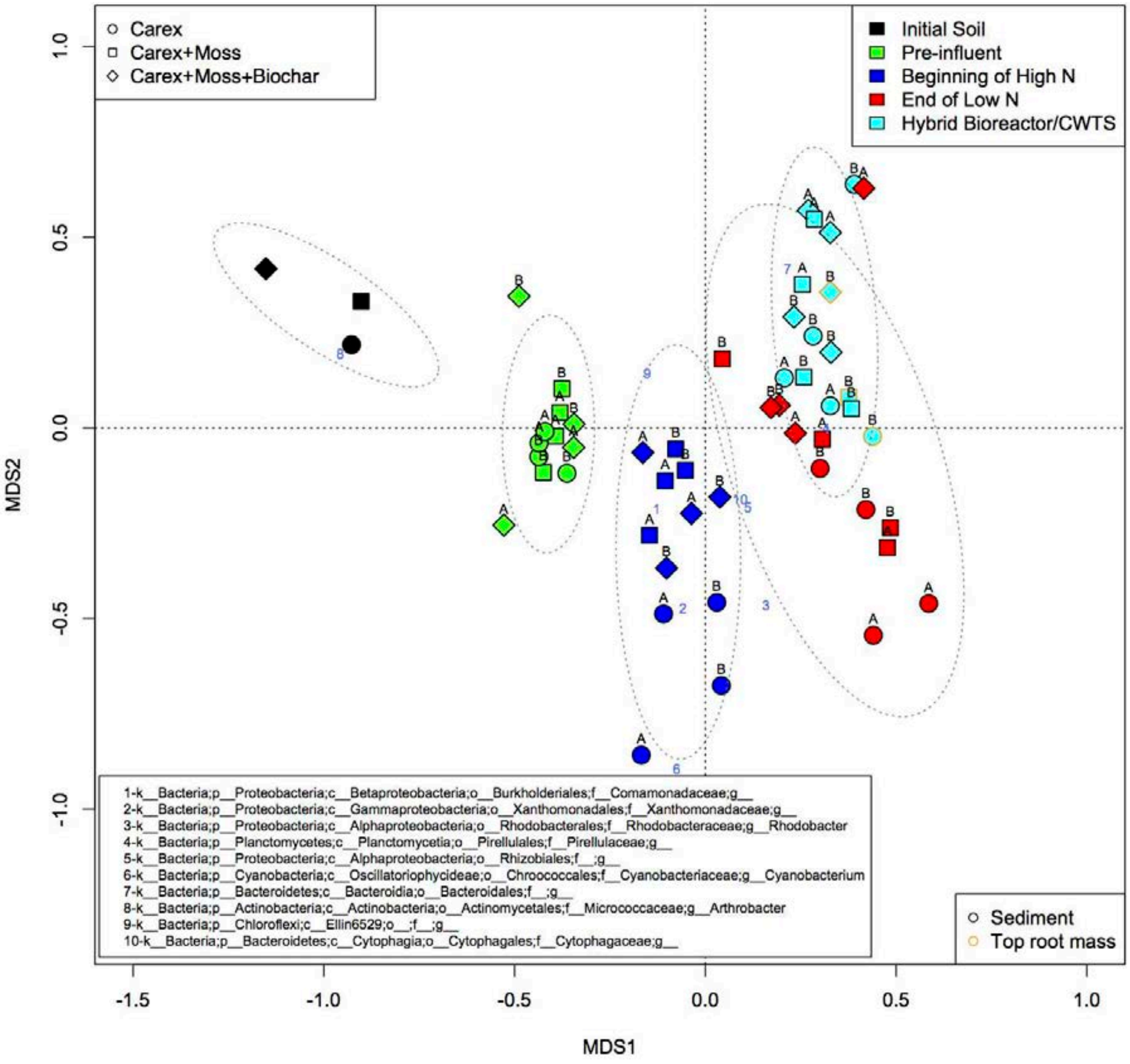
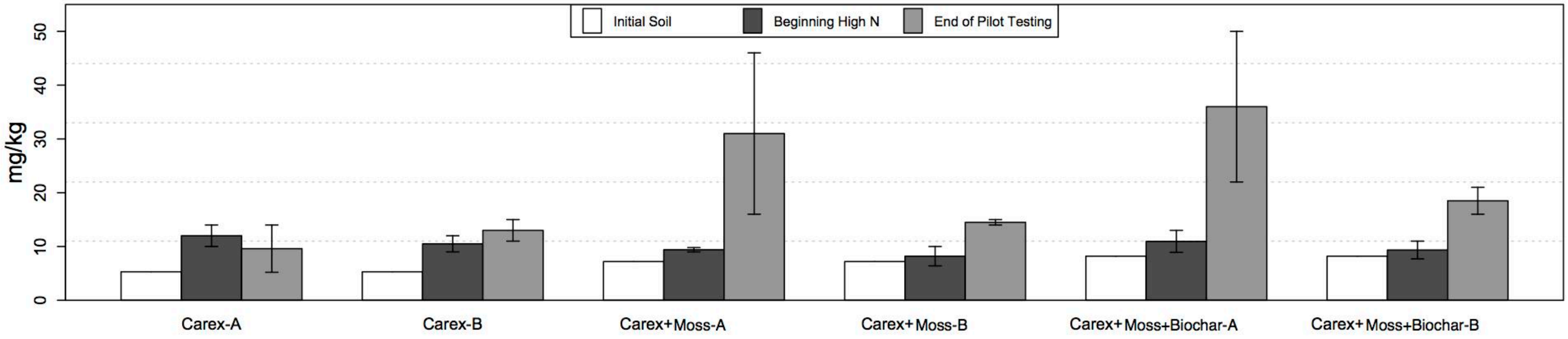
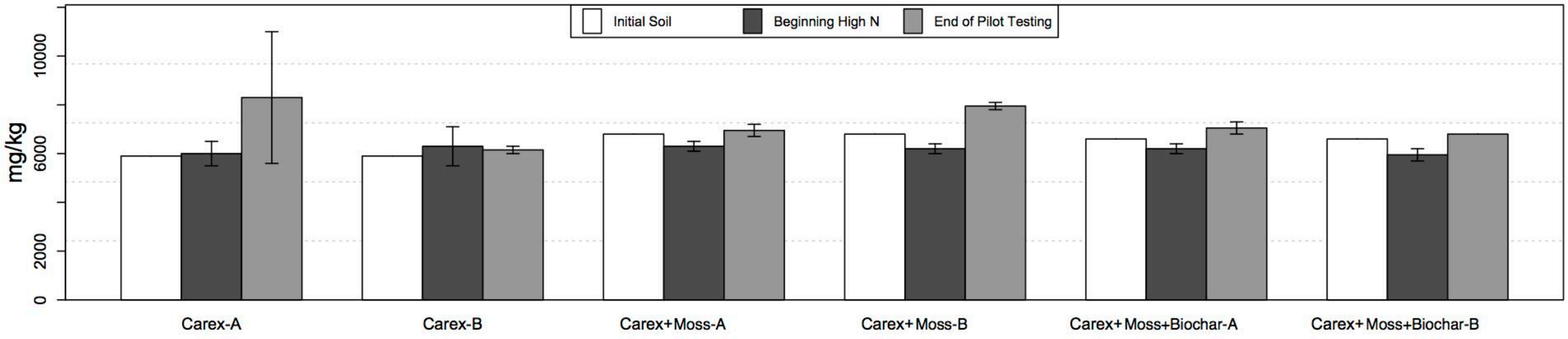


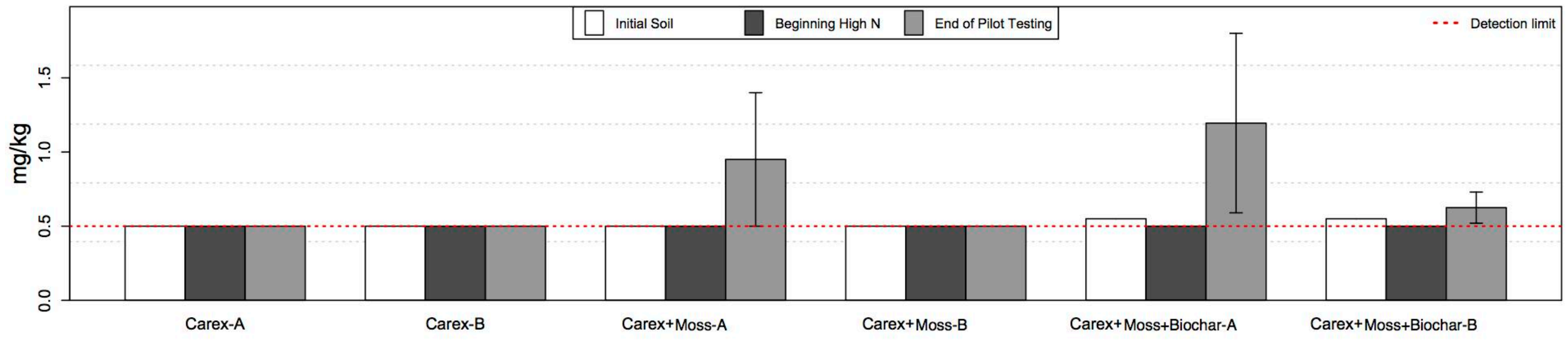
Figure 8: Copper, iron, selenium and sulphur concentrations in sediment throughout the pilot testing. Initial soil is the soil that was used to build the pilot systems, before any water was introduced. A and B cells for system designs are plotted separately, with error bars indicating the maximum and minimum values. The dotted red line indicates the selenium detection limit, as several samples were below this level. Selenium and sulphur plots are on the following page.

Total Copper (Cu)



Total Iron (Fe)




Total Selenium (Se)

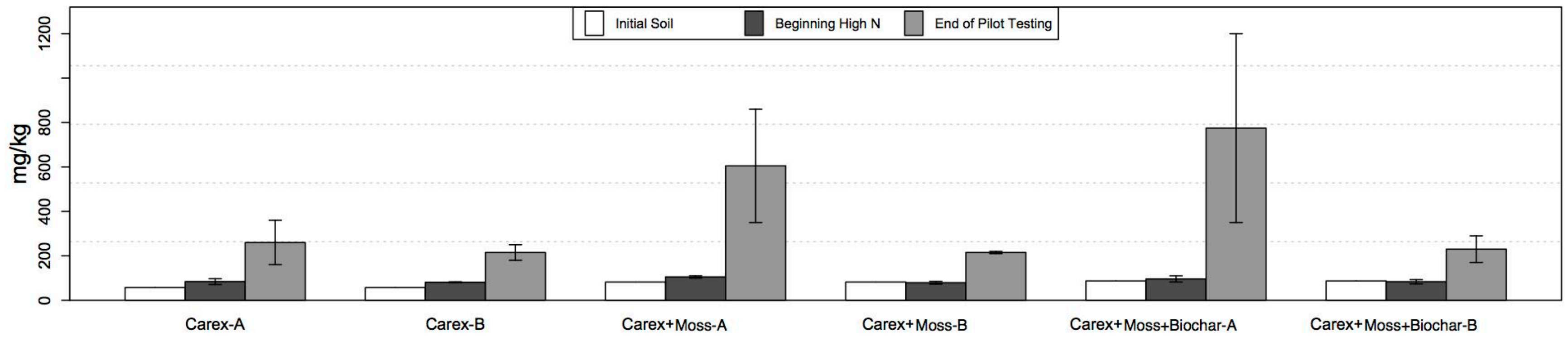

Total Sulphur (S)

Figure 9: Mass balance of copper in the pilot CWTS at the end of testing. The total amount of copper in the top 6 cm of sediment in A and B cells is shown for each system design, as well as the *Carex* in A and B cells. “Other” is the portion that was not analyzed for metals, and therefore cannot be differentiated. Examples of locations in the “Other” category would be plant roots, biofilms, and deeper sediment, as all of these were not analyzed. Additionally, it should be noted that the Moss did not survive the hybrid bioreactor-CWTS period, and therefore was not tested at the end of the pilot testing.

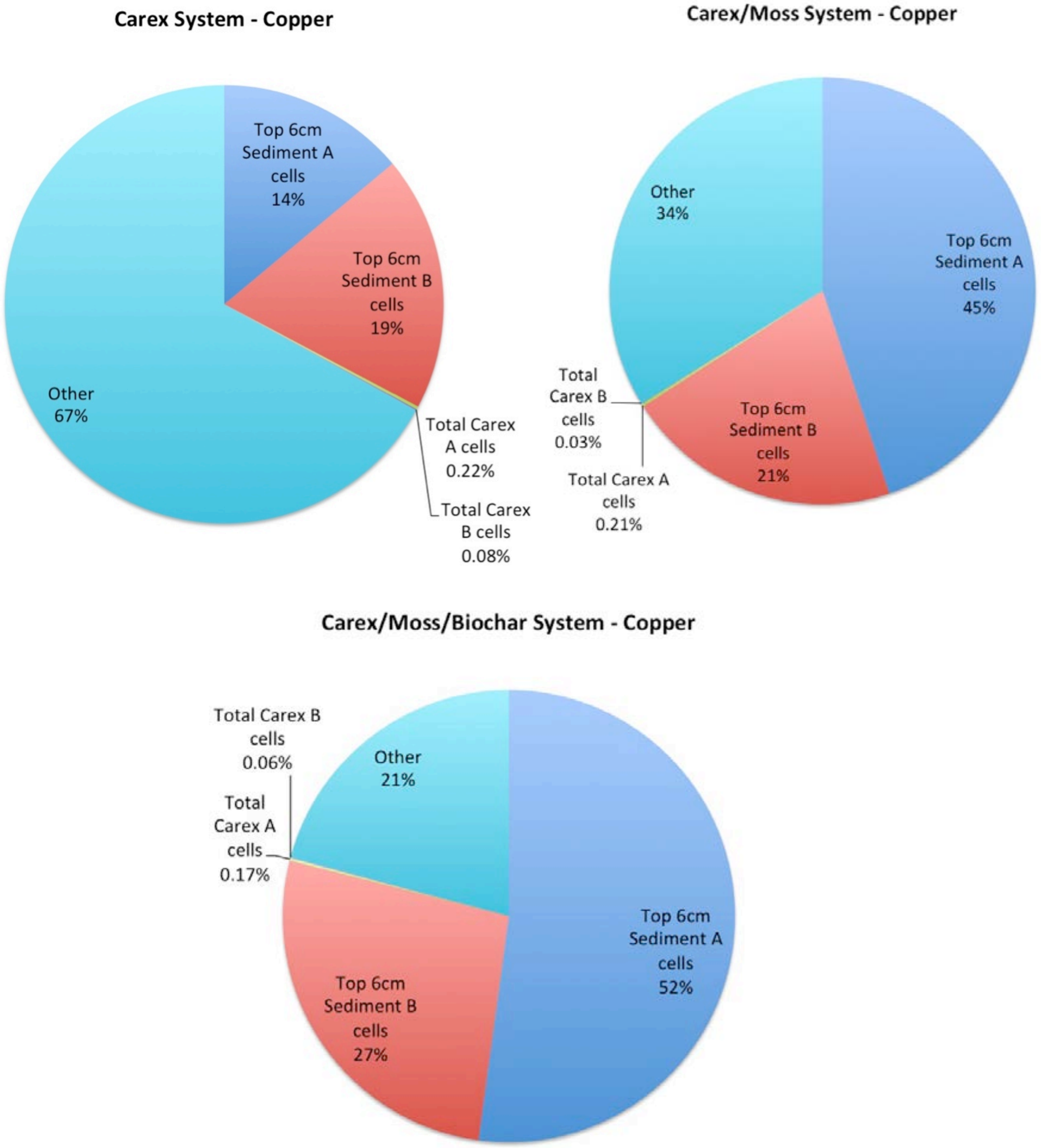


Figure 10: Mass balance of selenium in the pilot CWTS at the end of testing. The total amount of selenium in the top 6 cm of sediment in A and B cells is shown for each system design, as well as the *Carex* in A and B cells. “Other” is the portion that was not analyzed for metals, and therefore cannot be differentiated. Examples of locations in the “Other” category would be plant roots, biofilms, and deeper sediment, as all of these were not analyzed. Additionally, it should be noted that the Moss did not survive the hybrid bioreactor-CWTS period, and therefore was not tested at the end of the pilot testing.

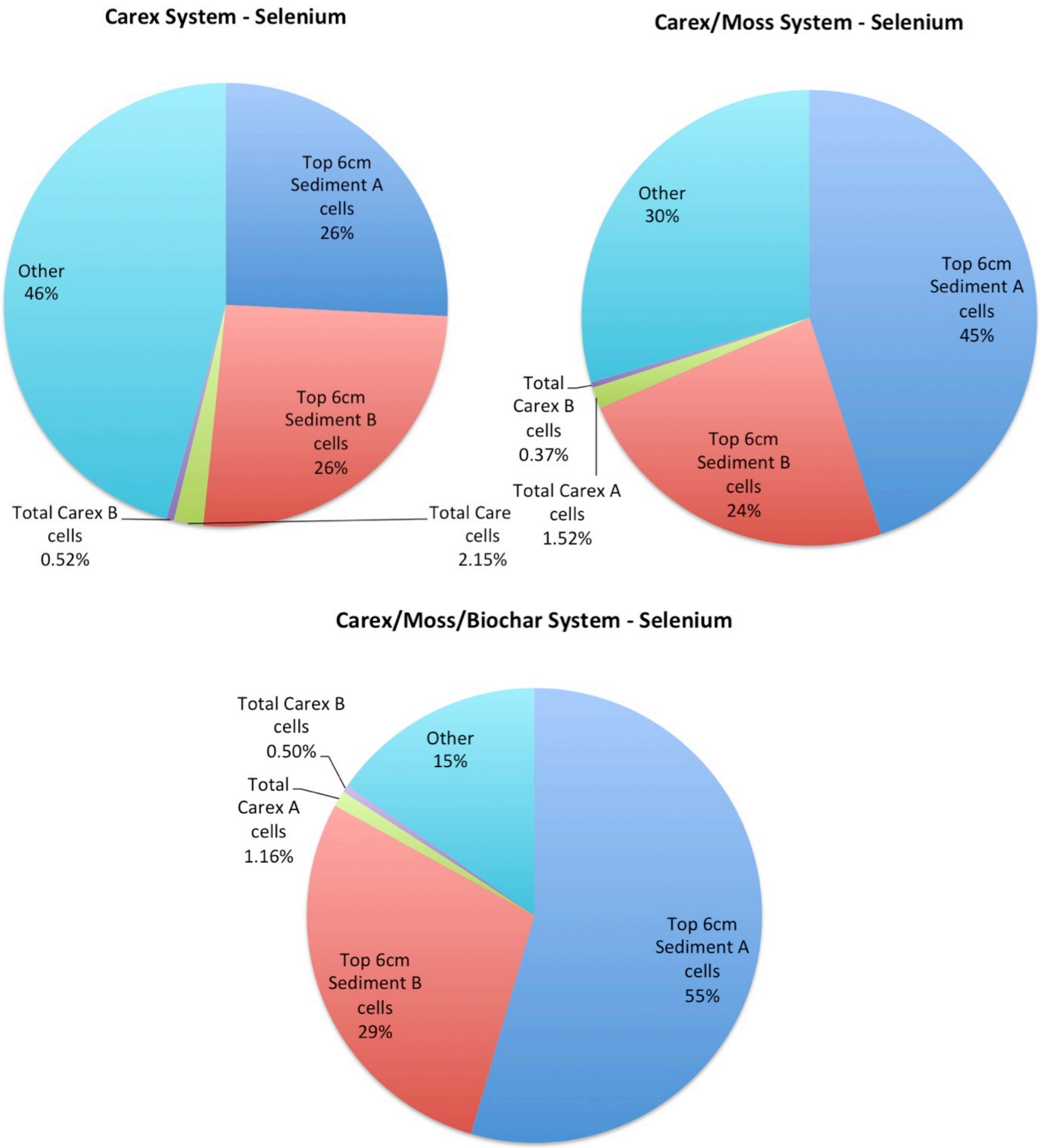
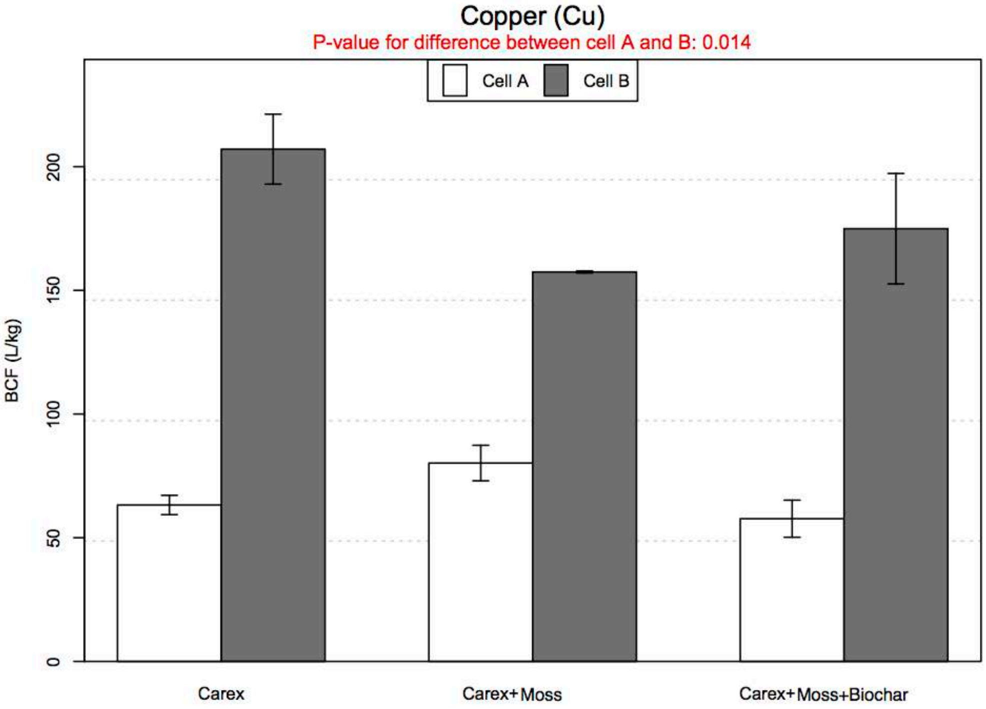


Figure 11: Comparison of bioconcentration factor for copper and selenium in *Carex* in A and B cells from each pilot system design. The p-value is calculated using Friedman test, with significant results shown in red. A significant test means that a difference between the BCF in A and B cells is found (e.g., A cells are always higher than B cells, or vice versa).



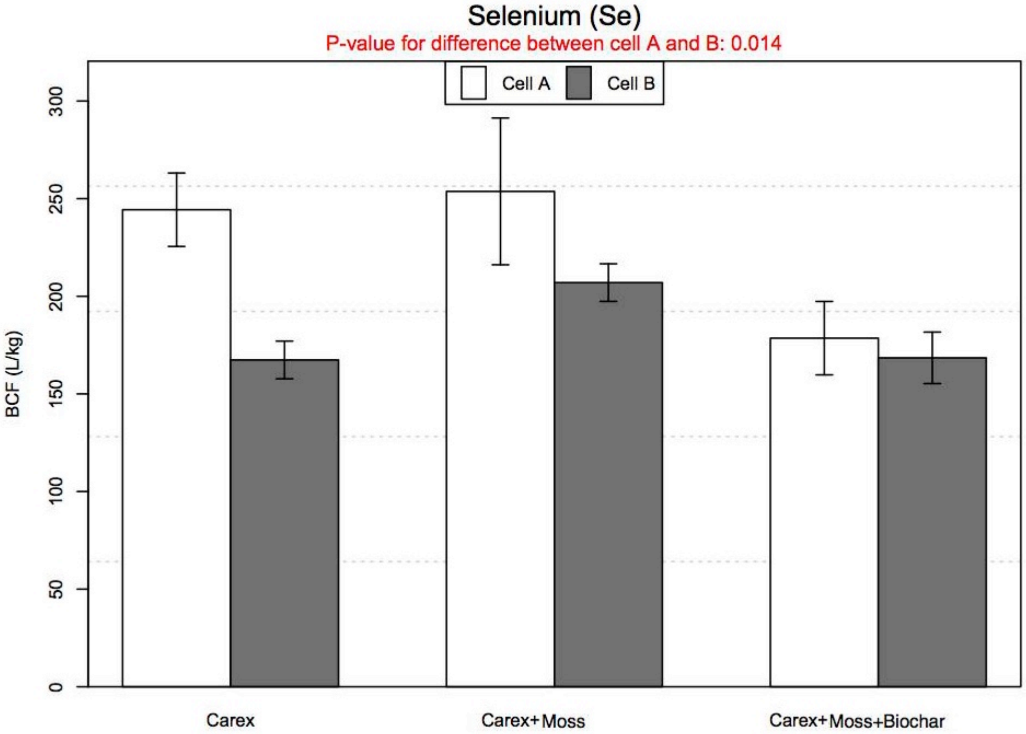


Figure 12: Copper and selenium concentrations in *Carex* before and after the freeze-thaw test, for all three system designs.

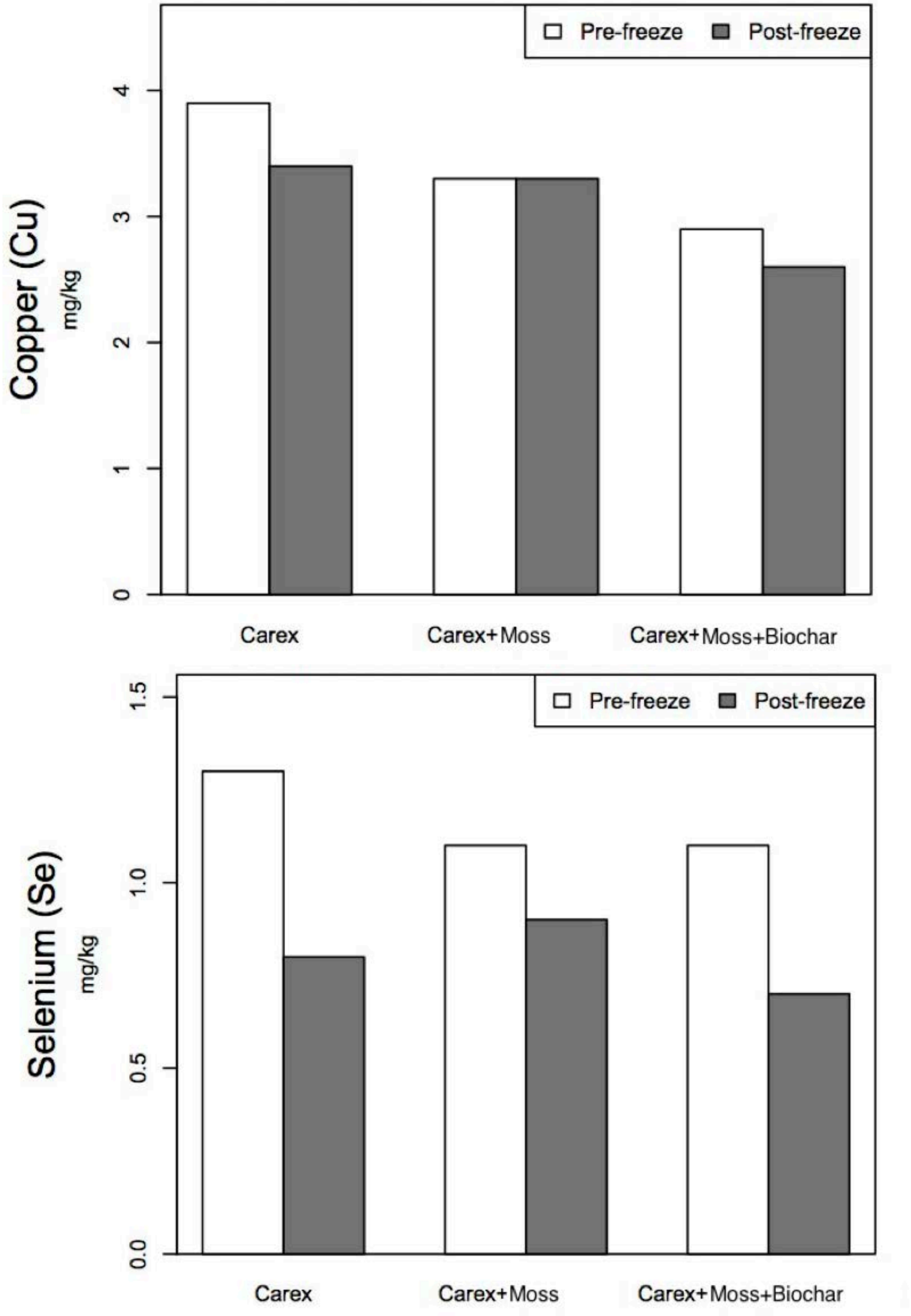


Figure 13: Copper and selenium concentrations in Moss before and after the freeze-thaw test, for the two system designs that had Moss.

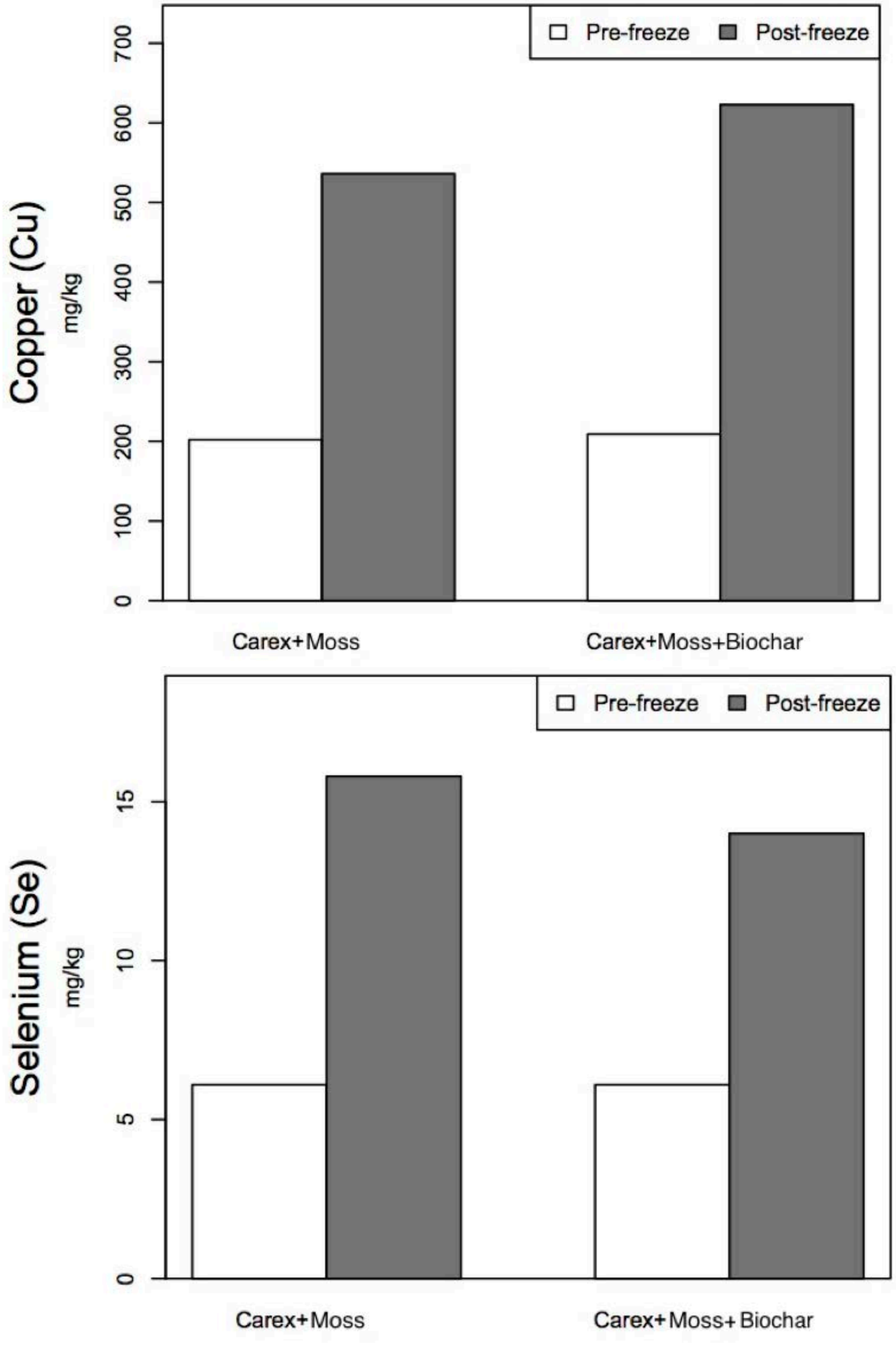
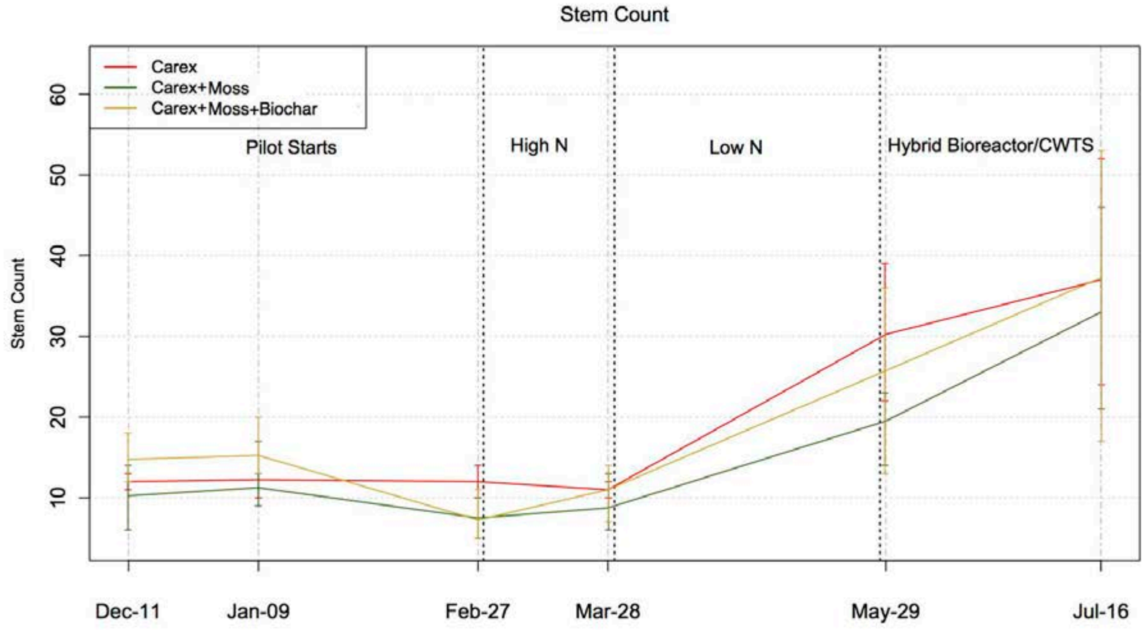


Figure 14: Photograph of *Carex aquatilis* (Sedge) roots at system takedown

Figure 15: Photograph of CWTS cell during takedown of the system. Orange-colored hydrosoil layer is approximately 18 cm, black detritus toproot zone is ~3 cm. Water depth was ~20 cm during the high and low nitrogen periods, and ~30 cm above the sediment during the hybrid bioreactor-CWTS period.

Figure 16: *Carex* stem counts (top) and height (bottom) of each system design, during all periods of testing.



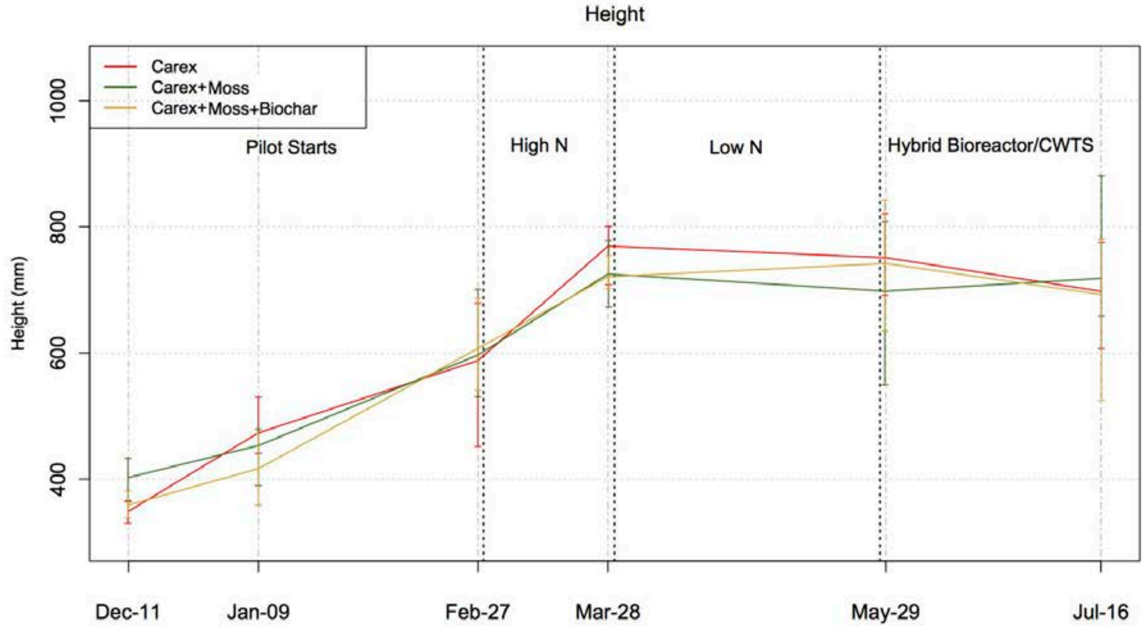
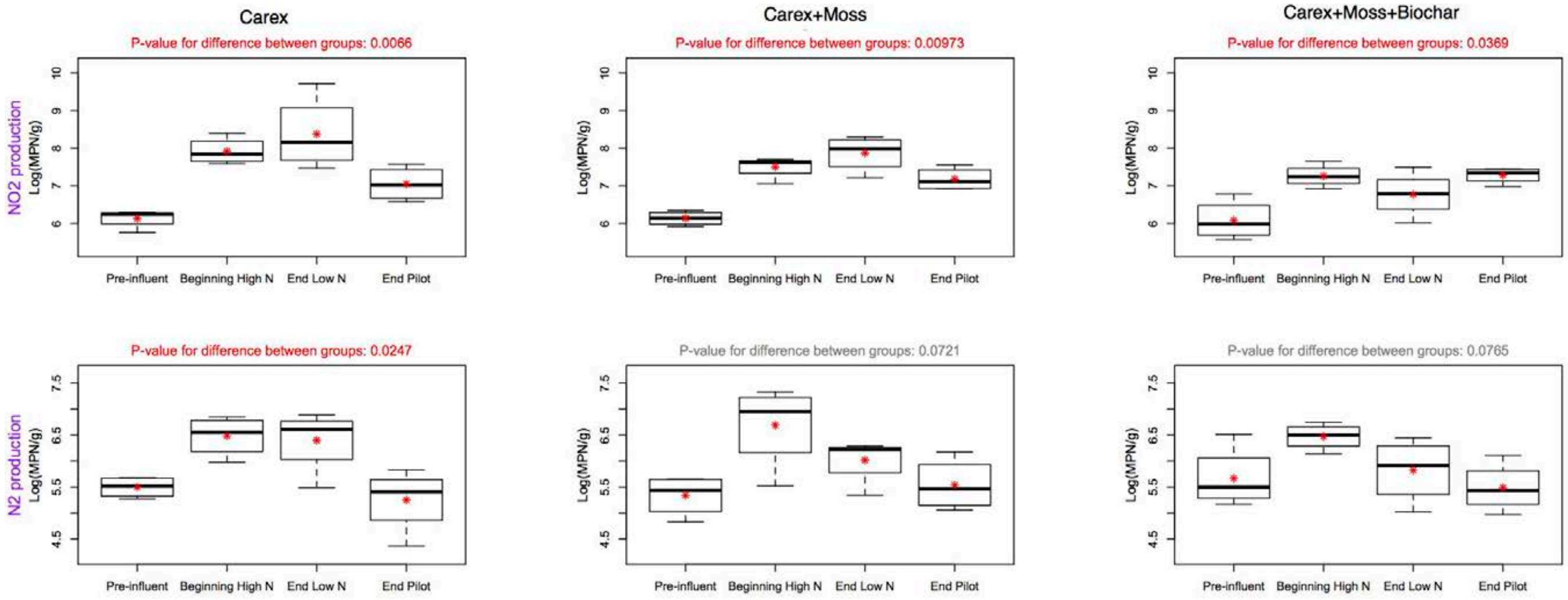
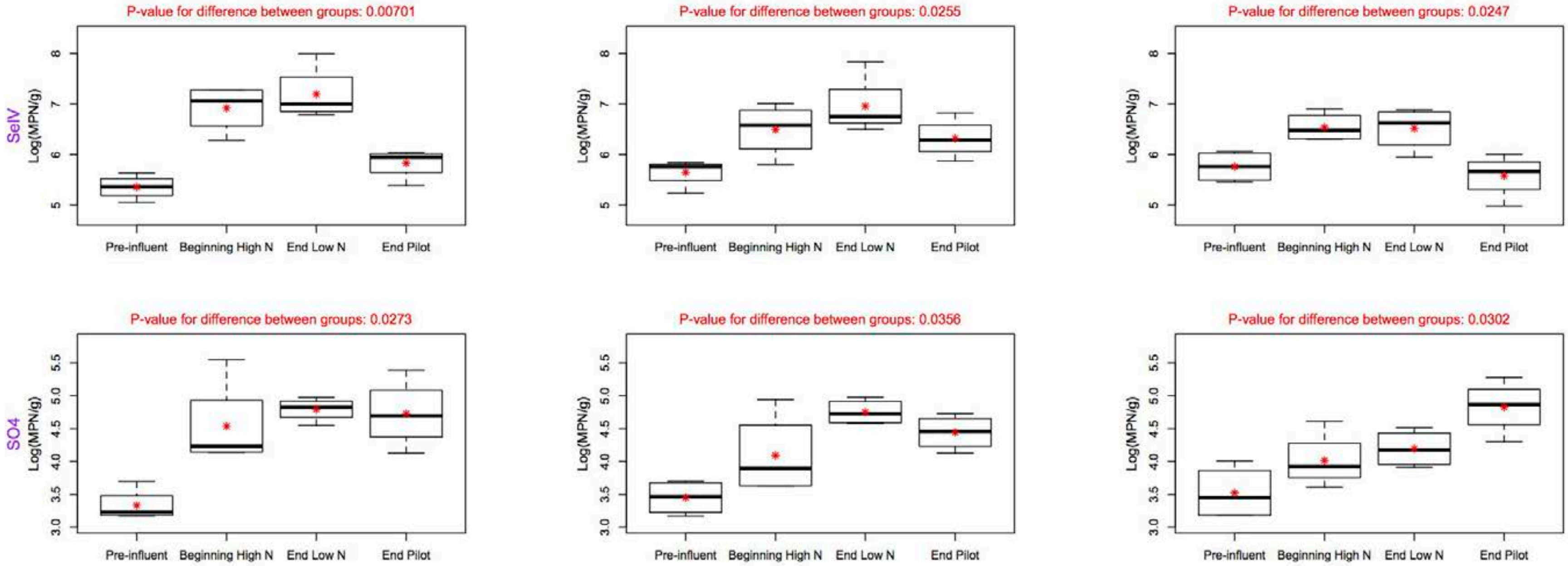


Figure 17: Comparison of the most probable number (MPN) of nitrate-, selenite-, and sulphate-reducing organisms in each system over time. NO_2 production indicates the MPN of organisms that are capable of reducing nitrate to nitrite. N_2 production shows the MPN of organisms that can reduce nitrate to nitrogen gas. The MPN was compared among the four time periods, and a P-value was calculated using the non-parametric Kruskal-Wallis test. The first plot represents systems with just *Carex*, the second plot is systems with *Carex* and Moss, while the third plot is systems with *Carex*, Moss, and biochar. Significant differences ($P<0.05$) are indicated in red, meaning a significant difference is found between the four testing periods in a given system design. Box plots are used to visualize the results; top and bottom edges of the box show the 25th and 75th percentile, respectively, while the thick black line depicts the median and the red asterisk shows the mean. The upper and lower whiskers provide the maximum and minimum non-outlier values. The remainder of the figure is provided on the following pages.




P-value for difference between groups: 0.00701
P-value for difference between groups: 0.0255
P-value for difference between groups: 0.0247
SeIV
Log(MPN/g)
5
6
7
8
Pre-influent
Beginning High N
End Low N
End Pilot
P-value for difference between groups: 0.0273
P-value for difference between groups: 0.0356
P-value for difference between groups: 0.0302
SO4
Log(MPN/g)
3.0
3.5
4.0
4.5
5.0
5.5
Pre-influent
Beginning High N
End Low N
End Pilot

Appendix 1:
Table 1: Biochar Analytical Results

Parameter	Units	Concentration
Cation exchange capacity	cmol+/kg	11
Total Organic Carbon (C)	%	54
As Received Basis Heat Value	MJ/kg	14.670
Available (NH4F) Nitrogen (N)	mg/kg	<2.0
Available (NH4F) Phosphorus (P)	mg/kg	1.3
Available (NH4OAc) Potassium (K)	mg/kg	1300
Sodium Adsorption Ratio	N/A	1.6
Soluble Calcium (Ca)	mg/L	61
Soluble Magnesium (Mg)	mg/L	1.0
Soluble Sodium (Na)	mg/L	46
Soluble Potassium (K)	mg/L	270
Saturation %	%	220
Soluble Sulphate (SO4)	mg/L	150
Moisture	%	4.6
Total Aluminum (Al)	mg/kg	7800
Total Boron (B)	mg/kg	<2.0
Total Calcium (Ca)	mg/kg	27000
Total Iron (Fe)	mg/kg	10000
Total Lithium (Li)	mg/kg	<10
Total Magnesium (Mg)	mg/kg	7400
Total Manganese (Mn)	mg/kg	250
Total Phosphorus (P)	mg/kg	3100
Total Potassium (K)	mg/kg	7400
Total Sodium (Na)	mg/kg	830
Total Strontium (Sr)	mg/kg	47
Total Sulphur (S)	mg/kg	1200
Total Antimony (Sb)	mg/kg	<1.0
Total Arsenic (As)	mg/kg	2.4
Total Barium (Ba)	mg/kg	77
Total Beryllium (Be)	mg/kg	<0.40
Total Cadmium (Cd)	mg/kg	0.12
Total Chromium (Cr)	mg/kg	13
Total Cobalt (Co)	mg/kg	2.6
Total Copper (Cu)	mg/kg	11
Total Lead (Pb)	mg/kg	3.6
Total Molybdenum (Mo)	mg/kg	0.82
Total Nickel (Ni)	mg/kg	6.4
Total Selenium (Se)	mg/kg	<0.50

Total Silver (Ag)	mg/kg	<1.0
Total Thallium (Tl)	mg/kg	<0.30
Total Tin (Sn)	mg/kg	<1.0
Total Uranium (U)	mg/kg	<1.0
Total Vanadium (V)	mg/kg	19
Total Zinc (Zn)	mg/kg	44
Acenaphthene	mg/kg	0.14
Benzo[a]pyrene equivalency	mg/kg	<0.10
Acenaphthylene	mg/kg	0.072
Acridine	mg/kg	0.020
Anthracene	mg/kg	0.053
Benzo(a)anthracene	mg/kg	0.0081
Benzo(b&j)fluoranthene	mg/kg	0.0056
Benzo(k)fluoranthene	mg/kg	<0.0050
Benzo(g,h,i)perylene	mg/kg	<0.0050
Benzo(c)phenanthrene	mg/kg	<0.0050
Benzo(a)pyrene	mg/kg	<0.0050
Benzo[e]pyrene	mg/kg	<0.0050
Chrysene	mg/kg	0.0095
Dibenz(a,h)anthracene	mg/kg	<0.0050
Fluoranthene	mg/kg	0.24
Fluorene	mg/kg	0.11
Indeno(1,2,3-cd)pyrene	mg/kg	<0.0050
2-Methylnaphthalene	mg/kg	0.13
Naphthalene	mg/kg	0.16
Phenanthrene	mg/kg	0.42
Perylene	mg/kg	<0.0050
Pyrene	mg/kg	0.18
Quinoline	mg/kg	0.028
D10-ANTHRACENE (sur.)	%	82
D12-BENZO(A)PYRENE (sur.)	%	17
D8-ACENAPHTHYLENE (sur.)	%	95
TERPHENYL-D14 (sur.)	%	112

Table 2: Alfalfa Analytical Results

Parameter	Units	Concentration
Available (NH4F) Nitrogen (N)	mg/kg	150
Available (NH4F) Phosphorus (P)	mg/kg	1200
Available (NH4OAc) Potassium (K)	mg/kg	20000
Available (CaCl2) Sulphur (S)	mg/kg	1200
Total Organic Carbon (C)	%	35
Antimony (Sb)	ug/g	<0.05
Arsenic (As)	ug/g	<0.5
Barium (Ba)	ug/g	60.7
Beryllium (Be)	ug/g	<0.05
Bismuth (Bi)	ug/g	<0.05
Boron (B)	ug/g	30.2
Cadmium (Cd)	ug/g	0.09
Calcium (Ca)	ug/g	12100
Chromium (Cr)	ug/g	1.6
Cobalt (Co)	ug/g	0.263
Copper (Cu)	ug/g	8.1
Iron (Fe)	ug/g	532
Lead (Pb)	ug/g	0.54
Magnesium (Mg)	ug/g	3430
Manganese (Mn)	ug/g	62.6
Molybdenum (Mo)	ug/g	1.48
Nickel (Ni)	ug/g	1.24
Phosphorus (P)	ug/g	1810
Potassium (K)	ug/g	18600
Selenium (Se)	ug/g	0.3
Silver (Ag)	ug/g	<0.05
Sodium (Na)	ug/g	451
Strontium (Sr)	ug/g	52.4
Thallium (Tl)	ug/g	0.011
Tin (Sn)	ug/g	<0.3
Titanium (Ti)	ug/g	8.7
Uranium (U)	ug/g	0.113
Vanadium (V)	ug/g	0.8
Zinc (Zn)	ug/g	27

Appendix A3

Minto Mine Constructed Wetland Treatment Research Program - Demonstration CWTS

Forward looking. Lateral thinking.

Minto Mine Constructed Wetland Treatment Research Program – Demonstration Scale

Document – 011_0315_01A

Prepared for

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Date:
March 22, 2015

Table of Contents

1. Introduction and Background

The Minto mine, operated by Capstone, is located 240 km northwest of Whitehorse on the west side of the Yukon River. The Minto property lies within the eastern part of the Dawson Range, with elevations from 700 to 1000 m; the landscape has rounded mountains intersected by broad valleys and drainages that are part of the Yukon River watershed.

The Minto mine has been in commercial operation since October 2007 and the deposits being mined are copper sulphide mineralized zones. Surface and groundwater water quality is a key consideration in the evaluation of potential effects of mining and mineral development projects and changes to water quality parameters have the potential to affect aquatic and human use of water resources. A Reclamation and Closure Plan (RCP) is required under both the Water Licence and the Quartz Mining Licence. The RCP is intended to address the long-term physical and chemical stability of the site and closure of the proposed features and disturbances associated with the mine. As a part of the RCP, a Constructed Wetland Treatment System (CWTS) is being designed, evaluated, and optimized for water treatment at closure through a phased program (Minto Phase V/VI Expansion Project, YOR Project Number 2013-0100).

Once established, wetlands can become self-sustaining ecosystems with plants providing yearly renewal of carbon to fuel microbial activity. As such, they possess the desirable potential to remediate contaminated mine drainage for as long as it is generated. In order for CWTSs to be effective, they must be designed, piloted, optimized, implemented, and maintained in a site-specific manner. A scaled approach for CWTS implementation allows for improvement, optimization, and flexibility for modifications along each step. Phases include: 1) site assessment and information gathering, 2) technology selection and conceptual design, 3) pilot-scale testing and optimization (controlled environment), 4) on-site demonstration-scale confirmation and optimization, and 5) full-scale implementation. Phases 1-3 have been completed (reports 2013-0100-256 and 2013-0100-257 on YESAB registry, and Contango, 2014) and confirmed plant amenability to transplantation and the CWTS design for further on-site testing. During pilot-scale trials, the selected CWTS design achieved 92% removal of copper (mean influent 146 µg/L, outflow 11.3 µg/L) and 41% removal of selenium (mean influent 10.2 µg/L, outflow 6 µg/L) using synthetic influent designed to mimic the worst-case water chemistry of a long-term closure scenario. Phase 4 of the project is now underway, with the on-site demonstration scale CWTS constructed at the Minto Mine during fall 2014. This document reports on the on-site demonstration scale CWTS design, construction, preliminary data, sampling schedule, and the long-term conceptual closure plan.

2. Design

2.1. System layout and dimensions

The demonstration-scale CWTS includes 2 systems in parallel with 2 cells in each series and a final catchment basin that both systems flow into (Figures 1-3). The location of the system in relation to the Minto site is provided in Figure 1. A stable foundation on waste rock fill was selected for the CWTS and a base of residuum (sandy gravel) material was placed in compacted lifts to allow for shaping of the structure to design specifications. The two parallel systems serve as a replicate for data analysis, but as testing progresses, it is also possible that one of the two systems may be subjected to alternate conditions for comparative purposes.

The four planted cells ranged slightly in width and length. The as built sizing of the cells (at soil surface), after soil and amendments were added, ranged from 2.8 m to 3.8 m in width and 8.7 m to 9.8 m in length (Figure 4, Table 1). This was consistent with the submitted design of the cells being 3 to 4 times longer than wide.

The 4 cells and catchment basin were roughed in and large sharp rocks hand picked and removed prior to final grading and survey. The finished surface was lined with an impermeable 4030 Enviro Liner® that was welded together and sandwiched between two layers of 12 ounce geotextile fabric.

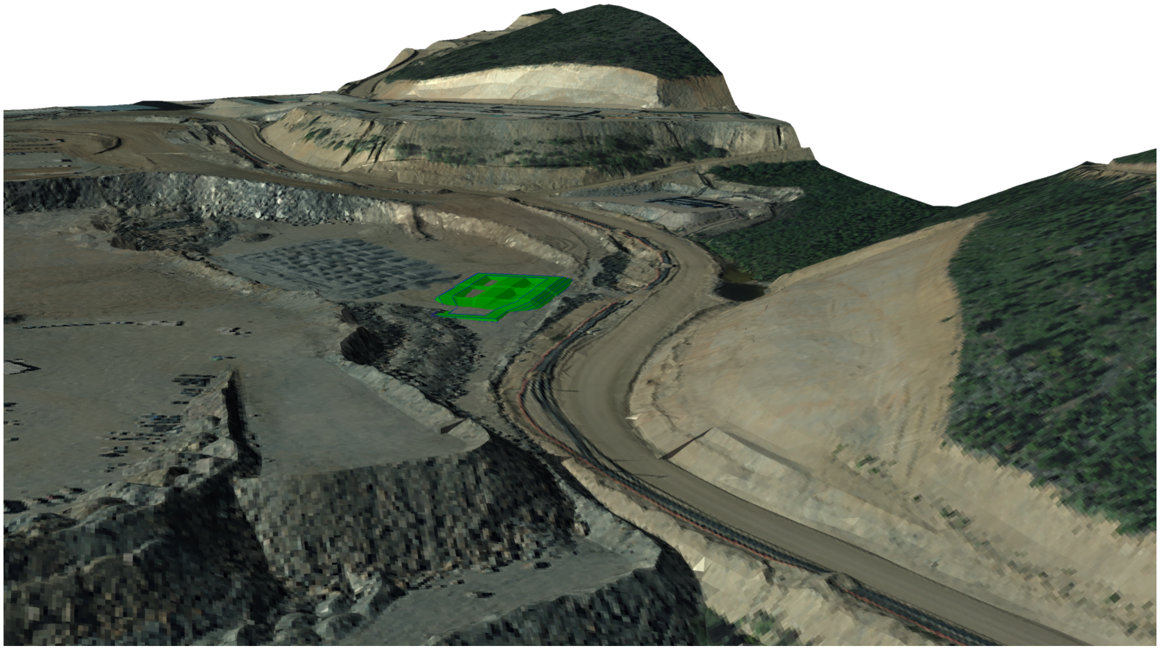

Figure 1. Location of demonstration-scale CWTS at Minto mine.

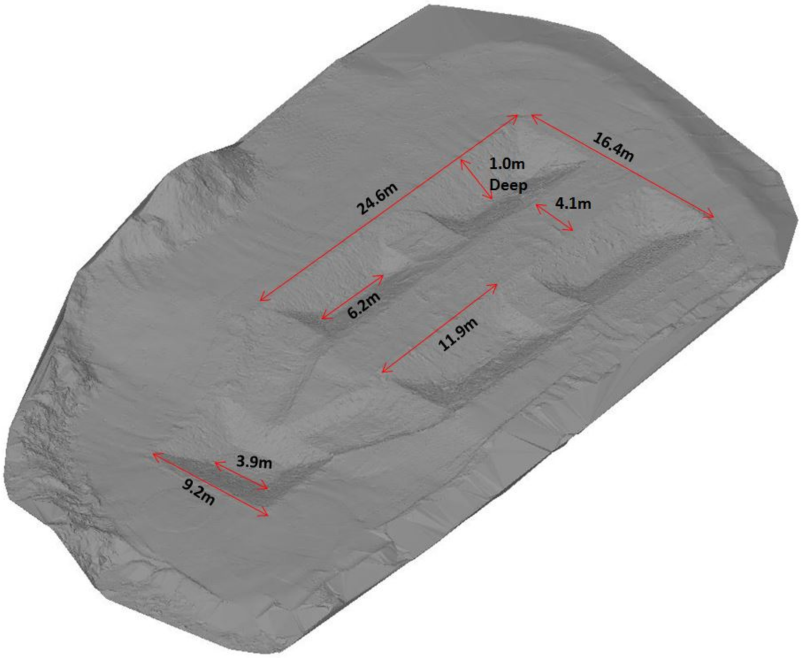

Figure 2. As built schematic of demonstration-scale CWTS.

Figure 3. Demonstration-scale CWTS prior to liner installation.

Table 1. Measurements of demonstration-scale CWTS cells at soil surface and resultant areas of treatment systems.

Measurement		1A	1B	2A	2B
Width (m)	Inflow	3.6	3.8	3.6	2.8
	Outflow	3.3	3.8	3.3	3.6
Length (m)		9.8	9.5	8.7	8.8
Approximate surface area at soil (m^2)		33.8	36.1	30.0	28.2
Total area of System at soil (m^2)		69.9		58.2	

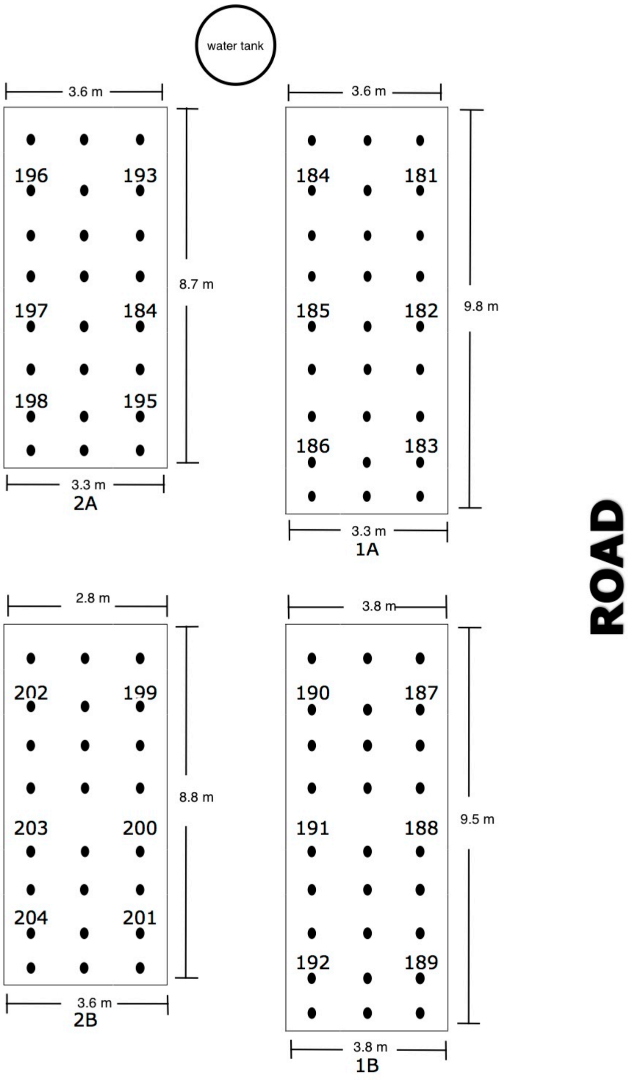

Figure 4. Diagram of demonstration-scale CWTS with dimension measurements at soil surface showing grid (by moss stakes; black dots) and locations of soil redox probes (with identifying numbers; Table 2).

2.2. Soil and Amendments

The recommended soil for the CWTS is sand, with 2-7% by volume as organic material (e.g., woodchips, peat). In the pilot-scale systems, this resulted in a total organic carbon (TOC) content of 0.2-0.6% (the sand itself was at 0.1% TOC prior to adding amendment). In this composition, the sand allows for circulation of water through the root zone of the plants, while the organic matter initiates reductive microbial processes that in future years will be sustained by decaying plant matter. In the case of this demonstration-scale system, the soil added to each of the 4 cells was from a local overburden site. The characteristics of this soil are provided in Appendix A. This borrow site was different than the site that was sampled during the Contango Strategies Ltd. (CSL) assessment in 2013, and also different than that tested in June 2014 (Appendix A, Table A1-A3).

The overburden soil used in the demonstration-scale CWTS was taken from stockpiled material that originated as richly organic soil from stripping of the Area 2 Pit. The calcium, magnesium and sulphate concentrations were higher than those of the pilot-scale tests, but this is not expected to negatively impact the performance of the CWTS. Owing to the general mineralization of the area, the concentration of copper was elevated in all soils tested as potential borrow sources. The synthetic precipitation leaching procedure (SPLP) analysis conducted on the soils used in the demonstration-scale wetland suggested there is between 148-608 µg/L of available copper and 0.35-0.69 µg/L of available selenium in the soil. This should be monitored and taken into consideration with wetland performance, and it may be necessary to investigate other sources of soil with lower copper concentration for final full-scale construction.

It was observed that the soil that was used for the demonstration-scale wetlands was higher in organic content and lower in sand than those used in the pilot-scale testing, or tested during the site assessment or June 2014 pre-construction sampling. This higher organic content was also associated with a more loamy texture. Due to the higher organics content in the soil being used for the demonstration-scale CWTS, there was less organic amendment added (by volume) than was initially planned. As the soil was added by the backhoe (Figure 5), there was 1 standard size straw bale (measuring 36 cm x 46 cm x 102 cm) and 50 rounded standard shovels of a 50:50 mix of spruce and pine wood shavings placed in each of the cells and mixed by hand with shovels and rakes (Figures 6 and 7). There was no biochar added as was proposed in the initial design as this was determined to not be required after the piloting phase at the CSL facilities (Contango, 2014).

The high organic content of this soil may actually be beneficial to the treatment of elements, through both sorption and increased microbial reductive processes. The drawback of using this organic material is that it may not facilitate the circulation of water in the root zone the way sand or gravel would, and it is also more difficult to work with for construction purposes. Specifically, the material used in the demonstration-scale CWTS did not support weight as a sandy soil would. For this reason, the wetland was planted while the soils were somewhat dry (before flooding), as the people planting the wetland would sink into the soil if it were wet. This should be taken into consideration if building the full-scale CWTS for the sake of ease of accessing monitoring points within the wetland, or if any revegetation campaigns are needed. Over time, however, the plant roots and moss will grow and provide greater physical stability to the soils.

Upon inspection, there was too much soil placed in the cells by the mini-backhoe; some of the soil was therefore removed to bring the outflow depth to 20 cm and maintain a level grade in each of the 4 cells to a tolerance of +/- 5 cm in order to provide a uniform water depth. A uniform water depth is necessary to prevent future issues such as channeling of water, open water spots due to plants being unable to grow because of excessive water depth, or conversely, drying out.

Figure 5. Soil being added to demonstration-scale CWTS cells.

Figure 6. Organic soil amendments used in demonstration-scale CWTS. Left, wood shavings 50:50 pine and spruce mixture; Right, straw.

Figure 7. Mixing organic amendments into soil in demonstration-scale CWTS cell 2A.

2.3.Plants

The demonstration-scale CWTS was planted with *Carex aquatilis* (Sedge) and mosses, as was determined by pilot-scale testing as being the best design for this site and application (Contango, 2014). These plant species were harvested for the demonstration scale CWTS from a location that was identified during the August/September 2013 site assessments in the vicinity of the W10 monitoring point (reports 2013-0100-256 and 2013-0100-257 on the YESAB registry). This site had *C. aquatilis* and aquatic mosses growing together as is desired for the CWTS design (Figures 8 and 9). Plant tissues were sent for analytical testing to determine initial concentrations (Appendix A, Table A4).

All 4 cells of the demonstration-scale CWTS were measured and the center of the width marked at both the inflow and outflow ends of each of the cells. The tape measure was then placed on the center axis down the length of each cell to start laying the center grid. The grid was created using wooden gardening stakes (50 cm in height), with aquatic moss tied to one end and inserted into the soil so that the moss was just above the soil (Figure 10; eventually to be submerged in the water). The grid for planting the *C. aquatilis* was created with these stakes, starting on the inflow end of each cell, with stake placement every 1 m progressing to the outflow (Figure 11). The final grid near the outflow of the cell was therefore sometimes less than 1 m of soil, but may look like a greater size due to the overlaying water. This was repeated moving outward from the center line, creating a grid of 1 m square areas for planting *C. aquatilis* to facilitate future monitoring of plant density. Depending on the varying width and length of the cells, along the sides of the length of the cells and the outflow of the cells the grids varied from 1 m squared to smaller than 1 m squared (Table 2).

Table 2. Number of planted grids in each demonstration-scale CWTS cell.

Item	Cell			
	1A	1B	2A	2B
Moss stakes	3*9=27	3*9=27	3*8=24	3*8=24
1 m squares	18	18	16	16
< 1 m squares (perimeter of CWTS cells)	22	22	20	20

Using the 4 stakes marking the edges of the grid, 5 *C. aquatilis* were planted into the soil inside each 1 m by 1 m grids, with one in the middle and 4 others approximately equidistant from the stakes to create an even distribution of 5 sedge per square meter (Figure 12). This placement and grid system was used to ensure even distribution of plants through the demonstration-scale CWTS, with the foresight of future monitoring for plant establishment and density. As the grids at the perimeter of each wetland cell varied and were often smaller than 1 m by 1 m, it was estimated based on the size of the grid how many sedge should be planted to maintain a consistent density of plants.

Figure 8. Harvesting plants from W10 location (top), and transporting back to demonstration-scale CWTS (bottom).

Figure 9. Images of *Carex aquatilis* and aquatic mosses harvested at W10 for planting the demonstration-scale CWTS. Left, aquatic mosses growing at water surface at edge of *C. aquatilis*; top right, underwater photograph of aquatic moss; bottom right, *C. aquatilis* and aquatic mosses growing together.

Figure 10. Example of moss tide to stakes, which then were used to make grid in each demonstration-scale CWTS (Figure 4, 11, 12 and Table2).

Figure 11. Moss stakes placed in demonstration-scale CWTS cell 2A, looking towards cell 2B.

Figure 12. *C. aquatilis* planted within grid of moss stakes in demonstration-scale CWTS cell 2A, and influent perforated pipe being laid in place.

2.4.Water

Water from the W36 area receiving seepage from the toe of the MVFE (Figure 13) was selected for the demonstration-scale CWTS testing as the leachate is similar to that expected upon closure in the Mill Valley Fill Extension (MVFE) area. The chemistry of this water at the time of bringing the demonstration-scale CWTS online (September 18, 2014) is provided in Appendix A, Table A5. A Grundfos CR1S-6 stage pump was selected to maintain the appropriate head of water in the holding tank to provide a range of flows between 0.1-1.1 m^3/hr on a 4-inch line with 30 m of head (Figure 13). The 3,000 Liter holding tank sits above and between the inflow of cells 1A and 2A and is kept at a constant head via pumping from the W36 sump (Figure 14). Overflow water is returned by gravity flow in a pipe to the W36 area. Meanwhile, water within the holding tank is gravity fed through control valves and flow meters prior to entering the parallel treatment cells (Figure 14). The tank was initially rinsed twice with the W36 water before releasing water into the demonstration CWTS because it had originally contained road dust suppressant (Envirobind). Water is constantly pumped from W36 to the tank that has been modified to maintain a constant head (and therefore pressure) to keep flow rate consistent when set using the manual valves. Flow rates are measured using ultra low flow and high accuracy/totalizer meters from GPI (Figure 14).

A flexible 1-inch braided rubber hose with perforations was attached to each of the flow meters and run to the inflow of cells 1A and 2A (Figure 12 and 14). The placement of these perforated hoses was adjusted to promote even flow across the width of the A cells. The system then operates by gravity flow, with Cell 1A and 2A flowing into 1B and 2B, respectively, before flowing into the catchment basin and returning by pipe to W36 (Figure 15).

Sandbags were used at the outflow of each cell to correct for unevenness in grade and prevent channeling to the lowest point. The average height of water in the cells above the soil was approximately 20 cm (Figure 16).

The flow rates for the systems were set to have a 10 day nominal hydraulic retention time (HRT), meaning water entering the wetland takes 10 days to exit. This is referred to as a nominal HRT because it is a calculation based on the size of the wetland and the amount of water entering, and not confirmed empirically using tracing dyes. The HRT was calculated based on the size of the CWTS at the soil, with a 20 cm overlay of water, but not adjusting for pore water because without dense vegetation, the pore spaces in the soil will only have minimal hydraulic relationship to the overlaying water. This HRT is much longer than what is necessary to achieve treatment based on the pilot-scale systems (~3 days), however, this was chosen to facilitate plant establishment and maturation. Because the sizes of the CWTS systems were slightly different, Series 1 (closer to the road) and Series 2 (further from road) were set with inflow rates of 13,928 L/day and 11,635L/day, respectively, both corresponding to an approximate 10 day HRT. As the flow meters record in US gal/min, this corresponds to 2.6 and 2.13 US gal/min.

Figure 13. Water source for demonstration-scale CWTS. Left, Grundfos CR1S-6 stage pump; Right, water source at W36.

Figure 14. Clockwise from left: holding tank, splitting control valve, and flow meters.

Figure 15. Demonstration-scale CWTS immediately after planting and filling with water (August 29, 2014). Top, photograph taken from camp behind kitchen looking down at inflow of CWTS; bottom, photograph taken from outflow holding pond looking towards camp in background.

2.5.Data Collection

Explanatory parameters are quantifiable aspects of a CWTS that can be used to assess the feasibility of treatment for a range of constituents, and therefore 'explain' the performance of a CWTS. These parameters, which often include acidity, alkalinity, conductivity, dissolved oxygen (DO), pH, oxidation reduction potential (ORP), ion balance, available electrons donors (e.g., organic carbon, reduced elements), and temperature, can be used to predict, promote, and/or optimize the ability of the system to treat different constituents.

The relative oxidation-reduction (redox) potential of the soil will be measured using inert electrodes (copper wire probes with platinum tips) permanently installed in the soil of the cells for the duration of the project (Faulkner et al., 1989; Figure 16). To take a reading of the relative redox potential between the soil and water, a reference electrode (Accumet Calomel) is suspended in the water column above the inert electrode and measured in millivolts by a voltmeter. There were 6 platinum tip probes distributed throughout each of the 4 demonstration-scale cells to try and achieve even distribution based on the varying cell sizes. The probes were inserted to cover the epoxy on the end of the probe and secured with flagging tape to the bamboo poles for visibility. The locations of each probe are provided in Figure 4 and Table 3.

Figure 16. Series 2 (cell 2B in foreground, cell 2A in background), showing sandbags used at inflows and outflows between cells.

Table 3. List of location and probe number for inert electrodes permanently installed in the soil of cells. General location also provided in Figure 4.

Stake - Row	Cell 1A	Cell 1B	Stake - Row	Cell 2A	Cell 2B
2nd - Inside	#181	#187	2nd - Inside	#193	#199
5th - Inside	#182	#188	5th - Inside	#194	#200
8th - Inside	#183	#189	7th - Inside	#195	#201
2nd - Outside	#184	#190	2nd - Outside	#196	#202
5th - Outside	#185	#191	5th - Outside	#197	#203
8th - Outside	#186	#192	7th - Outside	#198	#204

Probe numbers 205 to 209 were left as spares, in case of probe failure.

3. Sampling Schedule for 2015

The sampling schedule for 2015 was conceptually developed prior to beginning construction of the demonstration-scale CWTS (Table 4) and the analytical testing refined and summarized in Table 5. Actual dates of sampling will depend on timing of spring thaw and ability to bring the pumps online at the W36 pond to supply water to the demonstration-scale CWTS.

Table 4. Conceptual sampling parameters, locations, and frequencies.

Frequency	Parameter	Location	Sample Type
Weekly	Temperature (by data logger)	All Cells + Inflow to CWTS	Water
	pH		
	Dissolved Oxygen		
	Conductivity		
	ORP		
	Inflow rates/outflow rates (by meter)		
	Regulated Metals (ICP) (Total and dissolved)		
	Relative redox potential	All Cells	Soil
Monthly	Alkalinity	Outflow All cells + Inflow to CWTS	Water
	Hardness		
	Sulfate		
	Chemical Oxygen Demand		
	Total Organic Carbon		
	Ammonia		
	Nitrate/Nitrite		
	Total Kjeldahl Nitrogen		
	Biological Oxygen Demand	Outflow + Inflow of CWTS	
	Total Suspended Solids		

	Stem counts (and height)	All cells	Plant
Seasonally	Available NPKS	All cells	Soil
	Regulated Metals (ICP)		
	Total Organic Carbon		
	Cation Exchange Capacity (CEC)		
	Sodium Adsorption Ratio		
	Conductivity		
	Sequential Leaching		
	MPN for SeIV, NO_3, and sulphate reducing microbes, and total heterotrophs		
	Genetic microbial community profiles		
Twice per year	Detritus depth/accretion measurement	All Cells	Soil
	Regulated Metals (ICP)		Plant
	Available NPK and Sulphur		

Table 5. Summary of analytical sampling types, frequencies and locations

Water samples	
routine package: Ca, Mg, Na, K, Cl, SO_4, NO_3, NO_2, hardness, alkalinity, pH, EC, TDS	Monthly, outflow of each cell and inflow water
Chemical oxygen demand (COD)	Monthly, outflow of each cell and inflow water
Total organic carbon	Monthly, outflow of each cell and inflow water
Ammonia	Monthly, outflow of each cell and inflow water
Total Kjeldahl Nitrogen (TKN)	Monthly, outflow of each cell and inflow water
Total suspended solids	Monthly, outflow of series, and inflow water
Biological Oxygen Demand (BOD)	Monthly, outflow of series, and inflow water
Regulated metals water package (dissolved and total)	Weekly, outflow of each cell and inflow water
In-situ water testing (pH, DO, ORP, Conductivity)	Weekly, all cells and inflow water
Hydrosoil samples	
Relative soil redox	Weekly, all probes (6 per cell)
Cation exchange capacity (CEC)	Seasonally (3x per year), 3 places per cell
SAR, pH, EC, %sat, Ca, Mg, Na, K, Cl, SO4	Seasonally (3x per year), 3 places per cell
Available NPK and sulphur	Seasonally (3x per year), 3 places per cell
Total organic carbon	Seasonally (3x per year), 3 places per cell
Sequential Leaching	Seasonally (3x per year), 3 places per cell
Plant tissue samples	
ICP	2 plant types in triplicate (pre-planting in 2014)
Available NPK and sulphur	2 plant types in triplicate (pre-planting in 2014)
TOC	2 plant types in triplicate (pre-planting in 2014)

4. Long-term conceptual testing plan

A conceptual long-term testing plan has been developed for the demonstration-scale CWTS

(Table 6), which will be refined and adapted based on performance and scientific findings as the trials are conducted. The demonstration-scale wetlands will run for a minimum of 2 more years, until the end of 2016, but ideally longer in order to assess performance under a wider range of conditions. The conditions that could eventually be tested include both natural/environmental and selected influenced pressures, and can be imposed on the systems to mimic peak flow rates or droughts. In 2015 the systems will be allowed to continue to mature, with plants becoming more established and abundant, and microbial communities accordingly acclimating to the targeted conditions. Once plants are well established and showing signs of colonizing through the wetland, the water depth may be increased to 30 cm and the flow rate may also be increased. First, a 5 day HRT (i.e., twice as fast as currently) may be tested, and then fluctuations will be tested based on anticipated seasonal variation.

Table 6. Schedule as per proposed scope of work:

<table>
<tr><th colspan="2">Item</th><th>Proposed</th><th>Actual</th></tr>
<tr><td colspan="2">Identify potential location for demonstration scale CWTS (CSL site visit – 1 scientist)</td><td>June 1-14 2014</td><td>Completed</td></tr>
<tr><td colspan="2">Engineering and geotechnical (Minto)</td><td>June - July 2014</td><td>Completed</td></tr>
<tr><td colspan="2">Construction (Minto)</td><td>July 2014</td><td>Completed</td></tr>
<tr><td colspan="2">Planting and bringing system online (CSL site visit – 1 scientist, 1 technologist), coordinate for local students to assist.</td><td>August 2014</td><td>Completed (no students available, brought 2 technologists)</td></tr>
<tr><td rowspan="6">Monitoring</td><td rowspan="2">2014</td><td>Acclimation and maturation at constant flow rate of 10 d HRT</td><td>Completed</td></tr>
<tr><td>September - CSL site visit/checkup (1 technologist, 1 scientist)</td><td>Did not occur because constructed was last week of August.</td></tr>
<tr><td rowspan="4">2015</td><td>Continued maturation/acclimation. Operation at constant flow rate of 5-10 d HRT</td><td>On Schedule</td></tr>
<tr><td>Spring – CSL site visit/checkup (1 technologist, 1 scientist), includes micro sampling</td><td></td></tr>
<tr><td>Summer - Increase depth from 10 cm to 20 cm (1 technologist), includes micro sampling</td><td></td></tr>
<tr><td>Fall – CSL site visit/checkup (1 technologist), includes micro</td><td></td></tr>
</table>

		sampling	
	2016	Operation with weekly flow variations based on seasonal variations	
		Spring – CSL site visit/checkup (1 technologist), includes micro sampling	
		Summer - CSL site visit/checkup (1 technologist, 1 scientist), switch to hybrid bioreactor phase if appropriate, includes micro sampling	
		Fall - CSL site visit/checkup (1 technologist), includes micro sampling	
	2017	Hybrid Bioreactor/CWTS phase, late in operation 2016 or 2017, exact timing to be determined based on results from initial operations of the demo scale and results of hybrid CWTS/bioreactor pilot testing. This will involve adding solid organic matter (such as alfalfa hay, straw) to the CWTS cell(s).	
Reporting	2014-2016	Reporting will be performed twice annually, in the form of an interim update and comprehensive (all data to date) report.	On Schedule

5. Closure

We trust the information herein satisfies your present requirements. Should you have any questions, please contact the persons listed below. We appreciate the opportunity to provide the services detailed in this report, and look forward to discussing any comments you may have.

Respectfully submitted,
Contango Strategies Ltd

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Faulkner, S.P., Patrick, W.H. Jr. and Gambrell, R.P. (1989) Field techniques for measuring wetland soil parameters. Soil Science Society of America Journal, Vol. 53, pp. 883-890.

Table A1. Analytical results from initial soil sampled August 28, 2014

Parameter	Units	Rep1	Rep2	Rep3	Rep4	Wood Shavings	Straw	RDL
Calculated Parameters								
Anion Sum	meq/L	5.0	3.1	0.89	0.81	1.0	14	N/A
Cation Sum	meq/L	8.1	6.5	13	5.4	2.2	24	N/A
Cation/EC Ratio	N/A	11	11	10	11	10	9.4	0.10
Ion Balance	N/A	1.6	2.1	15	6.7	2.2	1.7	0.010
Cation exchange capacity	cmol+/Kg	22	20	18	20	<10	50	10
Soluble Parameters								
Soluble Chloride (Cl)	mg/L	41	16	240	26	12	310	5.0
Soluble Conductivity	dS/m	0.72	0.61	1.3	0.51	0.21	2.5	0.020
Soluble (CaCl2) pH	pH	6.46	6.44	6.56	6.47	3.95		N/A
Sodium Adsorption Ratio	N/A	0.55	0.53	2.0	0.65	0.30	0.63	0.10
Soluble Calcium (Ca)	mg/L	110	92	150	71	11	20	1.5
Soluble Magnesium (Mg)	mg/L	14	11	16	8.8	4.0	47	1.0
Soluble Sodium (Na)	mg/L	23	20	97	22	4.6	22	2.5
Soluble Potassium (K)	mg/L	7.6	7.4	8.5	7.1	39	710	1.3
Saturation %	%	47	48	47	44	620	1400	N/A
Soluble Sulphate (SO4)	mg/L	210	180	190	140	<5.0	210	5.0
Nutrients								
Available (NH4F) Nitrogen (N)	mg/kg	8.0	8.1	6.0	5.3	<10	<10	10
Available (NH4F) Phosphorus (P)	mg/kg	5.1	5.7	5.6	3.9	16	200	5.0
Available (NH4OAc) Potassium (K)	mg/kg	55	53	48	61	260	7700	10
Available (CaCl2) Sulphur (S)	mg/kg	29	24	27	24	<20	850	20
Nitrite (N)	mg/L	0.0165	0.0216	0.0156	0.0623	0.0127	<0.50	0.50
Nitrate (N)	mg/L	0.315	0.445	0.332	0.150	0.252	<2.0	2.0
Total Ammonia (N)	mg/L	<0.0050	0.0076	0.0086	0.0090	0.0428	0.067	0.050
Misc. Inorganics								
Fluoride (F)	mg/L	0.220	0.350	0.250	0.210	0.041	0.089	0.010

Parameter	Units	Rep1	Rep2	Rep3	Rep4	Wood Shavings	Straw	RDL
Dissolved Organic Carbon (C)	mg/L	6.55	5.91	4.96	6.85	355	815	50
Total Organic Carbon (C)	%	1.9	1.8	3.1	1.8	48	45	0.10
Alkalinity (Total as CaCO3)	mg/L	33.5	126	36.7	34.8	30.7	304	0.50
Alkalinity (PP as CaCO3)	mg/L	<0.50	13.2	2.49	8.01	<0.50	<0.50	0.50
Bicarbonate (HCO3)	mg/L	40.9	121	38.7	22.9	37.5	371	0.50
Carbonate (CO3)	mg/L	<0.50	15.9	2.99	9.61	<0.50	<0.50	0.50
Hydroxide (OH)	mg/L	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	0.50
Physical Properties								
% sand by hydrometer	%	59	60	55	57			
% silt by hydrometer	%	26	25	28	27			
Clay Content	%	15	16	17	16			
Texture	N/A	SANDY LOAM	SANDY LOAM	SANDY LOAM	SANDY LOAM			
Total Dissolved Solids	mg/L	80	200	104	222	692	2360	10
Dissolved Metals by ICPMS								
SPLP Aluminum (Al)	ug/L	6540	3640	4840	34400	145	151	2.5
SPLP Antimony (Sb)	ug/L	0.242	0.208	0.243	0.48	0.042	<0.10	0.10
SPLP Arsenic (As)	ug/L	3.24	2.19	2.67	15.0	0.446	1.57	0.10
SPLP Barium (Ba)	ug/L	141	79.9	102	476	46.8	396	0.10
SPLP Beryllium (Be)	ug/L	0.133	0.091	0.142	0.629	0.015	<0.050	0.050
SPLP Bismuth (Bi)	ug/L	0.0440	0.0240	0.0270	0.193	<0.0050	0.039	0.025
SPLP Boron (B)	ug/L	519	233	90	<250	127	<250	250
SPLP Cadmium (Cd)	ug/L	0.0470	0.0410	0.0740	0.158	0.137	0.484	0.025
SPLP Cesium (Cs)	ug/L	0.347	0.206	0.290	1.42	<0.050	0.29	0.25
SPLP Chromium (Cr)	ug/L	10.7	7.80	6.12	43.1	0.62	0.94	0.50
SPLP Cobalt (Co)	ug/L	2.53	1.44	2.13	10.5	0.106	0.291	0.025
SPLP Copper (Cu)	ug/L	248	148	186	608	11.0	116	0.25
SPLP Iron (Fe)	ug/L	8900	4950	7040	47400	49.4	308	5.0
SPLP Lanthanum (La)	ug/L	5.72	4.16	4.81	17.9	<0.050	0.27	0.25

Parameter	Units	Rep1	Rep2	Rep3	Rep4	Wood Shavings	Straw	RDL
SPLP Lead (Pb)	ug/L	3.00	1.79	2.21	12.4	1.10	14.7	0.025
SPLP Lithium (Li)	ug/L	2.90	1.66	2.00	12.6	1.05	3.5	2.5
SPLP Manganese (Mn)	ug/L	125	76.0	103	372	272	597	0.25
SPLP Molybdenum (Mo)	ug/L	1.75	1.46	1.94	1.86	0.230	2.52	0.25
SPLP Nickel (Ni)	ug/L	5.93	3.76	5.39	26.5	0.693	2.22	0.10
SPLP Phosphorus (P)	ug/L	132	84.6	107	503	416	1460	10
SPLP Rubidium (Rb)	ug/L	7.05	4.56	5.97	27.7	13.7	241	0.25
SPLP Selenium (Se)	ug/L	0.487	0.355	0.360	0.69	<0.040	1.09	0.20
SPLP Silicon (Si)	ug/L	14900	8970	11200	67100	425	24000	500
SPLP Silver (Ag)	ug/L	0.123	0.0950	0.123	0.325	0.0560	0.446	0.025
SPLP Strontium (Sr)	ug/L	14.2	12.7	12.2	35.6	11.3	156	0.25
SPLP Tellurium (Te)	ug/L	<0.020	0.024	0.021	<0.10	<0.020	<0.10	0.10
SPLP Thallium (Tl)	ug/L	0.0500	0.0310	0.0410	0.184	0.0110	0.103	0.010
SPLP Thorium (Th)	ug/L	1.44	1.06	1.25	4.56	0.0140	0.151	0.025
SPLP Tin (Sn)	ug/L	0.32	<0.20	0.22	1.1	<0.20	<1.0	1.0
SPLP Titanium (Ti)	ug/L	237	129	176	1280	1.28	4.7	2.5
SPLP Tungsten (W)	ug/L	0.093	0.080	0.086	0.203	0.054	<0.050	0.050
SPLP Uranium (U)	ug/L	0.176	0.134	0.151	0.865	0.0110	0.057	0.010
SPLP Vanadium (V)	ug/L	22.0	11.9	16.2	92.1	1.24	2.3	1.0
SPLP Zinc (Zn)	ug/L	19.9	13.2	15.4	74.4	16.0	84.5	0.50
SPLP Zirconium (Zr)	ug/L	1.72	1.42	1.49	5.77	0.12	<0.50	0.50
SPLP Calcium (Ca)	ug/L	3040	3290	3090	7240	3960	18000	250
SPLP Magnesium (Mg)	ug/L	1420	954	1110	6150	1670	38300	250
SPLP Potassium (K)	ug/L	1250	1010	1440	5780	14100	499000	250
SPLP Sodium (Na)	ug/L	43900	33900	22100	26900	8550	20500	250
SPLP Mercury (Hg)	ug/L	<0.050	<0.050	<0.050	<0.25	0.096	<0.25	0.25
SPLP Sulphur (S)	ug/L	<10000	<10000	<10000	<50000	<10000	<50000	50000

Table A2. Sequentially extracted ICP-MS analytical results from initial soil sampled August 28, 2014

mg/kg	Extraction 1				Extraction 2				Extraction 3				Extraction 4				Extraction 5				RDL
	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	
Al	-	-	-	-	34	28	30	34	800	640	890	720	920	1500	1300	1300	17000	17000	16000	15000	10
Sb	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2.0
As	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	6.5	6.7	6.7	6.3	2.0
Ba	45	24	39	46	91	51	80	76	120	100	120	110	46	150	63	65	540	620	510	530	5.0
Be	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2.0
B	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5.0
Cd	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.30
Cr	-	-	-	-	-	-	-	-	-	-	-	-	2.5	6.2	3.4	3.5	21	31	19	19	2.0
Co	-	-	-	-	-	-	-	-	2.6	2.4	2.4	2.2	-	-	-	-	12	11	11	11	1.0
Cu	2.9	4.9	2.8	3.7	93	35	67	120	270	180	240	290	480	380	630	650	1500	960	1400	1300	2.0
Fe	-	-	-	-	-	85	-	-	5000	4400	5300	4700	340	610	440	550	35000	31000	34000	33000	50
Pb	-	-	-	-	-	-	-	-	1.4	1.3	1.5	1.4	-	1.1	0.60	0.74	6.0	8.4	5.3	5.3	0.50
Mn	-	-	-	2.3	140	76	120	130	160	110	150	150	19	21	23	28	750	490	670	700	2.0
Mo	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2.9	2.0
Ni	-	-	-	-	-	-	-	-	3.7	5.9	3.7	3.4	-	3.3	-	-	18	28	17	17	2.0
Se	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2.0
Ag	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.50
Ar	14	13	12	14	7.7	7.3	6.9	6.2	-	5.8	-	-	-	-	-	-	48	58	45	47	5.0
Tl	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.22	0.16	0.20	0.20	0.10
U	-	-	-	-	0.19	0.46	0.17	0.15	0.17	0.38	0.17	0.15	-	0.45	0.10	0.11	0.87	2.1	0.78	0.77	0.10
V	-	-	-	-	-	-	-	-	10	12	11	9.3	-	3.8	-	-	80	79	75	74	2.0
Zn	-	-	-	-	-	-	-	-	11	9.1	12	10	-	6.1	5.2	5.5	89	70	83	82	5.0

Table A3. Sequentially extracted ICP-MS analytical results from initial wood shavings and straw amendments sampled August 28, 2014

mg/kg	Wood Shavings					Straw					RDL
	E1	E 2	E3	E4	E5	E1	E2	E3	E4	E5	
Al	-	-	-	-	-	-	-	-	-	35	10
Sb	-	-	-	-	-	-	-	-	-	-	2.0
As	-	-	-	-	-	-	-	-	-	-	2.0
Ba	-	-	-	-	10	-	11	10	-	55	5.0
Be	-	-	-	-	-	-	-	-	-	-	2.0
B	-	-	-	-	-	-	-	-	-	-	5.0
Cd	-	-	-	-	-	-	-	-	-	-	0.30
Cr	-	-	-	-	-	-	-	-	-	-	2.0
Co	-	-	-	-	-	-	-	-	-	-	1.0
Cu	-	-	-	-	-	-	-	-	-	3.5	2.0
Fe	-	-	-	-	-	-	-	-	-	140	50
Pb	-	-	-	-	-	-	-	-	-	2.6	0.50
Mn	21	13	5.4	-	86	3.5	14	7.5	-	70	2.0
Mo	-	-	-	-	-	-	-	-	-	-	2.0
Ni	-	-	-	-	-	-	-	-	-	7.1	2.0
Se	-	-	-	-	-	-	-	-	-	-	2.0
Ag	-	-	-	-	-	-	-	-	-	-	0.50
Ar	-	-	-	-	-	-	-	-	-	13	5.0
Tl	-	-	-	-	-	-	-	-	-	-	0.10
U	-	-	-	-	-	-	-	-	-	-	0.10
V	-	-	-	-	-	-	-	-	-	-	2.0
Zn	-	-	-	-	9.0	-	-	-	-	15	5.0

Table A4. Analytical results from plants sampled August 27, 2014

Parameter	Units	Carex						Moss			RDL
		Roots			Leaves						
		Rep 1	Rep 2	Rep 3	Rep 1	Rep 2	Rep 3	Rep 1	Rep 2	Rep 3	
Nutrients											
Available Nitrogen (N)	mg/kg	<10	<10	<10	<10	<10	<10	<10	<10	<10	10
Available Phosphorus (P)	mg/kg	240	48	91	640	520	810	470	340	150	5.0
Available Potassium (K)	mg/kg	8100	1400	3200	9100	8100	11000	4000	5400	2700	10
Available Sulphur (S)	mg/kg	210	670	700	170	340	530	290	400	220	20
Misc. Inorganics											
Total Organic Carbon (C)	%	39	36	37	38	38	43	43	45	40	0.10
Total Carbon	%	41	37	38	45	40	44	41	45	44	0.20
Inorganics											
Moisture	%	87	88	86	74	77	75	90	94	92	1.0
Metals											
Antimony (Sb)	mg/kg	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.05
Arsenic (As)	mg/kg	1.7	1.0	0.4	0.3	0.1	<0.1	0.2	0.1	<0.1	0.1
Barium (Ba)	mg/kg	53.9	34.3	28.2	31.0	23.3	17.9	29.9	22.3	10.5	0.3
Beryllium (Be)	mg/kg	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.05
Bismuth (Bi)	mg/kg	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.05
Boron (B)	mg/kg	<0.5	0.6	0.8	1.0	0.8	1.1	0.5	<0.5	<0.5	0.5
Cadmium (Cd)	mg/kg	0.02	<0.01	0.01	<0.01	<0.01	<0.01	0.01	<0.01	0.01	0.01
Calcium (Ca)	mg/kg	973	648	752	1160	944	743	1460	1210	1160	50
Chromium (Cr)	mg/kg	1.4	1.2	0.6	1.3	0.5	0.4	<0.3	<0.3	<0.3	0.3
Cobalt (Co)	mg/kg	1.45	0.864	0.965	0.594	0.333	0.164	0.645	0.464	0.166	0.005
Copper (Cu)	mg/kg	93.7	47.0	15.1	20.5	21.9	6.8	13.8	18.3	11.2	0.5
Iron (Fe)	mg/kg	7870	4540	2560	2080	1140	540	1190	1020	404	3
Lead (Pb)	mg/kg	0.27	0.11	0.11	0.08	0.06	<0.03	0.04	0.04	0.03	0.03
Magnesium (Mg)	mg/kg	910	477	327	653	321	325	293	229	190	100
Manganese (Mn)	mg/kg	98.3	128	151	116	282	141	272	179	27.1	0.3
Molybdenum (Mo)	mg/kg	0.18	0.21	0.15	0.31	0.41	0.17	0.29	0.09	0.25	0.05
Nickel (Ni)	mg/kg	0.87	0.41	0.37	0.32	0.20	0.11	0.36	0.49	0.13	0.05
Phosphorus (P)	mg/kg	<500	<500	<500	<1000	<1000	<1000	<500	<500	<500	500
Potassium (K)	mg/kg	1180	1070	1440	2860	3620	3430	674	363	315	100
Selenium (Se)	mg/kg	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	0.2
Silver (Ag)	mg/kg	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.05
Sodium (Na)	mg/kg	509	512	508	222	149	180	94	54	<50	50
Strontium (Sr)	mg/kg	5.8	4.4	5.7	5.7	5.4	4.7	10.1	8.2	7.1	0.5
Thallium (Tl)	mg/kg	0.007	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	0.003
Tin (Sn)	mg/kg	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	0.3
Titanium (Ti)	mg/kg	109	49	24.3	42	22.8	8.0	6.0	5.9	4.6	0.5
Uranium (U)	mg/kg	0.049	0.025	0.035	0.016	0.016	0.012	0.014	0.015	0.007	0.005
Vanadium (V)	mg/kg	11.8	4.9	3.2	3.5	1.8	0.7	0.7	0.8	0.4	0.3
Zinc (Zn)	mg/kg	12	6	4	7	7	4	5	4	2	2

Table A5. Analytical results from water sampled September 18, 2014

Parameter	Units	CWTS LINE 1	CWTS 1A	CWTS 1B	CWTS LINE 2	CWTS 2A	CWTS 2B	CWTS FINAL	RDL
Elements									
Total Aluminum (Al)	mg/L	0.13	0.031	0.044	0.011	0.021	0.016	0.026	0.0030
Dissolved Aluminum (Al)	mg/L	0.0062	0.0093	0.015	0.0091	0.0097	0.013	0.017	0.0030
Total Antimony (Sb)	mg/L	<0.00060	<0.00060	<0.00060	<0.00060	<0.00060	<0.00060	<0.00060	0.00060
Dissolved Antimony (Sb)	mg/L	<0.00060	<0.00060	<0.00060	<0.00060	<0.00060	<0.00060	<0.00060	0.00060
Total Arsenic (As)	mg/L	0.00041	0.00041	0.00044	0.00034	0.00039	0.00038	0.00039	0.00020
Dissolved Arsenic (As)	mg/L	0.00038	0.00038	0.00040	0.00034	0.00034	0.00039	0.00042	0.00020
Total Barium (Ba)	mg/L	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.010
Dissolved Barium (Ba)	mg/L	0.12	0.12	0.13	0.12	0.12	0.13	0.13	0.010
Total Beryllium (Be)	mg/L	<0.0010	<0.0010	<0.0010	<0.0010	<0.0010	<0.0010	<0.0010	0.0010
Dissolved Beryllium (Be)	mg/L	<0.0010	<0.0010	<0.0010	<0.0010	<0.0010	<0.0010	<0.0010	0.0010
Total Boron (B)	mg/L	<0.020	<0.020	<0.020	<0.020	0.024	0.020	<0.020	0.020
Dissolved Boron (B)	mg/L	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020	0.020
Total Cadmium (Cd)	ug/L	0.048	0.045	0.039	0.046	0.040	0.029	0.021	0.020
Dissolved Cadmium (Cd)	ug/L	0.046	0.036	0.030	0.041	0.038	0.022	<0.020	0.020
Total Calcium (Ca)	mg/L	130	130	130	130	130	130	130	0.30
Dissolved Calcium (Ca)	mg/L	130	120	120	130	120	120	120	0.30
Total Chromium (Cr)	mg/L	<0.0010	<0.0010	<0.0010	<0.0010	<0.0010	<0.0010	<0.0010	0.0010
Dissolved Chromium (Cr)	mg/L	<0.0010	<0.0010	<0.0010	<0.0010	<0.0010	<0.0010	<0.0010	0.0010
Total Cobalt (Co)	mg/L	<0.00030	<0.00030	<0.00030	<0.00030	<0.00030	<0.00030	<0.00030	0.00030
Dissolved Cobalt (Co)	mg/L	<0.00030	<0.00030	<0.00030	<0.00030	<0.00030	<0.00030	<0.00030	0.00030
Total Copper (Cu)	mg/L	0.088	0.047	0.046	0.053	0.047	0.041	0.041	0.00020
Dissolved Copper (Cu)	mg/L	0.046	0.041	0.039	0.047	0.042	0.036	0.034	0.00020
Total Iron (Fe)	mg/L	0.50	0.20	0.20	0.19	0.18	0.15	0.15	0.060
Dissolved Iron (Fe)	mg/L	0.13	0.11	0.12	0.15	0.12	0.10	0.10	0.060
Total Lead (Pb)	mg/L	<0.00020	<0.00020	<0.00020	<0.00020	<0.00020	<0.00020	<0.00020	0.00020
Dissolved Lead (Pb)	mg/L	<0.00020	<0.00020	<0.00020	<0.00020	<0.00020	<0.00020	<0.00020	0.00020

Parameter	Units	CWTS LINE 1	CWTS 1A	CWTS 1B	CWTS LINE 2	CWTS 2A	CWTS 2B	CWTS FINAL	RDL
Total Lithium (Li)	mg/L	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020	0.020
Dissolved Lithium (Li)	mg/L	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020	0.020
Total Magnesium (Mg)	mg/L	37	38	37	38	37	37	38	0.20
Dissolved Magnesium (Mg)	mg/L	37	36	37	37	36	36	36	0.20
Total Manganese (Mn)	mg/L	0.26	0.19	0.16	0.26	0.19	0.14	0.094	0.0040
Dissolved Manganese (Mn)	mg/L	0.25	0.18	0.15	0.25	0.20	0.14	0.090	0.0040
Total Molybdenum (Mo)	mg/L	0.0083	0.0082	0.0083	0.0084	0.0083	0.0081	0.0082	0.00020
Dissolved Molybdenum (Mo)	mg/L	0.0079	0.0076	0.0078	0.0077	0.0078	0.0079	0.0076	0.00020
Total Nickel (Ni)	mg/L	0.0013	0.0012	0.0015	0.0012	0.0012	0.0011	0.0012	0.00050
Dissolved Nickel (Ni)	mg/L	0.00075	0.00079	0.00079	0.00072	0.00074	0.00081	0.00068	0.00050
Total Phosphorus (P)	mg/L	0.12	<0.10	<0.10	<0.10	0.14	0.11	<0.10	0.10
Dissolved Phosphorus (P)	mg/L	<0.10	0.13	0.12	<0.10	<0.10	<0.10	<0.10	0.10
Total Potassium (K)	mg/L	4.5	4.5	4.4	4.5	4.5	4.4	4.6	0.30
Dissolved Potassium (K)	mg/L	4.3	4.3	4.4	4.3	4.3	4.3	4.4	0.30
Total Selenium (Se)	mg/L	0.0064	0.0065	0.0064	0.0066	0.0063	0.0063	0.0062	0.00020
Dissolved Selenium (Se)	mg/L	0.0063	0.0061	0.0061	0.0063	0.0061	0.0063	0.0059	0.00020
Total Silicon (Si)	mg/L	7.8	7.2	7.0	7.6	7.2	7.1	7.2	0.10
Dissolved Silicon (Si)	mg/L	7.3	6.9	6.8	7.3	6.9	6.9	6.8	0.10
Total Silver (Ag)	mg/L	<0.00010	<0.00010	<0.00010	<0.00010	<0.00010	<0.00010	<0.00010	0.00010
Dissolved Silver (Ag)	mg/L	<0.00010	<0.00010	<0.00010	<0.00010	<0.00010	<0.00010	<0.00010	0.00010
Total Sodium (Na)	mg/L	22	22	22	22	22	22	23	0.50
Dissolved Sodium (Na)	mg/L	22	21	22	22	21	22	22	0.50
Total Strontium (Sr)	mg/L	1.3	1.3	1.3	1.4	1.3	1.3	1.3	0.020
Dissolved Strontium (Sr)	mg/L	1.3	1.3	1.3	1.3	1.3	1.3	1.3	0.020
Total Sulphur (S)	mg/L	44	45	43	44	43	44	44	0.20
Dissolved Sulphur (S)	mg/L	42	41	42	42	41	42	42	0.20
Total Thallium (Tl)	mg/L	<0.00020	<0.00020	<0.00020	<0.00020	<0.00020	<0.00020	<0.00020	0.00020
Dissolved Thallium (Tl)	mg/L	<0.00020	<0.00020	<0.00020	<0.00020	<0.00020	<0.00020	<0.00020	0.00020

Parameter	Units	CWTS LINE 1	CWTS 1A	CWTS 1B	CWTS LINE 2	CWTS 2A	CWTS 2B	CWTS FINAL	RDL
Total Tin (Sn)	mg/L	<0.0010	<0.0010	<0.0010	<0.0010	<0.0010	<0.0010	<0.0010	0.0010
Dissolved Tin (Sn)	mg/L	<0.0010	<0.0010	<0.0010	<0.0010	<0.0010	<0.0010	<0.0010	0.0010
Total Titanium (Ti)	mg/L	0.014	0.0023	0.0038	<0.0010	0.0021	<0.0010	0.0015	0.0010
Dissolved Titanium (Ti)	mg/L	<0.0010	<0.0010	<0.0010	<0.0010	<0.0010	<0.0010	<0.0010	0.0010
Total Uranium (U)	mg/L	0.0031	0.0029	0.0031	0.0031	0.0031	0.0030	0.0031	0.00010
Dissolved Uranium (U)	mg/L	0.0032	0.0032	0.0032	0.0032	0.0032	0.0034	0.0032	0.00010
Total Vanadium (V)	mg/L	0.0011	<0.0010	<0.0010	<0.0010	<0.0010	<0.0010	<0.0010	0.0010
Dissolved Vanadium (V)	mg/L	<0.0010	<0.0010	<0.0010	<0.0010	<0.0010	<0.0010	<0.0010	0.0010
Total Zinc (Zn)	mg/L	0.075	0.055	0.049	0.071	0.059	0.042	0.029	0.0030
Dissolved Zinc (Zn)	mg/L	0.068	0.049	0.037	0.068	0.052	0.038	0.022	0.0030
Misc.									
Dissolved Nitrite (N)	mg/L	0.016	0.020	0.020	0.016	0.020	0.022	0.026	0.010
Dissolved Nitrate (N)	mg/L	12	12	12	12	12	12	12	0.020
Total Ammonia (N)	mg/L	<0.050	<0.050	<0.050	<0.050	<0.050	<0.050	<0.050	0.050
Total Nitrogen (N)	mg/L	13	13	13	13	13	13	13	0.050
Biochemical Oxygen Demand	mg/L	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	2.0
Total Chemical Oxygen Demand	mg/L	27	28	31	26	41	27	27	5.0
Conductivity	uS/cm	920	920	910	930	920	910	900	1.0
pH	pH	8.27	8.23	8.34	8.20	8.32	8.30	8.44	N/A
Total Organic Carbon (C)	mg/L	9.7	9.3	9.7	9.5	10	11	10	0.50
Total Suspended Solids	mg/L	0.67	1.1	1.3	<0.40	0.53	0.67	0.40	0.40
Alkalinity (PP as CaCO3)	mg/L	<0.50	<0.50	0.90	<0.50	<0.50	<0.50	5.0	0.50
Alkalinity (Total as CaCO3)	mg/L	300	300	300	300	300	300	290	0.50
Bicarbonate (HCO3)	mg/L	360	360	360	370	360	360	350	0.50
Carbonate (CO3)	mg/L	<0.50	<0.50	1.1	<0.50	<0.50	<0.50	6.0	0.50
Hydroxide (OH)	mg/L	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	0.50
Dissolved Sulphate (SO4)	mg/L	140	140	140	140	140	140	140	1.0
Dissolved Chloride (Cl)	mg/L	22	21	22	21	22	21	21	1.0

Appendix A4

Minto Mine Constructed Wetland Treatment Research Program - Demonstration Scale 2015 Update

Forward looking. Lateral thinking.

Minto Mine Constructed Wetland Treatment Research Program – Demonstration Scale 2015 Update

Document – 011_0316_03B

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March 2016

Table of Contents

1. Introduction and Background

The Minto Mine, operated by Capstone Mining Corp., is located 240 km northwest of Whitehorse on the west side of the Yukon River. The Minto property lies within the eastern part of the Dawson Range, with elevations from 700 to 1,000 m; the landscape has rounded mountains intersected by broad valleys and drainages that are part of the Yukon River watershed.

The Minto Mine has been in commercial operation since October 2007 and the deposits being mined are copper sulphide mineralized zones. Surface and groundwater water quality is a key consideration in the evaluation of potential effects of mining and mineral development projects and changes to water quality parameters have the potential to affect aquatic and human use of water resources. A Reclamation and Closure Plan (RCP) is required under both the Water Licence and the Quartz Mining Licence. The RCP is intended to address the long-term physical and chemical stability of the site and closure of the proposed features and disturbances associated with the mine. As a part of the RCP, a Constructed Wetland Treatment System (CWTS) is being designed, evaluated, and optimized for water treatment at closure through a phased program (Minto Phase V/VI Expansion Project, YOR Project Number 2013-0100).

In order for CWTSs to be effective, they must be designed, piloted, optimized, implemented, and maintained in a site-specific manner. A scaled approach for CWTS implementation allows for improvement, optimization, and flexibility for modifications along each step. Phases include: 1) site assessment and information gathering, 2) technology selection and conceptual design, 3) pilot-scale testing and optimization (controlled environment), 4) on-site demonstration-scale confirmation and optimization, and 5) full-scale implementation. Phases 1-3 have been completed (reports 2013-0100-256 and 2013-0100-257 on YESAB registry, and Contango, March 2014; Contango, November 2014) and confirmed plant amenability to transplantation and the CWTS design for further on-site testing. During pilot-scale trials, the selected CWTS design achieved on average 92% removal of copper (mean influent 146 µg/L, outflow 11.3 µg/L) and 41% removal of selenium (mean influent 10.2 µg/L, outflow 6 µg/L) using synthetic influent designed to mimic the worst-case water chemistry of a long-term closure scenario, but tested under the controlled conditions (e.g., controlled flows, known temperature, etc) of an off-site treatability testing center (Contango, November 2014). It should be noted that lower influent concentrations will have a lower percent removal even when achieving the same final outflow concentrations.

Phase 4 of the project is underway, with the on-site demonstration scale CWTS constructed at the Minto Mine during fall 2014 (Contango, March 2015). This document reports on the on-site demonstration scale CWTS data from construction through 2015.

2. Construction

2.1. System layout and dimensions

The demonstration-scale CWTS includes 2 systems in parallel with 2 cells in each series and a final catchment basin that both systems flow into (Figure 1). Dimensions and construction details are available in the Minto Demonstration Scale Report Document 011_0315_01A (Contango, March 2015). The two parallel systems serve as a replicate for data analysis, and as testing has progressed, the two systems have also allowed for comparison of different management techniques. Dimensions of the systems are provided here in Table 1.

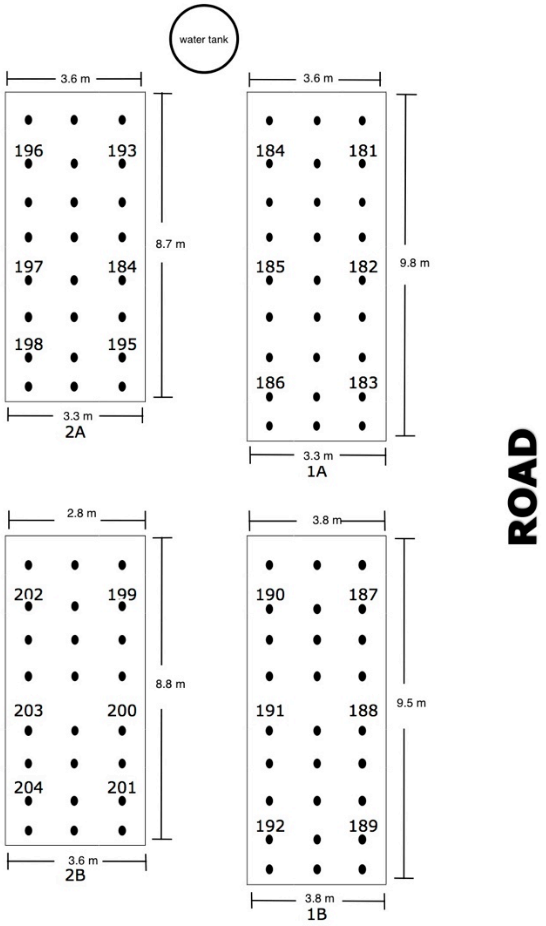


Figure 1 – Diagram of demonstration-scale CWTS.
Dimension measurements are indicated at soil surface. Black dots indicate initial construction grid marked by moss stakes, and locations of soil redox probes with identifying numbers.

Table 1. Measurements of demonstration-scale CWTS cells at soil surface and resultant areas of treatment systems.

Measurement		Series 1		Series 2	
		1A	1B	2A	2B
Width (m)	Inflow	3.6	3.8	3.6	2.8
	Outflow	3.3	3.8	3.3	3.6
Length (m)		9.8	9.5	8.7	8.8
Approximate surface area at soil (m^2)		33.8	36.1	30.0	28.2
Total area of system at soil (m^2)		69.9		58.2	

2.2.Substrate Soils in Construction

Soils used to construct the CWTS are described in the initial report that outlines construction (Contango, March 2015). In brief, the recommended soil for the CWTS was sand, with 2-7% by volume as organic material (e.g., woodchips, peat). In the pilot-scale systems, this resulted in a total organic carbon (TOC) content by weight of 0.2-0.6% (the sand itself was at 0.1% TOC prior to adding amendment). Ideally, this number could be higher, approximately 2-10% by weight to stimulate the desired reducing conditions. For the demonstration-scale system, the soil added to each of the 4 cells during construction was from a local borrow site. As is expected in a mining area, the soils are likely mineralized. Although a potential borrow source was tested prior to construction ("Tested Soil"; Table 2), a different borrow source was available upon construction of the demonstration-scale wetland ("Soil Used"; Table 2). The material used in the construction of the demonstration-scale wetland was an organic peat, and analyses received after construction indicated an elevated concentration of leachable copper (Table 2). It should be noted that in a full-scale system, the variability in soil substrate would be normalized by the larger volume of soil used. The substrate in the wetland (composed of the organic peat soil, wood chips, and straw) had a TOC content of 1.8-3.1%. The implications of this are discussed in Section 4 if this report.

Table 2. Comparison of Copper Concentrations in Soils of Pilot- and Demonstration-Scale CWTS

Test Method	Pilot-scale	Demonstration-scale	
	Initial Soil	Tested Soil (June, 2014)	Soil Used (August, 2014)
SPLP Copper (mg/L)[1]	-	0.00546-0.0296[2]	0.148-0.608
Total Copper (mg/kg)	5.3-5.5	210-1400[2]	960-1400[3]

[1] SPLP - Synthetic Precipitation Leaching Procedure

[2] For the June 2014 samples, the soil with the highest total copper concentration also had the lowest leachable copper concentration, and was therefore deemed acceptable for use.

[3] Total copper value for soils used was taken in June 2015 (no data for August 2014).

2.3. Vegetation Used in Planting

The demonstration-scale CWTS was planted with *Carex aquatilis* (aquatic sedge) and aquatic mosses from the W10 area of the Minto Site. The plant selection and borrow source was previously determined through the site assessment (reports 2013-0100-256 and 2013-0100-257 on the YESAB registry) and pilot-scale testing (Contango, November 2014). Five *C. aquatilis* were planted per square meter, with moss tied to stakes that outlined the 1 m x 1 m grid for planting (details provided in Contango, March 2015).

2.4. Water source

Water from the W36 area receiving seepage from the toe of the Mill Valley Fill Extension (MVFE) was selected for the demonstration-scale CWTS testing as the leachate is similar to that expected upon closure in the MVFE area. The chemistry of this water at the time of bringing the demonstration-scale CWTS online (September 18, 2014) is provided in Contango, March 2015.

After construction, the flow rates for the systems were planned to be set to have a 10 day nominal hydraulic retention time (HRT), meaning water entering the wetland takes 10 days to exit. This is referred to as a nominal HRT because it is a calculation based on the size of the wetland and the amount of water entering, and not confirmed empirically using tracing dyes. This HRT is much longer than what is necessary to achieve treatment based on the pilot-scale systems (~3 days), and was chosen to facilitate plant establishment and maturation. However, due to the leachable copper concentrations in the soils used for construction, it was instead decided to run the systems at a faster flow to wash as much leachable copper from the soils as possible. As such, a shorter nominal HRT of ~20 hrs was used as a starting point (HRT calculated using measured water depths of approximately 15 cm and negligible pore water involvement [30cm of soil at 10% pore volume] due to peat soils). The actual HRT will be confirmed by a tracer study in 2016 (Section 8). Despite the shorter HRT resulting from the faster flow of water, the systems have acclimated and matured as was expected for the longer HRT. Because the sizes of the CWTS systems are slightly different, Series 1 (closer to the road) and Series 2 (further from road) are set with flow rates to result in similar HRTs in each system. Flow rates were monitored and adjusted throughout 2015 based on CWTS establishment and maturation (Sections 3 and 4).

3. Commissioning

The time period between the construction of the CWTS and achieving the expected treatment performance is referred to as the commissioning period. This period is needed for operational adjustments to be made (e.g., raising water depth, modifying outflow patterns), and for plant and microbial populations to establish and mature. Based on pilot-scale testing (Contango, November 2014), the estimated commissioning period for the Minto demonstration-scale CWTS is 4 months of operation (i.e., period when water is flowing). In 2014, the demonstration-scale CWTS operated for less than one month prior to freezing, and was restarted along with spring thaw (freshet) in mid-May 2015. Based on these timelines, September 2015 was month 4 of commissioning, and the demonstration-scale system is trending towards performance as expected during the commissioning period.

Functionality similar to that of the matured pilot-scale systems is expected to occur by summer 2016.

Operational adjustments made in 2015 include:

- Increasing water depth
- Adding more aquatic moss
- Modifying inflow and outflow distribution
- Removing *Carex utriculata* (a small quantity was erroneously planted)
- Wrapping inflow tank to prevent algae growth

While full treatment functionality of the demonstration-scale system is not expected during the commissioning period, there is important data that should be collected during this period as it applies to the full-scale system in the following ways:

- evaluation of construction effectiveness and optimizations that could be made.
- assessment of timelines to reach targeted operational parameters to allow for effective phasing of implementation (e.g., soil redox, percentage and abundance of sulphate reducing bacteria).
- Effectiveness of *Carex aquatilis* and aquatic moss transplantation to assess planting density, time period to full density, and if plant propagation and/or a replanting schedule is necessary.

4. Timeline and Sampling Schedule

Major events and operational adjustments are listed in Table 3. The actual dates as well as relative days of operation are provided, which adjusts for time that the CWTS was not receiving water as it was frozen. The relative days of operation allows for comparison to expected timelines from the pilot-scale testing, and for planning and scheduling to be done for full-scale construction and commissioning in the context of mine closure planning.

The sampling schedule for 2015 was conceptually developed prior to beginning construction of the demonstration-scale CWTS (Appendix A). Actual dates of sampling were dependent on timing of spring thaw and winter freeze-up, and the associated ability to have the pumps operating at the W36 pond to supply water to the demonstration-scale CWTS.

Table 3. Events and sampling activities since construction

Event	Key Activity	Flow Rate Setting m^3/day (gal/min)		Calendar Date	Day of Operation
		CWTS Series 1	CWTS Series 2		
CWTS constructed and planted	First sampling, water started.	-	-	August 27 – 31, 2014	0-4
Freeze up for winter	Feed water pumps turned off.	-	-	September 19, 2014	23
Start up for 2015	Feed water pumps turned on.	14.17 (2.60)	11.61 (2.13)	May 16, 2015	24
Contango Site Visit #1	Microbiology, soils, water tested. *Carex* stem counts. Added more aquatic moss. Put black wrap on water tank to prevent algal growth. Water depth adjusted with sandbags.			June 18, 2015	57
Flow rate increased	Flow rates increased.	17.44 (3.20)	15.81 (2.90)	July 13, 2015	82
Contango Site Visit #2	Microbiology, soils, water tested. Added more aquatic moss.			August 16, 2015	116
Contango Site Visit #3	Water tested. Started Fe-EDTA test on System 2.			September 17, 2015	148
	Microbiology, soils, plants, water tested.			September 18, 2015	149
Fe-EDTA Testing	Daily total and dissolved copper analysis conducted at Minto.			September 19 – 26, 2015	150-157
Freeze up for Winter	Feed water pumps turned off.	-	-	September 29, 2015	160

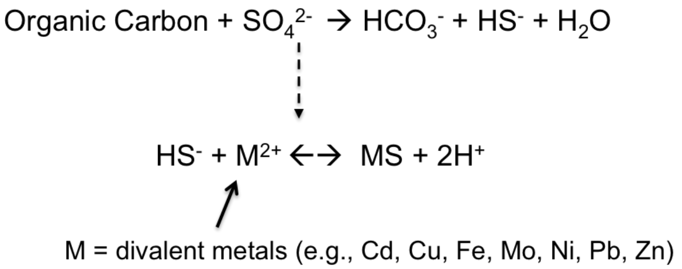
5. Monitoring Explanatory Parameters

Explanatory parameters are quantifiable aspects of a CWTS environment that can be used to assess feasibility of treatment for a range of constituents, and therefore 'explain' the performance of a CWTS. These parameters, which often include acidity, alkalinity, conductivity, dissolved oxygen (DO), pH, oxidation reduction potential (ORP), ion balance, available electrons donors (e.g., organic carbon, reduced elements), and temperature, can be used to predict, promote, and/or optimize the ability of the system to treat different constituents (Haakensen et al., 2015). A YSI ProPlus meter was used in the field to test for water temperature, DO, conductivity (and specific conductivity; SPC), pH, and ORP.

Average water temperature of the demonstration-scale CWTS was 12.9°C, ranging from 0.5°C to 25°C through 2015. As would be expected, both the month of testing and time of day were found to affect temperature variation. DO concentrations of the CWTS feed and cells were on average 10 mg/L, which is higher than the pilot-scale systems (average 4.8 mg/L), which make it more difficult to carry out nitrate and selenium treatment, and sulphide production for copper and cadmium treatment. The conductivity, pH and ORP of the demonstration-scale CWTS cells are all very similar to the pilot-scale systems.

An additional explanatory parameter that can be used to monitor maturation of the wetland during the commissioning period is the soil redox potential, which is measured using platinum tip probes (in soil) and Calomel electrodes (in water). This measurement offers insight into the direction of electron flux between the sediment/soil/pore water and overlying water column (Faulkner et al., 1989; Huddleston & Rodgers, 2008), and can be used to confirm reducing conditions in the soil. Based on the information gathered in pilot-scale testing, the targeted soil redox for the demonstration-scale CWTS is between -100 and -250 mV. In these redox ranges, bacterial sulphide-production through reduction of sulphur compounds (e.g., sulphate) is expected. Sulphide production directly results in metals and metalloid treatment for elements such as cadmium, copper, molybdenum, nickel, lead, and zinc by precipitation as metal sulphides (Figure 2).

This maturation period is necessary for sufficient quantities of microbes to populate the wetland and become active in decomposing organic material. It is the electrons produced by the decomposition of organic material that is reported by the soil redox measurements. The decomposition of organic material then feeds the sulphate-reducing bacteria the type of energy they need to produce the sulphides that remove the copper from the water. The microbial activity of the system is discussed further in Section 6.5.



$$\text{Organic Carbon} + SO_4^{2-} \rightarrow HCO_3^- + HS^- + H_2O$$

$$HS^- + M^{2+} \leftrightarrow MS + 2H^+$$

M = divalent metals (e.g., Cd, Cu, Fe, Mo, Ni, Pb, Zn)

Figure 2 – Example equation of sulphate reduction

Equation is not balanced; demonstrates sulphate reduction with creation of alkalinity and sulphides, which can then form metal sulphide complexes.

As expected from the pilot-scale testing, the soil redox in all of the demonstration-scale CWTS cells decreased over time, indicating maturation of the system (Figure 2). At the end of 2015, only Series 1 had begun to achieve targeted soil redox values that are conducive to sulphide production (ahead of anticipated schedule). It is possible that Series 1 had more organic material in the soils than Series 2, because of how construction occurred and this wasn't reflected in the small sample size sent for analytical testing.

Some soil redox probes were reporting negative values in the targeted range by July 18, 2015 (87 days); however, in general the CWTS took approximately 4 months of operation to establish generally reducing conditions. By September 17, 2015 (day 148), most of the soil redox probes within Series 1 were reporting redox values within the targeted performance range, with Series 2 still trending downwards but not yet within the targeted range. In comparison, the pilot-scale systems were stable and reducing within approximately 4 months of construction (Figure 2).

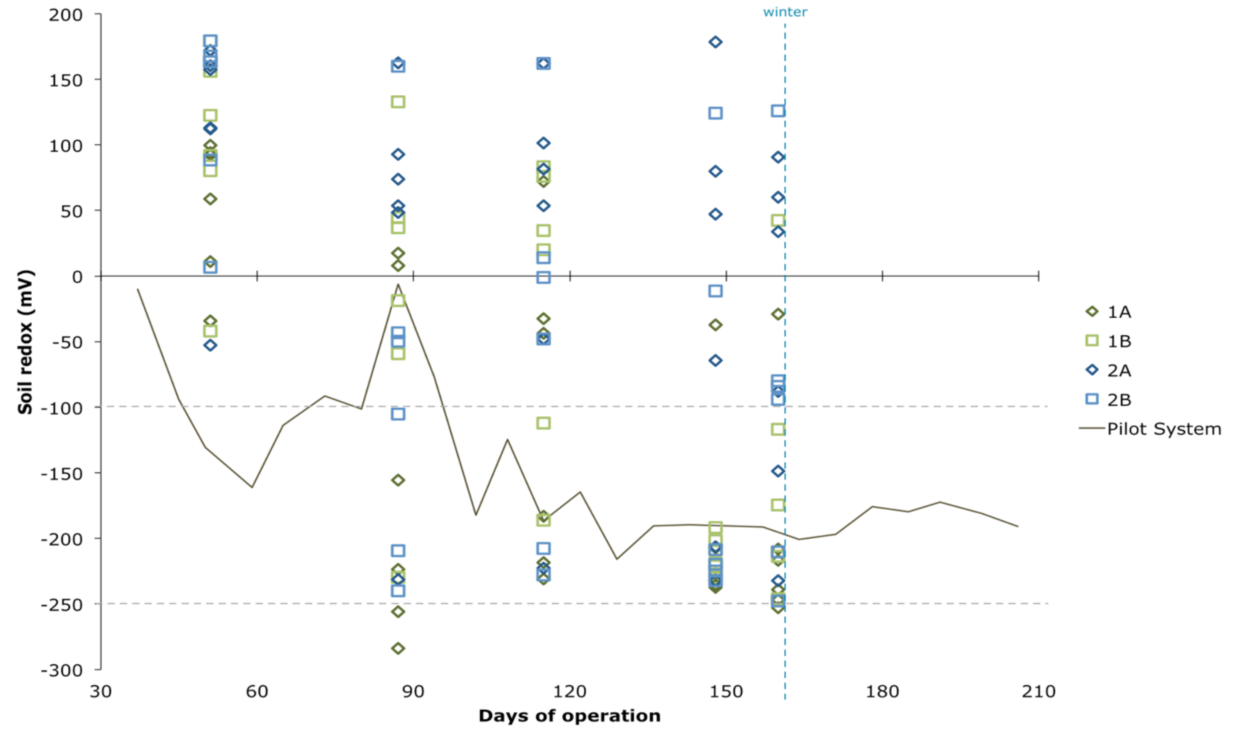


Figure 3 – Soil redox potential of each CWTS cell over time

All demonstration-scale CWTS soil redox measurements are plotted, along with the average soil redox of the pilot-scale systems. Targeted soil redox values based on pilot-scale testing are indicated with dotted lines. The blue dotted line indicates winter 2015.

6. Performance progress during commissioning period

6.1. Soils

To assess the effect of copper in the soils on CWTS functionality, three soil analytical test methods were used:

- total concentration of elements in the soils by ICP
- leachable concentrations of elements in the soils by Synthetic Precipitation Leaching Procedure (SPLP), which is a method to assess the mobility of elements in soils at the pH of rain water (i.e., if the wetland were to entirely dry out, then be subjected to leaching by rain water)
- concentration of elements in chemical extractions by sequential ICP-MS to assess the stability and form of elements in soils (Table 4)

Table 4. Summary of extractable fractions from sequential ICP-MS analysis [1]

Fraction	Description	Elements Unstable when
1	Exchangeable fraction for adsorbed minerals	Readily released (i.e., soluble and exchangeable)
2	Mineral fraction bound to carbonates	Decreased pH
3	Mineral fraction bound to Fe-Mn oxides	Reducing conditions
4	Mineral fraction bound to organic matter and sulphides	Oxidizing conditions
5	Residual mineral fraction (primary and secondary minerals)	Not expected to be released in solution over time under conditions normally encountered in nature

[1] Method based on Tessier *et al.,* 1979

Although unintentional, the use of soils in the CWTS with high initial leachable copper concentrations (Table 2) allowed for additional types of testing to be carried out on these systems. Because the soil substrates used for construction of the CWTS were from overburden sources, the copper was not in a mineral form that would typically be found in a reducing CWTS (i.e., negative relative soil redox). Therefore, there has been some initial leaching of copper (and other elements, such as aluminum) from the soils into the water (Figure 5 and Figure 7).

While the total copper concentrations have not changed significantly, the leachable copper (measured by SPLP) has decreased over time. By day 58 of operation, the top 5 cm of soil was decreased to only 10-20% of the initial leachable copper concentration, and the lower 10-20 cm layers reached similar concentrations by day 149 (Table 5). Analysis of the soils by ICP-MS with sequentially extracted acid analysis shows that despite elevated initial leachable copper concentrations, the soils have become more stable (less leachable) over time in the wetland setting as the soils have aged (Figure 4). This beneficial aging of soils to less soluble (sulphide) mineralized form is expected for this type of treatment wetland design. It should be noted that due to the starting soil substrate containing leachable copper and other metals such as aluminum (Appendices A and B) that these elements are leaching from the substrate into the water, putting additional treatment demands on the systems. It is recommended that for construction of the full-scale systems, soils with low total and leachable copper concentrations should be used.

Table 5. Total and Leachable Soil Copper Concentrations in First Year of Operations.

Cell	Sampling Date	Days in Operation	Sample Depth (cm)	Total Cu (mg/kg)	SPLP Cu (mg/L)
CWTS 1A	28-Aug-14	1	Initial Composite	-	0.298 (0.148-0.608)
	19-Jun-15	58	0-5	960	0.055[1]
	16-Aug-15	116	10-20	950	0.187
	18-Sep-15	149	10-20	1300	0.049
	29-Sep-15	160	10-20	910	0.069
CWTS 1B	28-Aug-14	1	Initial Composite	-	0.298 (0.148-0.608)
	19-Jun-15	58	0-5	1400	0.033[1]
	16-Aug-15	116	10-20	1400	0.209
	18-Sep-15	149	10-20	830	0.065
	29-Sep-15	160	10-20	880	0.059
CWTS 2A	28-Aug-14	1	Initial Composite	-	0.298 (0.148-0.608)
	19-Jun-15	58	0-5	1175	0.037[1]
	16-Aug-15	116	10-20	660	0.139
	18-Sep-15	149	10-20	880	0.081
	29-Sep-15	160	10-20	1000	0.073
CWTS 2B	28-Aug-14	1	Initial Composite	-	0.298 (0.148-0.608)
	19-Jun-15	58	0-5	1100	0.039[1]
	16-Aug-15	116	10-20	1000	0.201
	18-Sep-15	149	10-20	830	0.078
	29-Sep-15	160	10-20	540	0.059

[1] Samples collected in June 2015 were at a shallow depth (0-5 cm) and copper content had therefore likely already been removed by washing from the faster flows of the CWTS system. The aging of the deeper (10-20 cm) soil copper concentrations over time to a less soluble form is shown in Figure 4.

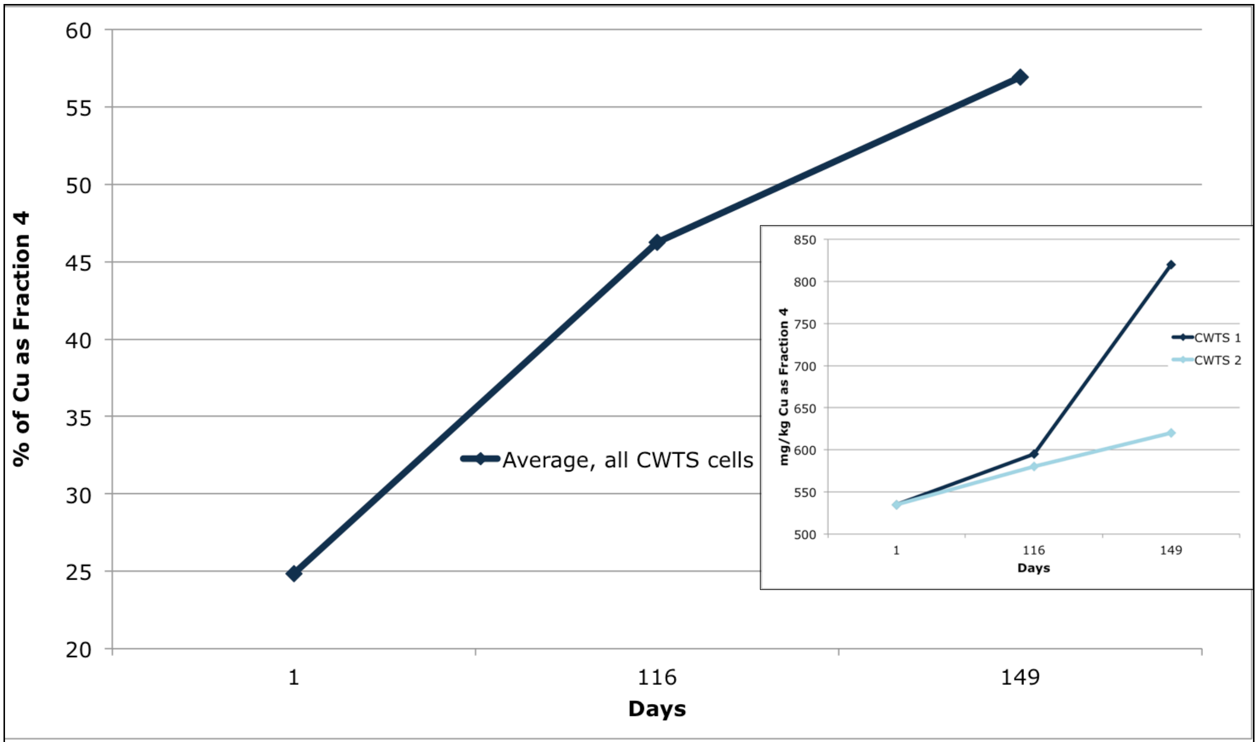


Figure 4 – Copper as sequential leach fraction 4 over time.
Copper in the form of the targeted Fraction 4 (sulphide mineral form and bound to organics), increased in the CWTS over time as the soils matured. Additional information in Appendix B.

6.2. Water

Pilot-scale testing was performed with water that mimicked the worst-case long-term post-closure water chemistry (mean influent concentrations of 146 µg/L copper and 10.2 µg/L selenium). In contrast, the on-site demonstration-scale system uses water from the W36 pond and therefore has inflow concentrations that are currently occurring during operations (mean influent concentrations of 58 µg/L copper and 6 µg/L selenium). Because of this, a lower percent removal will achieve the same extent of removal and associated outflow concentrations than was required in the pilot-scale systems. For example, the pilot-scale system achieved on average 92% removal of copper (mean outflow of 11.3 µg/L) and 41% removal of selenium (mean outflow of 6 µg/L). To achieve these same outflow concentrations with the demonstration-scale system, 80% removal of copper and minimal (or no) removal of selenium would be needed.

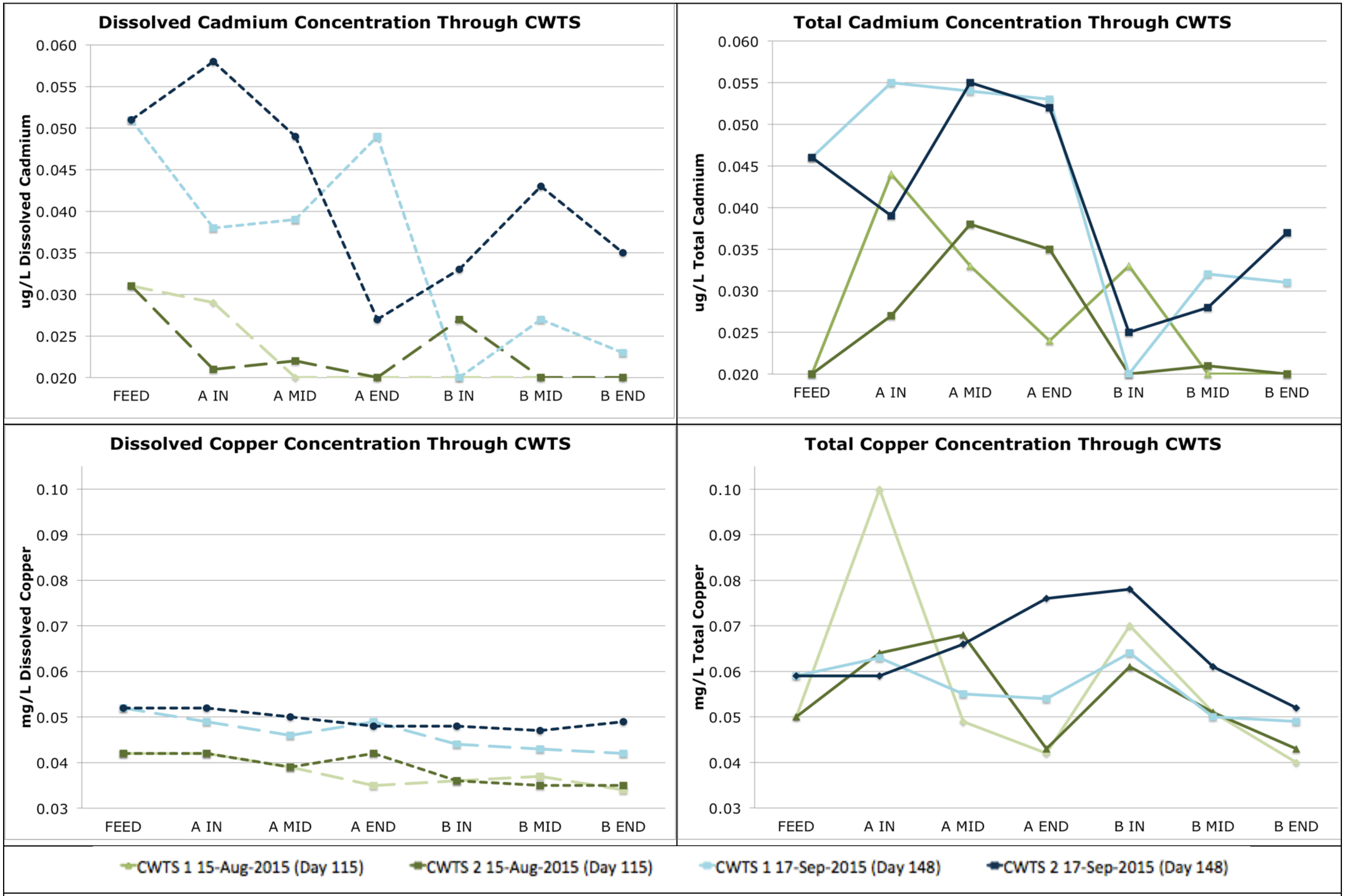
The treatment of copper has been improving through commissioning as the system has matured (Figure 7). However, as shown in Figure 5 and Appendix B, several elements are being released through the wetland by the soils, such as aluminum, cadmium, and copper (discussed further in Section 6.1). Because of this, negative percent removals of copper have been observed, especially in early operations (Figure 7). It was initially theorized that this was occurring when the May and June 2015 data reported outflow concentrations higher than the influent. This paired with the soils data (Section 6.1 and Appendix A) led to the design of a new sampling scheme to determine whether detectable levels of metals were being released from the soils within the wetland. For two timepoints (August 15, 2015 and

September 17, 2015), water was sampled not only at the feed and the outflow of each cell, but also through the cell. Beginning at the outflow of cell B and working upwards towards the feed, samples were taken at the B cell outflow, 1 m upstream of the B cell outflow, B cell mid point, 1 m downstream of the B cell inflow, and then the same 4 points for the A cell (Figure 6). In each case, the sample was taken from within a reaching distance of the side shore to ensure that sediments were not suspended in sampling.

It was found that significant metals concentrations were leaching from the wetlands soils of all cells (Figure 5). Moreover, metal types and concentrations (e.g., Aluminum, Appendix B) that could not be accounted for by the influent water chemistry were elevated at random points within the wetland. This suggested that because of metals leaching from the soils, the treatment occurring within the wetlands was far greater than what was being observed by simply measuring the inflow and outflow points (Figure 7). For example, in August of 2015, influent copper concentrations were measured as 50 µg/L, but within the first meter of cell 1A increased to 100 µg/L, and by the outflow of cell A, down to 42 µg/L (58 µg/L decrease), they then increased to 70 µg/L at the beginning of cell B, and again were treated to a final outflow concentration was 40 µg/L (30 µg/L) for a total of at least 88 µg/L removed by Series 1 of the treatment wetland. This suggests the wetland is actually achieving much greater copper treatment (88 µg/L removed), than would be suggested by only measuring the inflow and outflow of the system (suggests 10 µg/L removed). Similar leaching was observed through the wetland during testing in September 2015.

Copper, cadmium, zinc, and other metals and metalloids are being noticeably decreased in concentration from the water entering the wetlands (Figure 7 and Appendix B), while other metals/metalloids of potential concern are below background water quality for the area or below the detection limit in the influent of the wetland. Dissolved zinc had on average 65% removal in the wetland systems and by September 2015, the outflow concentrations were on average 20% and 50% lower than influent concentrations for dissolved copper and cadmium, respectively. This suggests that not only is the wetland maturing as expected, creating reducing sulphide-producing conditions, but that it is already performing far beyond what was anticipated from the design, sequestering orders of magnitude more copper than would be apparent by looking at the influent water alone (i.e., is also removing copper that has leached from the soils over time).

Removal rate coefficients (*k*) based on the HRT of each system would normally be calculated to compare treatment efficiency. However, because of the leaching of various elements from the soil, calculation of *k* for constituents of concern is not representative of what is ongoing in the system, as there is concurrent leaching and treatment occurring throughout a given cell (Figure 5). Furthermore, because the soil used for construction of the demonstration-scale system is different than what was used for pilot-scale systems, the hydrology and pore volume of the system is not known; a parameter that is needed for accurate calculation of the HRT and therefore *k*. As the same wetland substrate was used to construct both demonstration-scale systems, the removal rate coefficients can be estimated and compared between these two systems; however, comparison with removal rates achieved during pilot-scale testing is not possible until the HRT is defined. It is therefore recommended that a tracer study be performed in 2016 to assess the hydrology and pore volume of the CWTS (see Section 8).



Dissolved Cadmium Concentration Through CWTS

Total Cadmium Concentration Through CWTS

Dissolved Copper Concentration Through CWTS

Total Copper Concentration Through CWTS

Figure 5 – Concentrations of key elements through the CWTS.

The y-axis values start at the detection limits.

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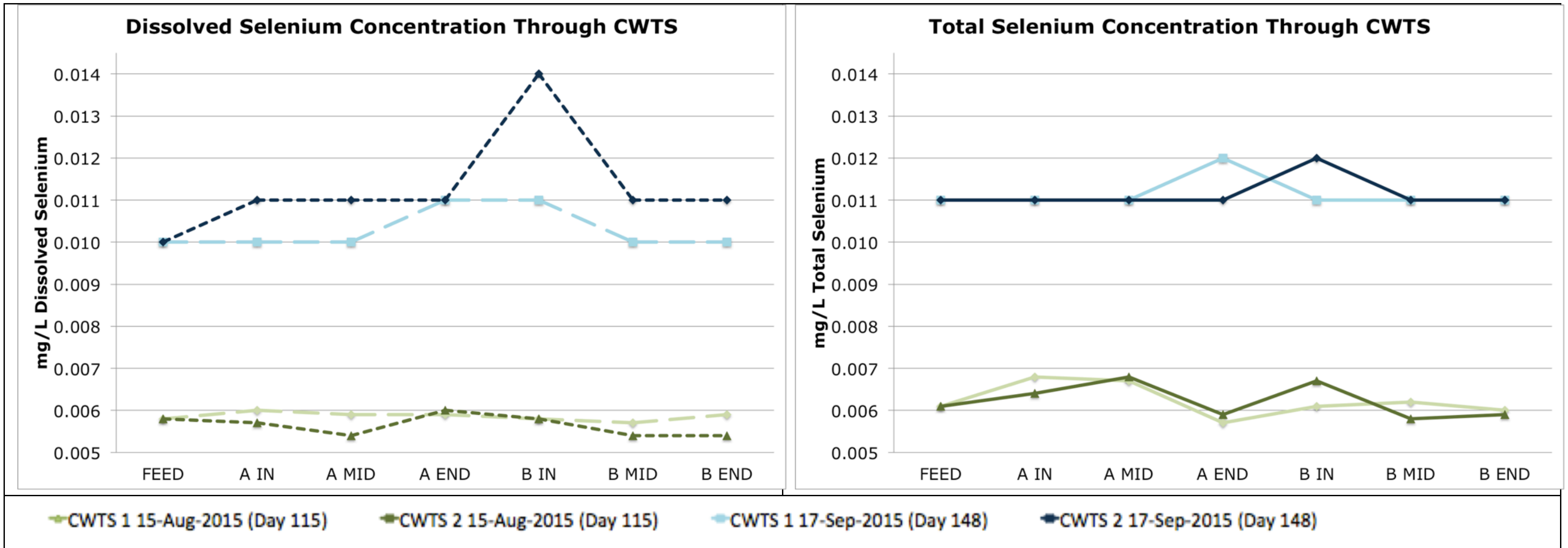

Figure 5 – Continued

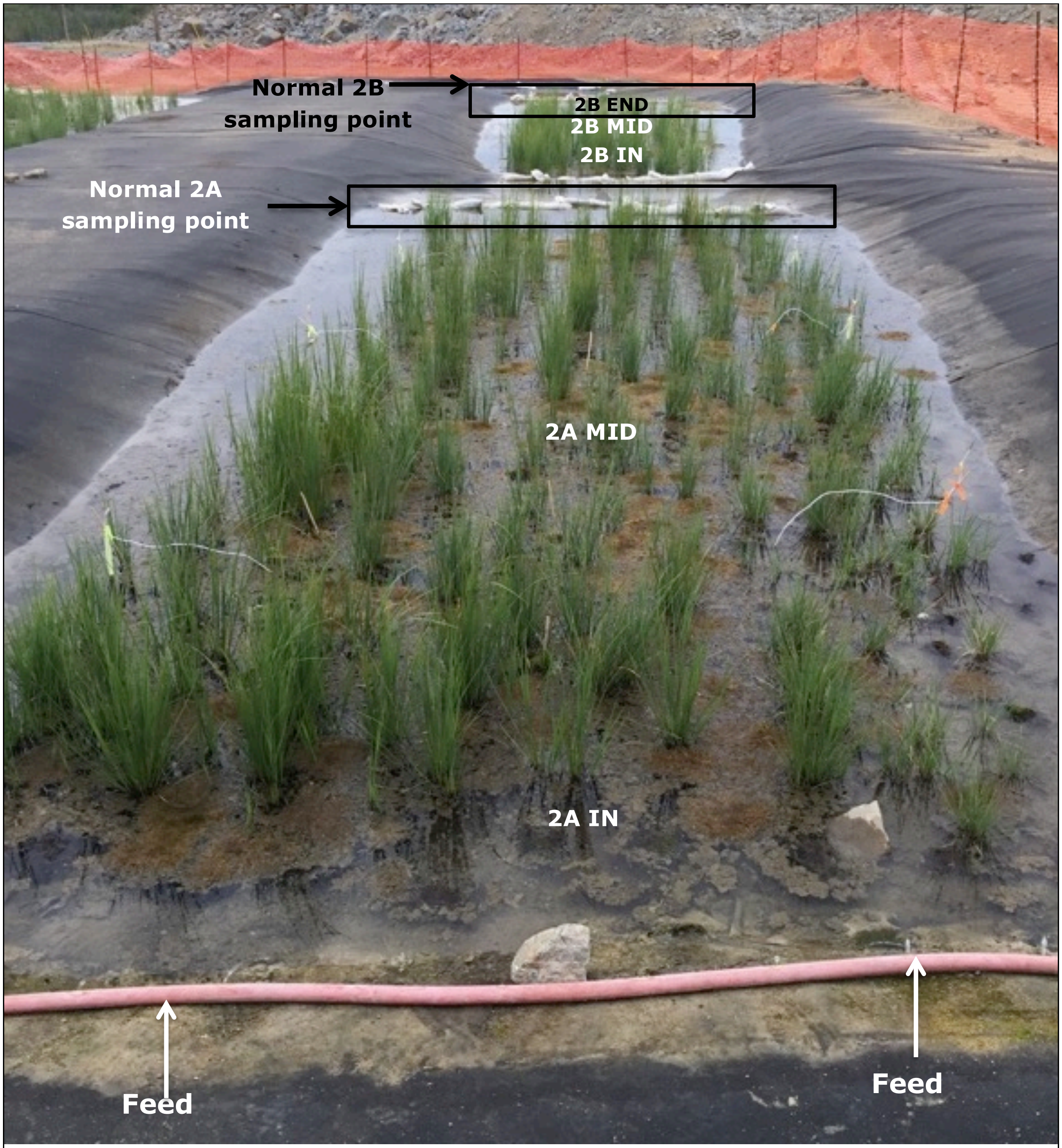

Figure 6 – Sampling points through the CWTS.

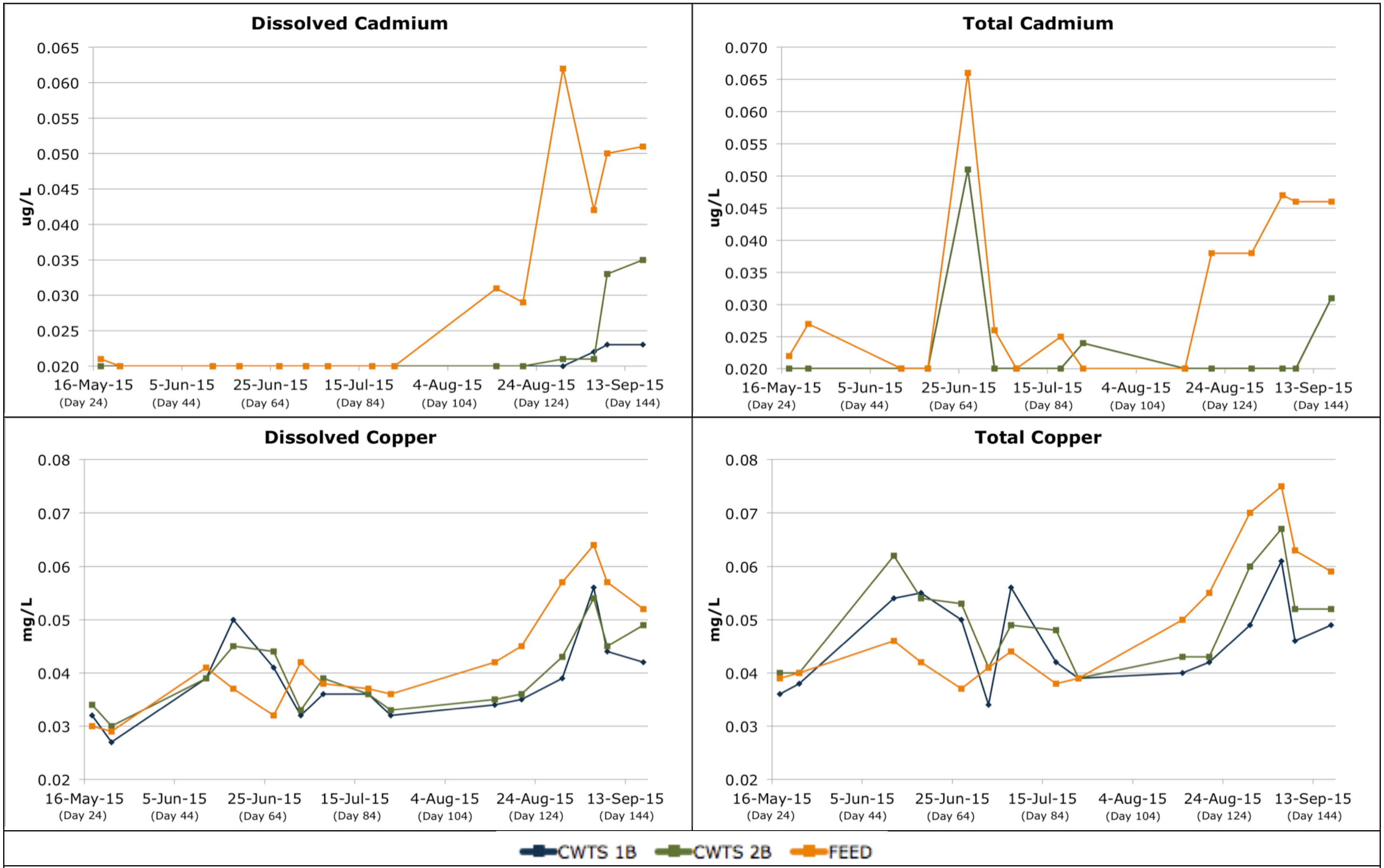

Figure 7 – Element concentrations in the demonstration scale wetland from May 17, 2015 to Sept 17, 2015. The Measurement Uncertainty (MU) for cadmium is +/- 0.020 µg/L. The MU for copper and selenium is +/- 0.0002 mg/L. Timepoints where the dissolved cadmium concentration is higher than the total concentration are within the limit of uncertainty (Maxxam Analytics). Detection limits for cadmium, copper, and selenium are at or below y-axis values.

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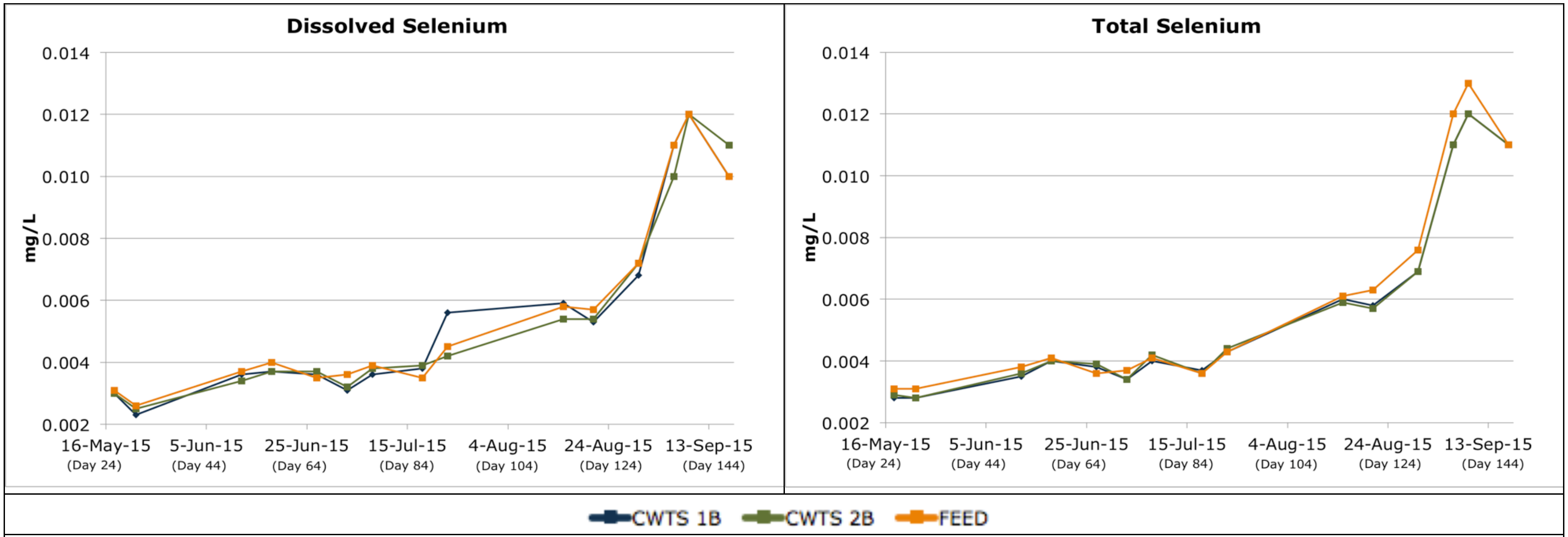

Dissolved Selenium

Total Selenium

Figure 7 - Continued

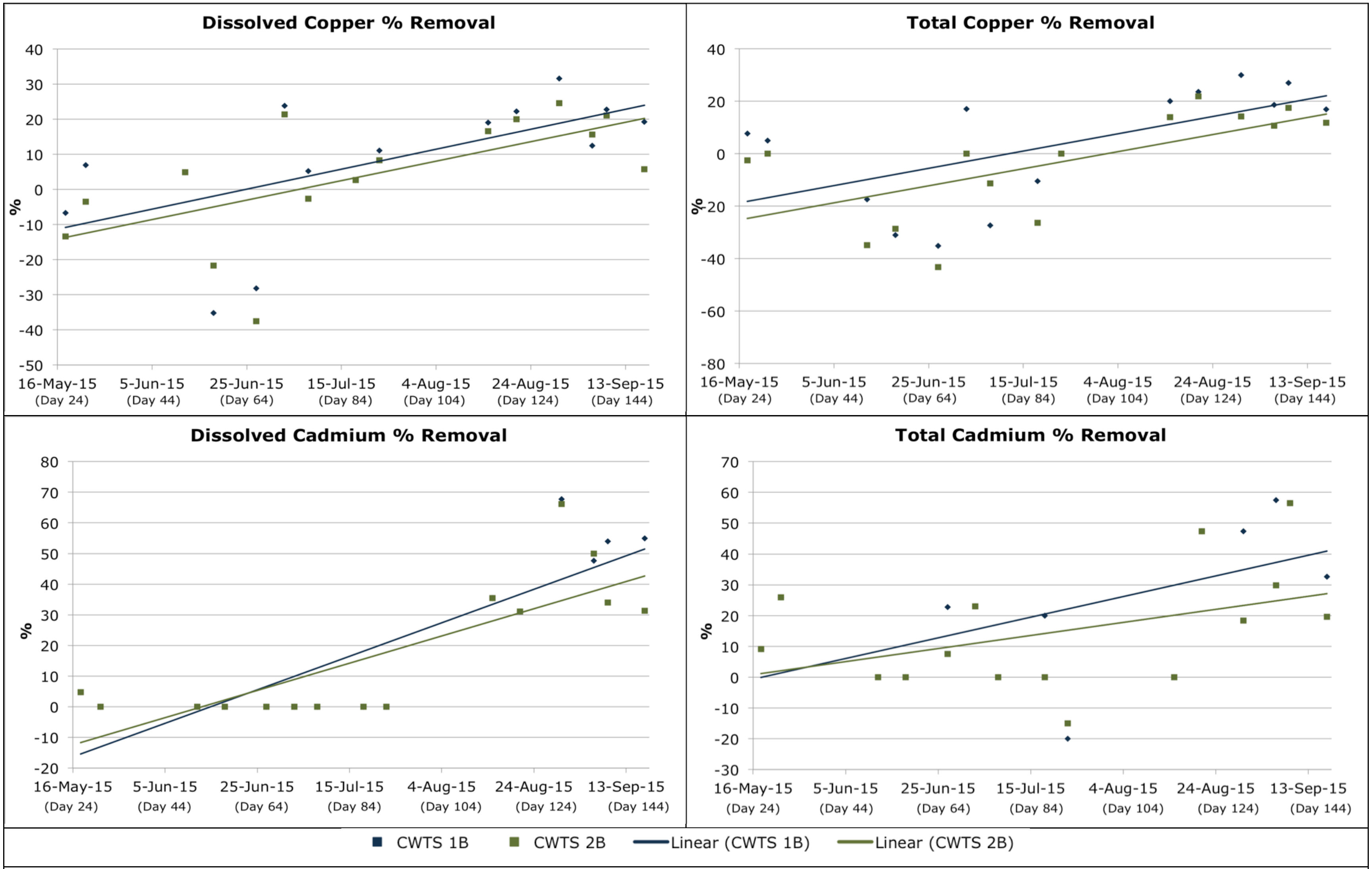

Figure 8 – Percent removal of elements in the demonstration scale wetland from May 17, 2015 to Sept 17, 2015. If the concentration was below the detection limit of the assay, the detection limit was used to calculate the percent removal. Note the Measurement Uncertainty (MU) for cadmium was +/- 0.020 µg/L. The MU for copper and selenium is +/- 0.0002 mg/L (Maxxam Analytics) (Appendix A). The percent removal calculations for cadmium are therefore estimations within this range of error.

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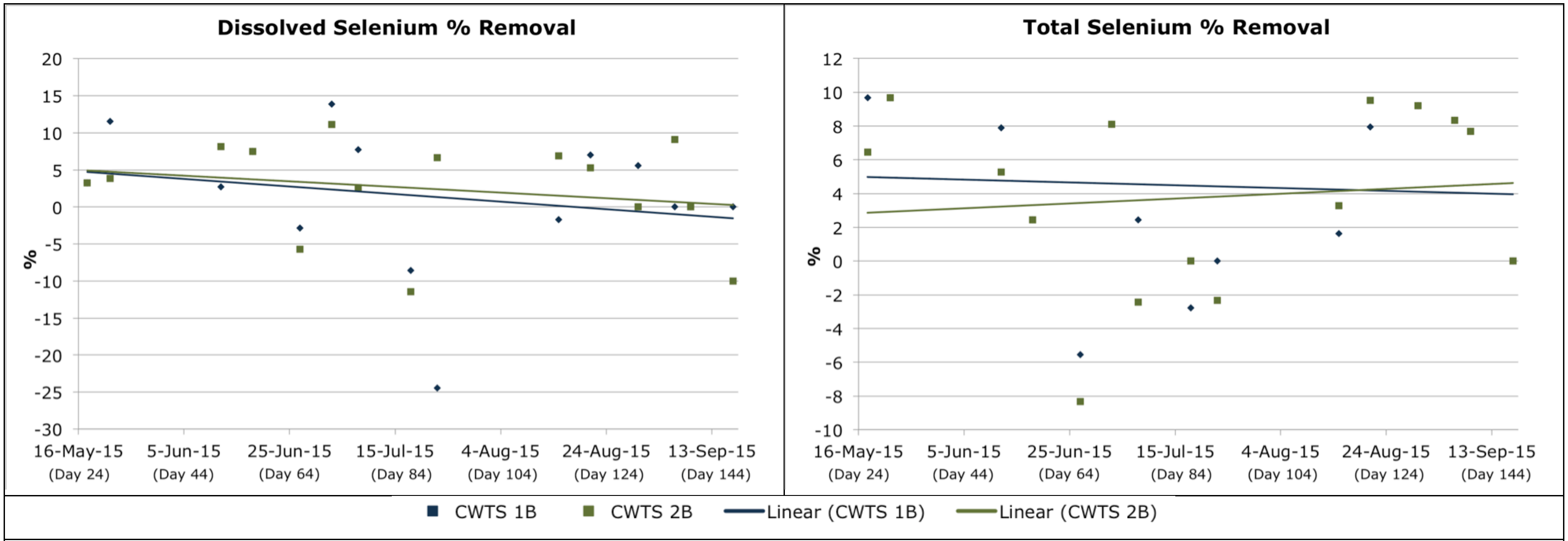

Figure 8 – Continued

6.3.Chelated iron (fertilizer micronutrient) treatment

Because elevated metals were present in the soils used for construction, there was an opportunity to assess whether non-invasive treatments could be used to further leach the metals and improve soil quality. A chelated iron (Fe-EDTA) product was added to the Series 2 wetland on September 17, 2015. The product selected is Fe-EDTA called Plant-Prod 13.2% Iron Chelate (containing 68% of the chelating agent Ethylenediaminetetraacetic acid (EDTA)), and is routinely used in the agricultural industry as a micronutrient supplement for iron-deficient soils. Fe-EDTA is also commonly used in remediation of metals contaminated soils (e.g., Thayalakumaran *et al.,* 2003).

The Fe-EDTA dissociates based on the pH of the water, and the free EDTA will be available to bind other elements such as copper and remove them from the soils, leaving the Fe in the wetland. Fe-EDTA was chosen instead of fertilizer with EDTA (which is also a commonly used agricultural product), as the fertilizer would provide additional nitrogen sources, which can interfere with selenium treatment, and phosphate which could cause an algal bloom that would be detrimental to the active water treatment facility at Minto that receives the CWTS outflow water. The Fe-EDTA treatment was performed on Series 2, with Series 1 remaining untreated for comparison purposes.

After addition of Fe-EDTA, copper concentrations in the wetland water for both CWTS Series 1 and 2 were monitored daily by Minto's internal laboratory. Increases in copper concentrations were observed in the outflow from both cells in CWTS Series 2 after the addition of Fe-EDTA (Figure 9). Unfortunately, the CWTS feed copper concentration also increased, as the outflow from the demonstration-scale wetlands reports to the same area as the feed water draws from at the W36 area. As such, the leached copper (and presumably, also EDTA) is recirculating through the wetland (including Series 1).

In the 10 days following the addition of Fe-EDTA, approximately 75 g of copper was removed from the wetland Series 2. This is approximately 1.25 g of copper per m^2 of wetland. Testing of the soils at different depths in Spring 2016 will determine how much copper has been removed from the wetland as a result of this treatment.

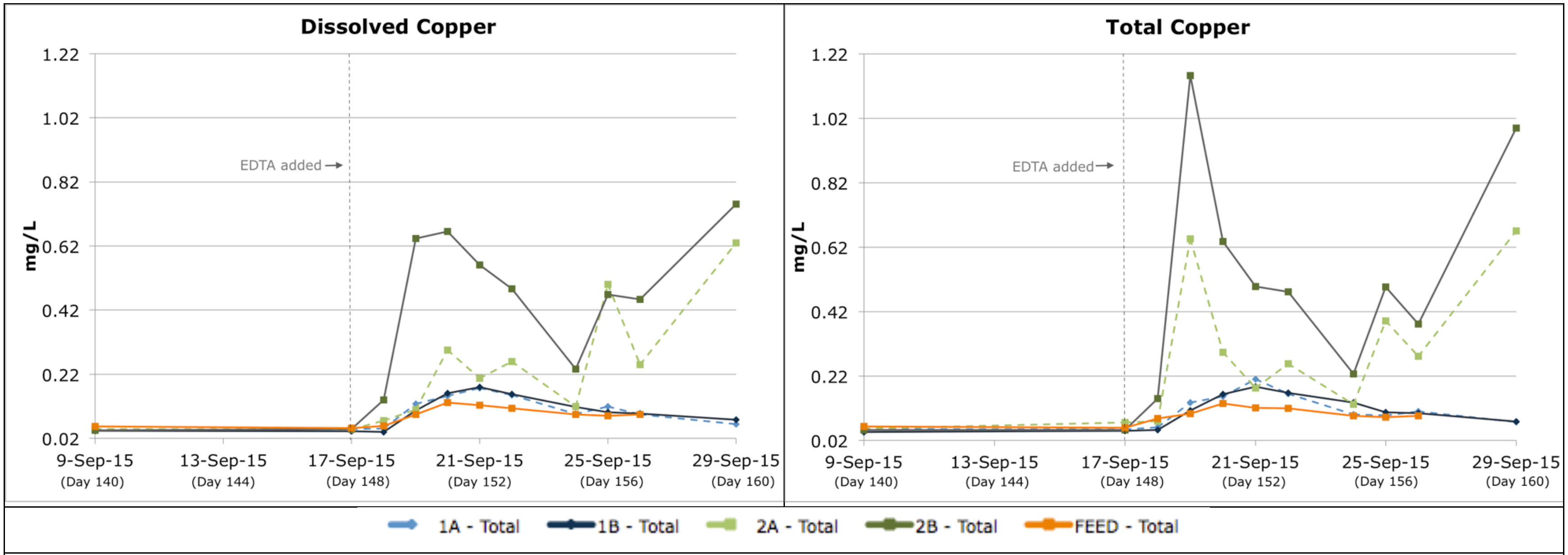

Figure 9 – Copper concentrations in the wetland after the addition of Fe-EDTA to CWTS Series 2

Detection limits are below y-axis values. No influent (feed) was tested September 29th as the system had frozen and was turned off for the winter.

6.4.Plants

During the commissioning period, plants establish and mature, with density expected to increase over time. When counted at the first site visit in June 2015, >95% of the plants were found to have survived their first winter. This survival rate is impressive considering the late fall planting of August 28, 2014 and suggests the *C. aquatilis* are very robust and reaffirms they are a good candidate for use in the full-scale CWTS at Minto. Additionally, there was a greater than 20% increase in total stems in the short growing season up to June 2015 (as counted by new shoots/runners). By the second site visit in August 2015, the plants were too dense to count stems, and therefore the survival and establishment was considered a success and no longer monitored by counting (Figure 6). Despite several mosses drying out during the winter after planting, there was 100% survival and establishment. However, their growth was much slower than the sedge and therefore they were supplemented with additional aquatic moss (harvested from the same W10 area as the original plants for the CWTS) in June and August 2015 to augment their general abundance and bring the CWTS through commissioning more quickly (Figure 10).

Pilot-scale testing suggested that *C. aquatilis* would increase more quickly the number of stems once the maximum plant height was achieved, and also that maximum plant height is dependent upon water depth (with deeper water resulting in taller plants). This was also seen in the demonstration-scale wetland on site, with the density of plants filling in greatly through July and August (Figure 11). It is anticipated that the *C. aquatilis* will have grown uniformly across the wetland by end of the 2016 or 2017 growing season.

Of note, it was observed that during the last site visit of the year by Contango (September 17-18th, 2015), the *C. aquatilis* in the demonstration-scale CWTS were still predominantly green, while other plants in the area had turned brown. This suggests that the CWTSs may have a longer range of activity than natural systems in the area, possibly due to liners and separation from colder ground water.

Concentrations of various elements in *C. aquatilis* and moss from the demonstration-scale systems were compared to those from pilot-scale testing. It is expected that the concentrations would be higher in the demonstration-scale system as the CWTS is not yet fully functional (i.e., elements are in greater bioavailability when in dissolved form) and also due to the composition of the soils used for construction. Accordingly, *C. aquatilis* and moss in the demonstration-scale system had higher copper concentrations than the pilot systems. However, concentration of copper in the *C. aquatilis* at the end of 2015 was not significantly different than that of the plants borrowed from the W10 area for planting of the systems in 2014 (Figure 12). The moss had higher copper and cadmium concentrations which is expected as it removes these elements in the wetland through sorption (and will eventually mineralize in subsequent years). As mosses are not a significant food source for any fauna, this is a safe mechanism to transfer elements from water eventually into stable mineral forms.

Cadmium concentrations were either below or close to the detection limit in *Carex* (Figure 12). Similarly, cadmium concentrations in moss and selenium concentrations in both plant types tested were lower in the demonstration-scale compared to pilot-scale. This result was presumably due to lower concentrations of both cadmium and selenium in the water of the demonstration-scale system than pilot scale. As mosses continue to grow and fill in the wetland, selenium treatment performance is expected to increase as mosses are a source of sorption, and also harbor the highest abundance of selenate-reducing microorganisms of all samples tested (see Section 6.5.2).

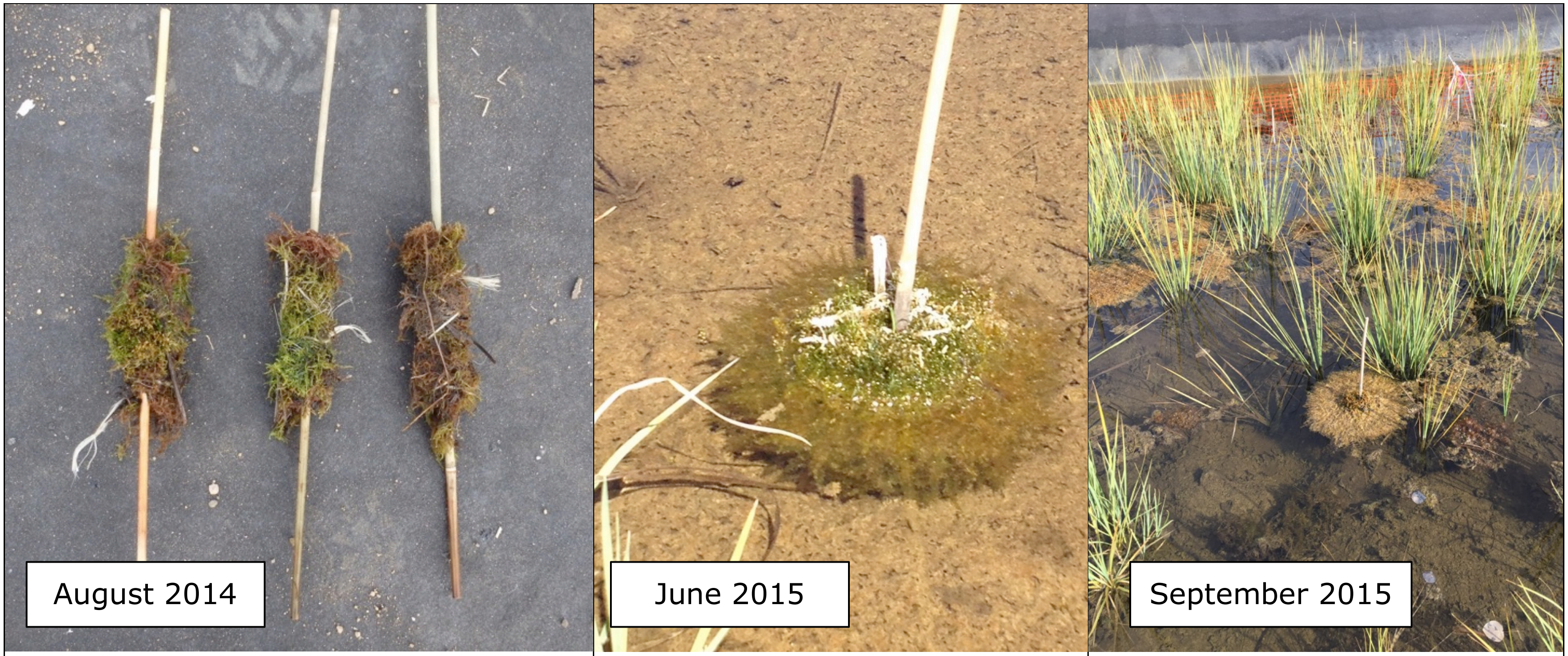

Figure 10 – Moss maturation in CWTS.

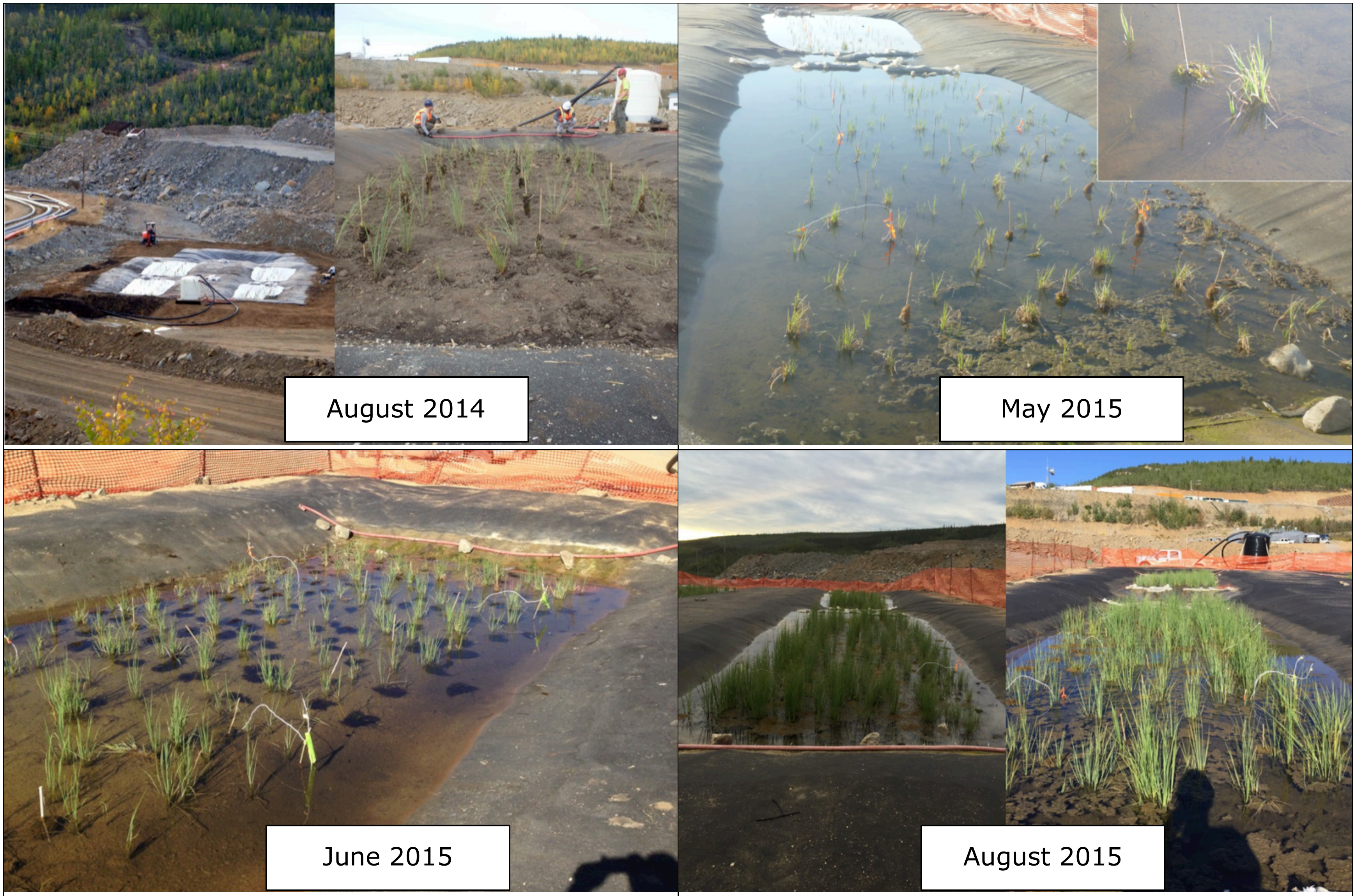

Figure 11 – Maturation of the CWTS from construction to year-end 2015.

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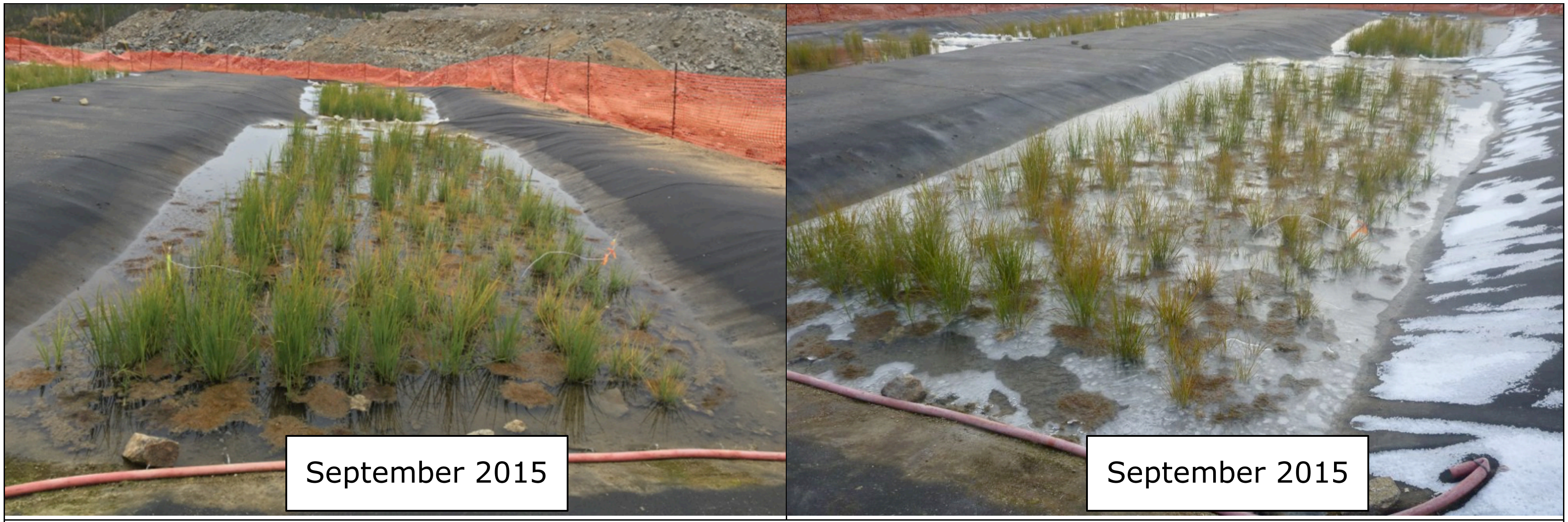
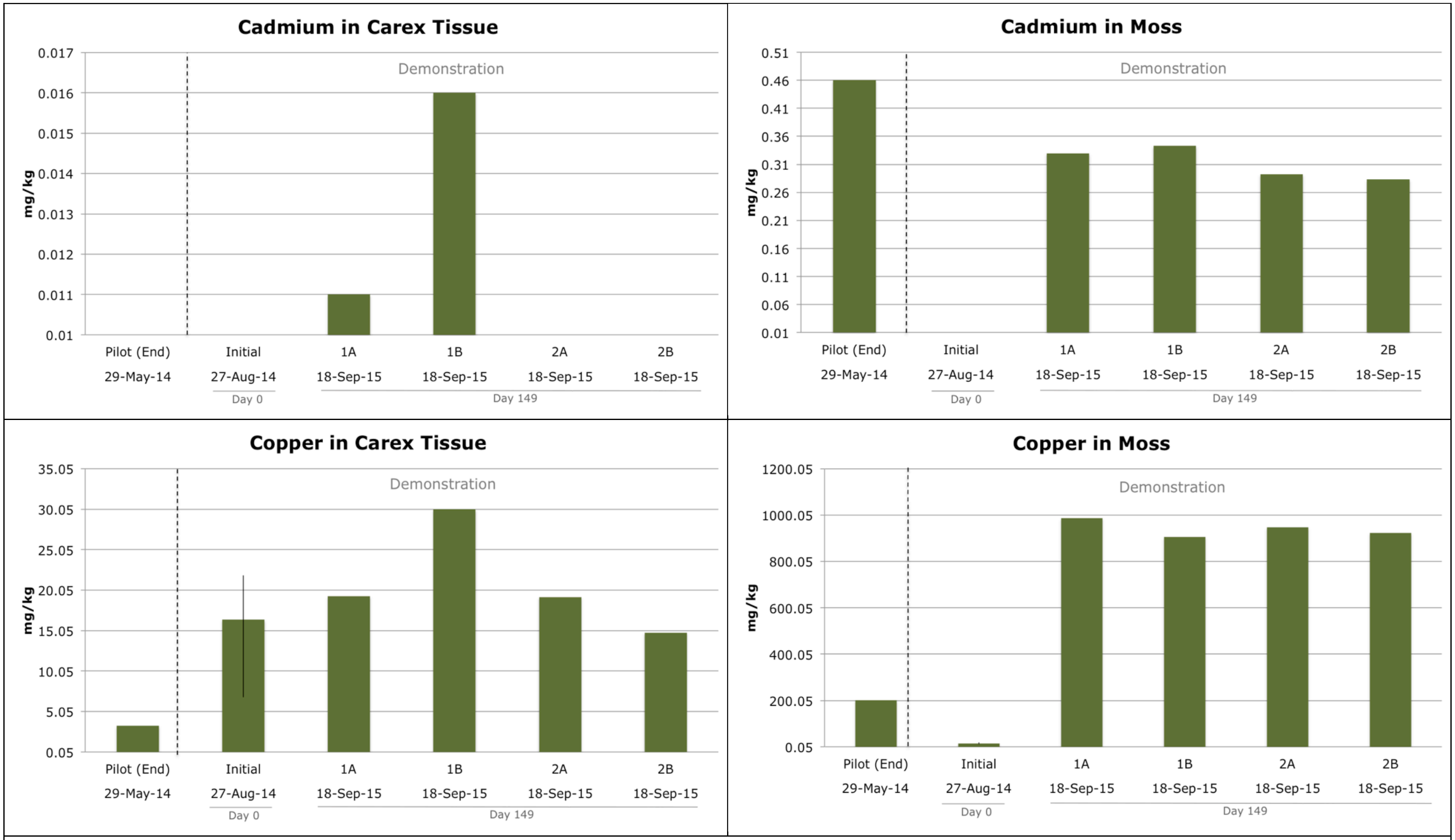


September 2015

September 2015

Figure 11 - Continued



Cadmium in Carex Tissue

Cadmium in Moss

Copper in Carex Tissue

Copper in Moss

Figure 12 – Element concentrations in plant tissue.

Y-axis starts at the 2015 detection limit (DL). The 2014 DL for Cadmium is the same as 2015. The 2014 DL for Copper is 0.5 mg/kg, and Selenium is 0.2 mg/kg. The initial data set is the average value of CWTS 1A-2B. The error bars indicate the minimum and maximum values in that data set.

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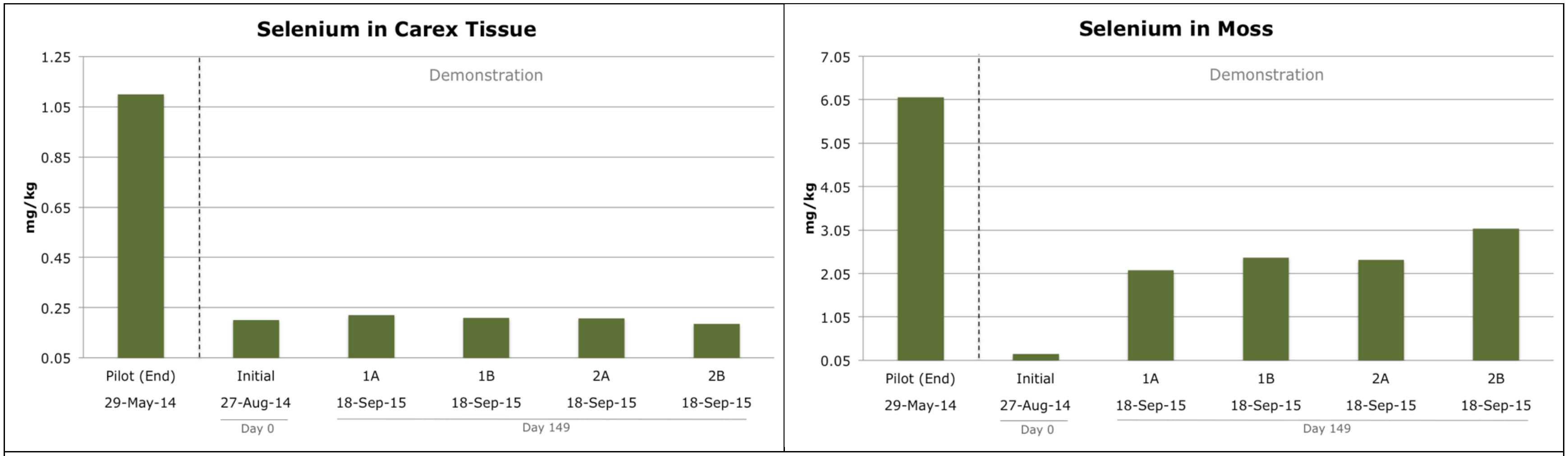

Figure 12 - Continued

6.5. Beneficial Microbes

Microbes are the driving force of many treatment pathways that are targeted in CWTSs. The beneficial microbes in these systems catalyze biogeochemical cycles for remediation of specific constituents of concern. Careful design of CWTSs can mimic the environmental conditions needed to enhance the abundance and metabolic activity of these beneficial microbes. Accordingly, complimentary methods of genetic and growth-based testing were used to characterize the microbial populations associated with a range of microbial habitats in the demonstration-scale CWTS (e.g., soils, sediment, biofilms, aquatic mosses, and plant roots).

In the context of the Minto Mine CWTSs, beneficial microbes include those that are involved in the reduction of selenium (selenate and selenite), nitrate, and sulphur compounds (which in turn treats copper and cadmium). Information on each of these mechanisms and the associated microbial populations in the demonstration-scale system is outlined in the following sections.

6.5.1. Sulphide-producing bacteria

Treatment is achieved by targeting the lithic biogeochemical sequestration of divalent metals through sulfide (i.e., S^{2-}, HS^{-}) precipitation as mineralized species (e.g., chalcocite [CuS], covellite [Cu_2S]). These sulfide bound species are relatively insoluble (CuS; $ksp=10^{-16}$; Stumm and Morgan 1996), and are transferred from the water column into the CWTS soil as non-bioavailable fractions (Murray-Gulde et al., 2003; Huddleston et al., 2008). Moreover, similar reactions occur with cadmium rending it non-bioavailable. As such, sulphide production is a key biogeochemical treatment mechanism for water treatment at Minto Mine. Sulphides can be created by beneficial microorganisms through the reduction of sulphur-containing compounds, such as sulphate, sulphite, thiosulphate, and elemental sulphur.

Based on the information gathered in pilot-scale testing, the targeted soil redox for the demonstration-scale CWTS is between -100 and -250 mV. This is in agreement with literature that indicates anaerobic conditions with relatively low ORP (-250 to -100 mV) are necessary for promoting anaerobic metabolisms in bacteria which oxidize organic matter, producing electrons which reduce sulfate to hydrogen sulfide (H_2S) and other reduced sulfide species (i.e. bisulfide ion (HS^{-}), sulfide ion [S^{2-}]; Mitsch and Gosselink 2007). In these redox ranges, bacterial sulphide-production through reduction of sulphur compounds is expected, alongside increases in the proportion (percentage) and abundance of these microbes.

The percentage of sulphate-reducing bacteria in the community increased over time in the demonstration-scale CWTS (Figure 13), as would be expected during the commissioning period. The percentage of sulphate-reducing bacteria is similar to what was present in pilot-scale systems at a comparable time point in operation (i.e., day 114 vs. day 80 in Figure 13), however, the types of microbes differ. Conversely, when considering all sulphide-producing bacteria (i.e., including those capable of sulphur, sulphate, sulphite, and thiosulphate reduction), the demonstration-scale systems have a higher percentage than the pilot-scale systems at a comparable time point (Figure 14), indicating the commissioning period is proceeding well. Sulphide-producing organisms identified during the site assessment at W10 and in low proportions at W15 (Contango, March 2014) were also present in both the pilot- and demonstration-scale systems, indicating that harvested plants were also a source of beneficial microbes.

As expected, the proportion of sulphide-producing bacteria increased as the soil redox decreased (Figure 14). Furthermore, the overall abundance of sulphide-producing bacteria has increased in the soil of the CWTSs over time as reducing conditions are achieved during the commissioning period (Figure 15). This is particularly notable in Series 1, which achieved targeted soil redox conditions quicker than Series 2, which is still establishing reducing conditions (see Section 5). The soils and *C. aquatilis* roots had the highest abundance of sulphide-producing organisms of all sample types tested, with the deeper soil (10-20 cm) having higher abundances than the shallow soils (0-5 cm) at day 149. As expected, algae and biofilm samples had very low abundances of sulphide-producing bacteria. Interestingly, the aquatic mosses had a large variability in the abundance of sulphide-producing bacteria (sometimes having as many or more than the soils). This variability may be related to general growth habits of the moss, with live, photosynthetic (oxygenating) parts of the moss having fewer sulphide-producing bacteria, while the older, decomposing regions have more. This fits with the targeted processes in the CWTS, where metals are first sorbed to moss, then eventually mineralized through sulphide-production.

The microbial analysis of various sample types in the CWTS has therefore confirmed that the commissioning period is proceeding as expected, with beneficial sulphide-producing bacterial populations establishing in the soils alongside reducing conditions.

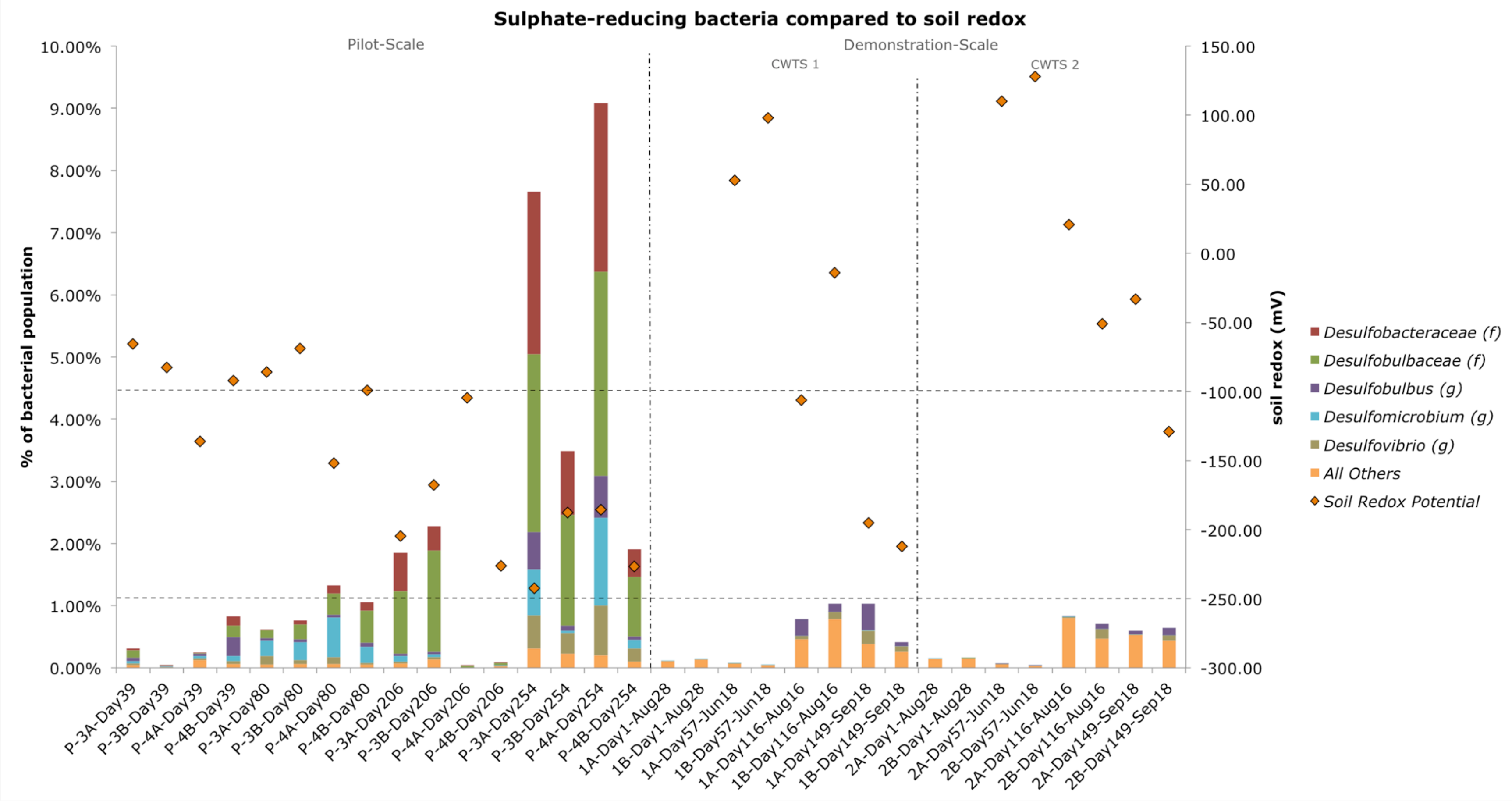

Figure 13 – Percentage and identity of sulphate-reducing bacteria in soil of the pilot-scale and demonstration-scale CWTSs

The vertical dashed lines separate the pilot-scale system data from the demonstration-scale system 1 and system 2 data. The horizontal dashed lines indicate the targeted soil redox range.

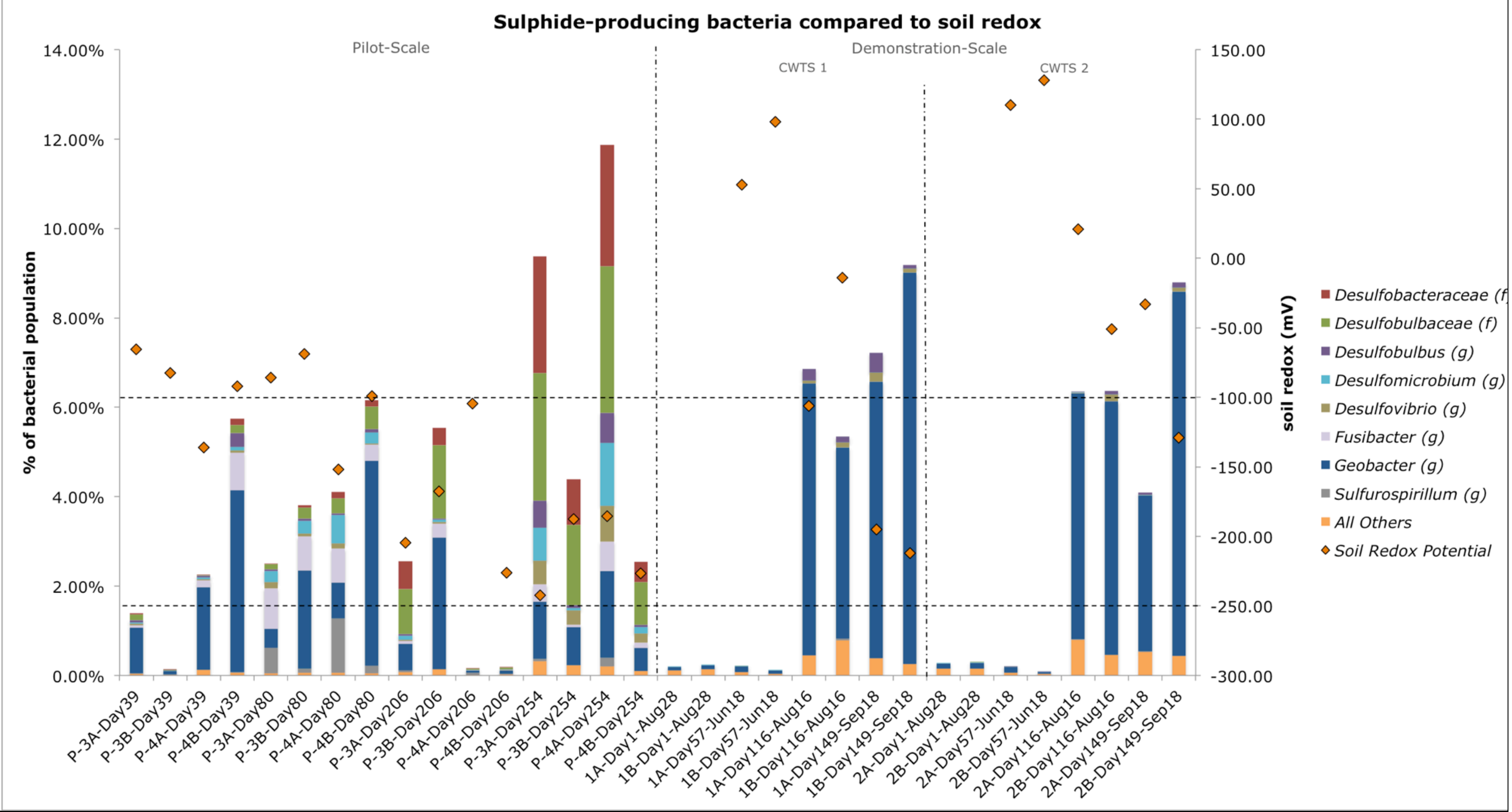

Figure 14 – Percentage and identity of sulphide-producing bacteria in soil of the pilot-scale and demonstration-scale CWTSs

The vertical dashed lines separate the pilot-scale system data from the demonstration-scale system 1 and system 2 data. The horizontal dashed lines indicate the targeted soil redox range.

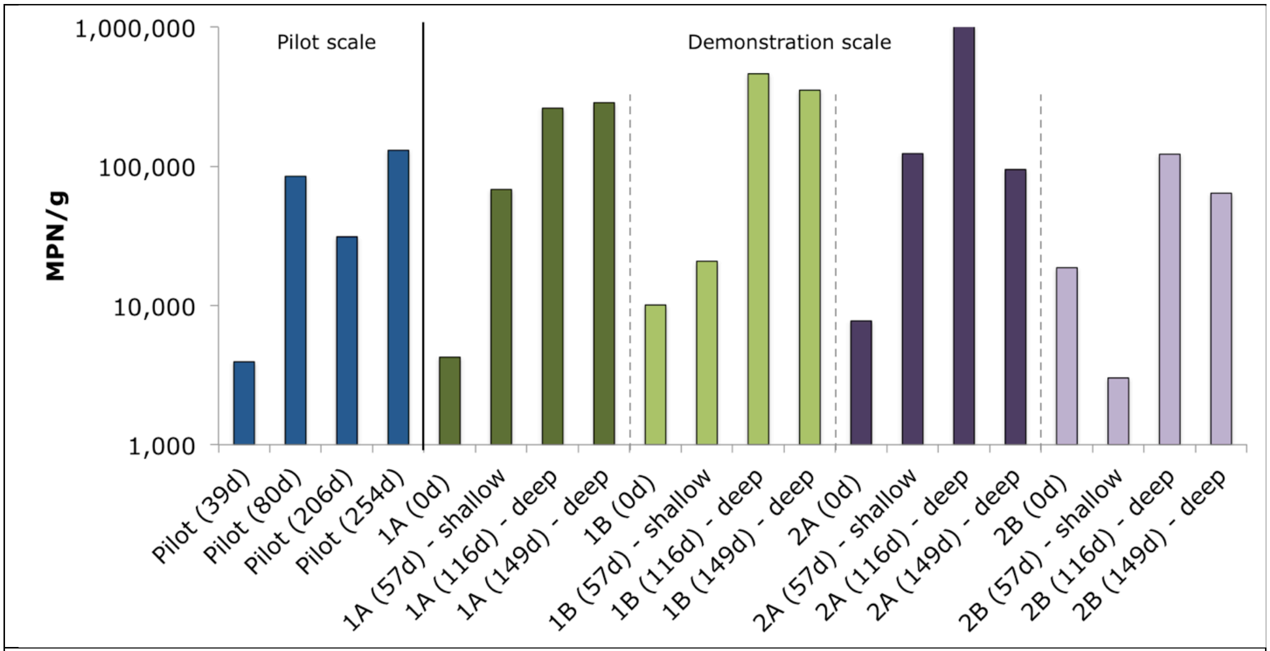

Figure 15 – Inferred abundance of sulphide-producing bacteria in soil of the pilot- and demonstration-scale CWTSs
Inferred abundance is calculated based on a combination of genetic and growth-based data.
- shallow soil (0-5 cm); deep soil (10-20 cm); soil at 0d was that used for construction of wetland

6.5.2. Selenium-reducing bacteria

The targeted selenium treatment pathways in the Minto CWTS include sorption to moss and soils, and subsequent microbial reduction of soluble (sorbed) selenate (Se(VI)) and selenite (Se(IV)) to insoluble elemental selenium (Se(0)). This reductive process can also be achieved directly in the water column, but is more effective associated with mosses and biofilms due to their sorptive properties that bring the selenium in contact with beneficial selenium-reducing bacteria. This is achieved within the range of soil redox conditions targeted for sulphate-reduction as suggested by pilot-scale testing and literature (see Section 5).

Selenite-reducing organisms are ubiquitous in nature and as expected, were detected in all sample types, including algae, biofilm, moss, soil, sediment, and roots. Although selenate-reducing organisms are generally less abundant in the environment, they were found associated with all sample types, indicating that the conditions conducive to their proliferation have been created within the CWTS. Moreover, the abundance of selenite- and selenate-reducing organisms increased over time in the demonstration-scale system during the commissioning period (Figure 16). Aquatic mosses were found to host the highest abundances of both selenate- and selenite- reducing organisms, affirming the importance of the inclusion of moss in the CWTS. Additionally, shallow soils (i.e., top few centimeters, including associated biofilms) were found to host an abundance of selenite-reducing organisms, particularly in Series 1. The abundance of selenite-reducing organisms associated with the demonstration-scale moss and shallow soils is similar if not higher than that observed in the soil of the pilot-scale testing, indicating the commissioning period is proceeding as anticipated (selenate-reducing organisms were not tested for at pilot-scale).

6.5.3. Nitrate-reducing bacteria

Nitrate is sometimes a constituent of concern during operations and early closure owing to residuals from blasting activities. Even if not in exceedance of water quality guidelines in terms of receiving environment objectives, nitrate often requires attention in order to achieve treatment of other constituents. The presence of nitrate can interfere with the treatment of certain elements in water (such as selenium). Nitrate can be removed from water by different types of microbes, including nitrate reducing bacteria which are capable of reducing nitrate (NO_3) to nitrite (NO_2), and also denitrifying organisms that are capable of fully reducing nitrate to nitric oxide (NO), nitrous oxide (N_2O), and dinitrogen gas (N_2 - which is the most abundant gas in air). MPN analysis was therefore used to quantify these organisms.

Nitrate-reducing and denitrifying organisms were found associated with all sample types in the demonstration-scale CWTS (Figure 17). Soil samples had an increase in nitrate reducers over time, with the highest abundance of all samples found in the deeper soil sample from day 149. In contrast, denitrifying organisms were found to be associated primarily with the shallower soil depths and also a high abundance associated with moss, which increased in abundance over the commissioning period.

Although the pilot-scale systems had higher nitrate concentrations (30 mg/L as N during High Nitrogen testing phase) than the demonstration-scale systems (average 10 mg/L as N), the abundance of nitrate-reducing and denitrifying organisms are both similar. As such, these results also confirm that the demonstration-scale system is establishing as expected during the commissioning period.

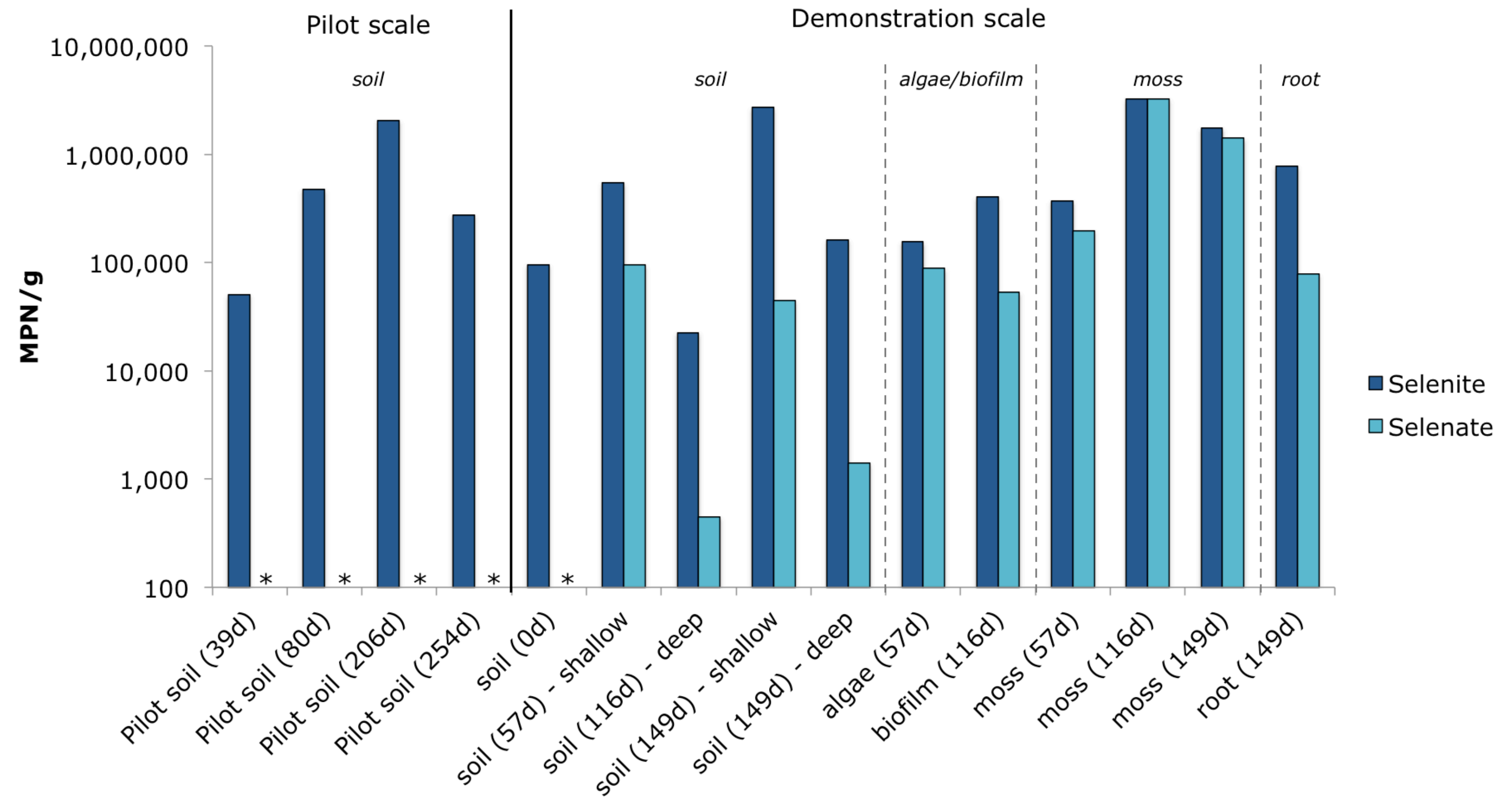

Figure 16 – Abundance of selenite- and selenate-reducing organisms in various CWTS sample types over time
* - pilot-scale system and initial timepoint for demonstration-scale system not tested for selenate-reduction
- shallow soil (0-5 cm); deep soil (10-20 cm); soil at 0d was that used for construction of wetland

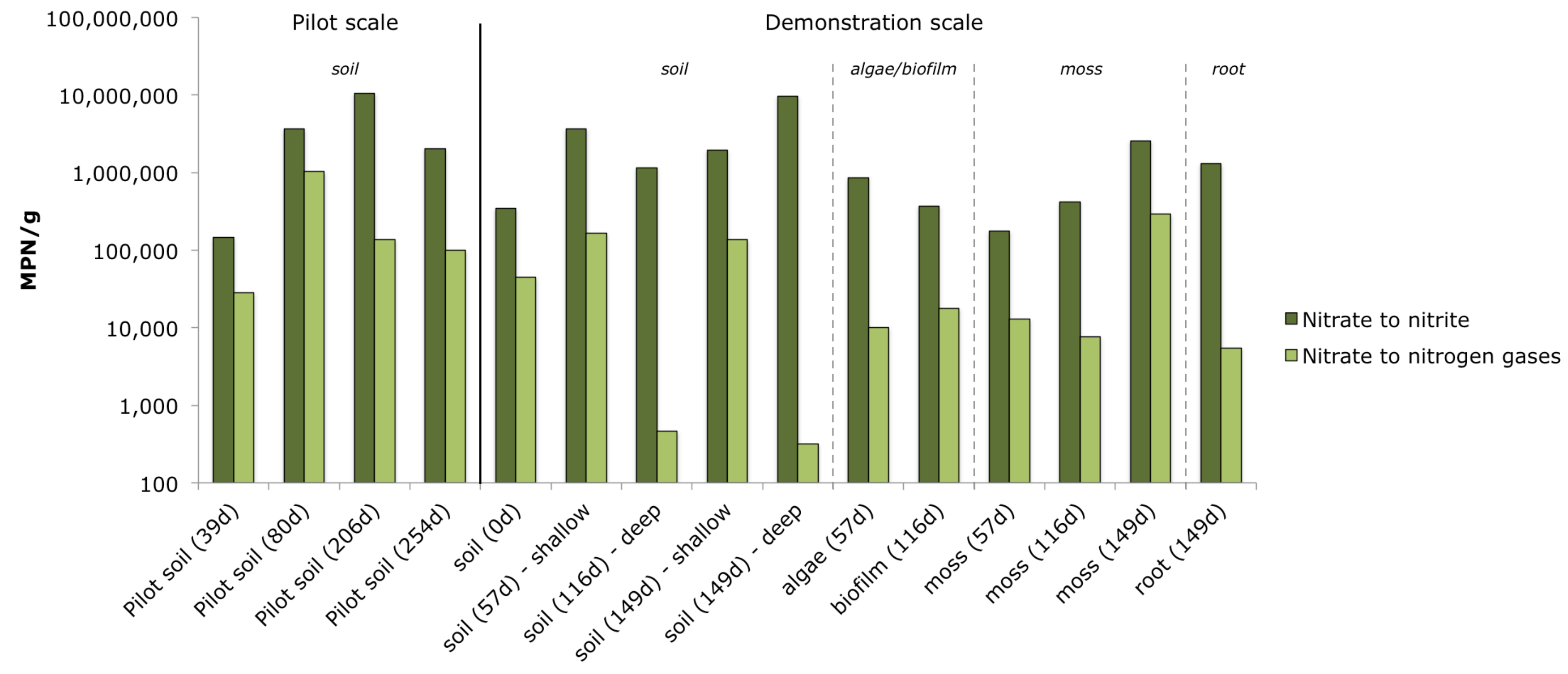

Figure 17 – Abundance of nitrate-reducing and denitrifying organisms in various CWTS sample types over time

Nitrate-reducing = reduction of nitrate to nitrite; denitrifying = reduction of nitrate to nitrogen gases. Shallow soil (0-5 cm); deep soil (10-20 cm); soil at 0d was that used for construction of wetland.

7. Summary of Results

Table 6 summarizes results and findings from 2015 commissioning of the demonstration-scale system at Minto.

Table 6. Summary of Minto Demonstration-scale 2015 Testing

Objective	Purpose	Key Findings
Evaluate construction	Optimize construction and effectiveness of operation of full-scale systems	**Layout** -Outflow collection pond should have outflow at base (not top), with shutoff valve -Increased slope on sides, and riprap or sandbags added at shores would prevent water short circuiting and deter wildlife access
		Soils -Use substrate with less total and leachable metals and metalloids (especially copper) -Higher sand content would improve hydrology, constructability (ability to level soils, ease of planting) and accessibility for sampling -Organics should be mixed in bulk to soils prior to adding to cells
Assess commissioning timelines	Allow for proper phasing of implementing full-scale systems for closure	**Water** -Copper treatment improving through commissioning period; wetland achieving better treatment than suggested by inflow and outflow concentrations of system, as soils are leaching copper -Cadmium and selenium are also being removed from water -Wetland is maturing as expected and is performing beyond anticipated from the design -Tracer study recommended for 2016 to assess hydrology and pore volume of CWTS and determine HRT and removal rate coefficients for full-scale sizing

Objective	Purpose	Key Findings
		Soils -Soil redox has decreased as expected, reaching targeted ranges in Series 1 by the end of 2015, while Series 2 continues to establish -Significant amounts of metals are leaching from soil substrate into water, putting additional treatment demands on system
		Microbes -Sulphide-producing bacteria needed for copper and other metals removal have increased over time as soil redox achieved target ranges. Proportions are comparable to those in pilot system at similar point in commissioning -Abundance of selenium- and nitrate-reducing organisms are similar to those in pilot testing, indicating maturation as expected -Selenium treatment performance expected to increase as mosses continue to grow, as they can sorb dissolved selenium and harbour highest abundance of selenate-reducing microorganisms to render the selenium insoluble
Carex aquatilis transplantation effectiveness	Determine if plant propagation and/or replanting schedule will be needed for full-scale systems	->95% survival from transplanting -Within first 2 months a further increase of >20% -Full-scale system could be planted more densely to bring online faster, or less densely if time is less of an issue than sourcing plants (the plants are vigorous and will fill in the wetland in due time)
Moss colonization/distribution		-100% survival from transplanting -Slower to spread, needs to be started more densely -Staking helps maintain moss in 'upstream' parts of wetland, or could be transplanted multiple times through commissioning period

8. Tentative Schedule and Action Items for 2016

Based on progress of commissioning and early performance results in 2015, an action plan for CWTS optimization and testing for 2016 has been developed (Table 7). An updated multi-year schedule as per the proposed scope of work in the Minto Demonstration Scale Report Document 011_0315_01A (Contango, March 2015) is provided in Appendix C.

Table 7. Minto 2016 CWTS Demonstration-scale Action Items

Who/When	Task	Contango Action Required	Additional Information
Minto Staff, prior to first site visit	Add sandbags to perimeter of CWTS to minimize short circuiting	Provide diagram of sandbag location	Use sand that was confirmed to be good borrow source in 2016 (i.e., low copper)
	W15 creek monitoring	Develop research plan and schedule of testing	This is the creek(s) feeding the W15 area pond
Site visit 1 (May 2016)	Tracer study (salt)	Experimental design	Ensure salt tracer study will not affect other planned activities at the site (e.g., hydrogeology studies)
	Change AgCl probes	Replace old probes with new ones	These are the reference probes for soil-redox testing
	Develop flow rates for 2016	Based on tracer study	Flow rates will be set (and varied) according to expected flows at water storage pond in closure, and theoretical hydraulic retention times needed to develop outflow water quality predictions
	Check on W15 creek monitoring	Confirm monitoring locations	Because at least 3 entry points exist from the creek to the W15 pond, check which creek is being monitored and how this compares to the W15 sampling point water quality
Site visit 2 (July 2016)	Add organic material to System 2	Determine amount and type to add	This will only be performed if soil redox conditions have not consistently met targeted ranges by July 2016
Site visit 3 (September 2016)	General follow up	Final sampling for year	

9. Monitoring plan

A conceptual long-term testing plan was developed for the demonstration-scale CWTS and has been refined and adapted based on performance and scientific findings (Appendix A). The demonstration-scale wetlands are expected run until at least the end of 2016, and ideally longer in order to assess performance under a wider range of conditions. The conditions that could eventually be tested include both natural/environmental and selected influenced pressures, and can be imposed on the systems to mimic peak flow rates or droughts. In 2016 the systems are expected to continue to mature (i.e., complete commissioning), with plants becoming more established and abundant, and microbial communities accordingly acclimating to the targeted conditions. We expect to achieve targeted ranges of soil redox in 2016, which will indicate that the commissioning period has completed and allow for the monitoring program to shift focus to testing of operations and performance. A multi-year plan is provided in Appendix C, and includes work performed to date as well as a schedule for 2016 and potential activities for 2017.

10. Closure

We trust the information herein satisfies your present requirements. Should you have any questions, please contact the persons listed below. We appreciate the opportunity to provide the services detailed in this report, and look forward to discussing any comments you may have.

Respectfully submitted,

Contango Strategies Ltd

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Appendix A

Table 1. Summary of analytical sampling types, frequencies and locations

Water	
Dissolved and total metals	Weekly, outflow of each cell and feed
Flow rate	Weekly, feed
pH, DO, ORP, Conductivity (in situ)	Weekly, all cells and feed
Anion Sum	Monthly, outflow of each cell and feed
Cation Sum	
Hardness ($CaCO_3$)	
Ion Balance	
Total Dissolved Solids (TDS)	
Chloride (Cl)	
Sulphate (SO_4)	
Nitrate	
Nitrite	
Nitrogen (Total)	
Alkalinity	
pH	
Conductivity	
Chemical Oxygen Demand (COD)	
Total Organic Carbon (TOC)	
Ammonia	
Total Kjeldahl Nitrogen (TKN)	
Total Suspended Solids	
Biological Oxygen Demand (BOD)	
Bicarbonate (HCO_3)	
Carbonate (CO_3)	
Hydroxide (OH)	
Soil	
Relative soil redox (in situ)	Monthly, all probes (6 per cell)
Cation exchange capacity (CEC)	Seasonally (3x per year)
SAR, pH, EC, %sat, Ca, F, Mg, Na, K, Cl, SO4	
Available NPK and sulphur	
Alkalinity	
Bicarbonate (HCO_3)	
Carbonate (CO_3)	
Hydroxide (OH)	
Total Organic Carbon (TOC)	
Dissolved Organic Carbon	
Metals Analysis (Total)	
Metals Leachable (SPLP)	

Ammonia	
Nitrate	
Nitrite	
Total Dissolved Solids	
Anion Sum	
Cation Sum	
Cation/EC ratio	
Ion Balance	
Sequential Leaching (5 Acid Test)	
Cation exchange capacity (CEC)	
Plant tissue samples	
Metals Analysis	*Carex aquatilis* and aquatic moss, each cell, year end
Microbial samples	
Growth-based most-probable number analysis (nitrate reduction, selenite and selenate reduction, total heterotrophs)	Seasonally (3x per year)
Genetic sequencing analysis for bacterial community composition and distribution	Seasonally (3x per year)

Appendix B – Copper Sequential Leach and Aluminum Graphs

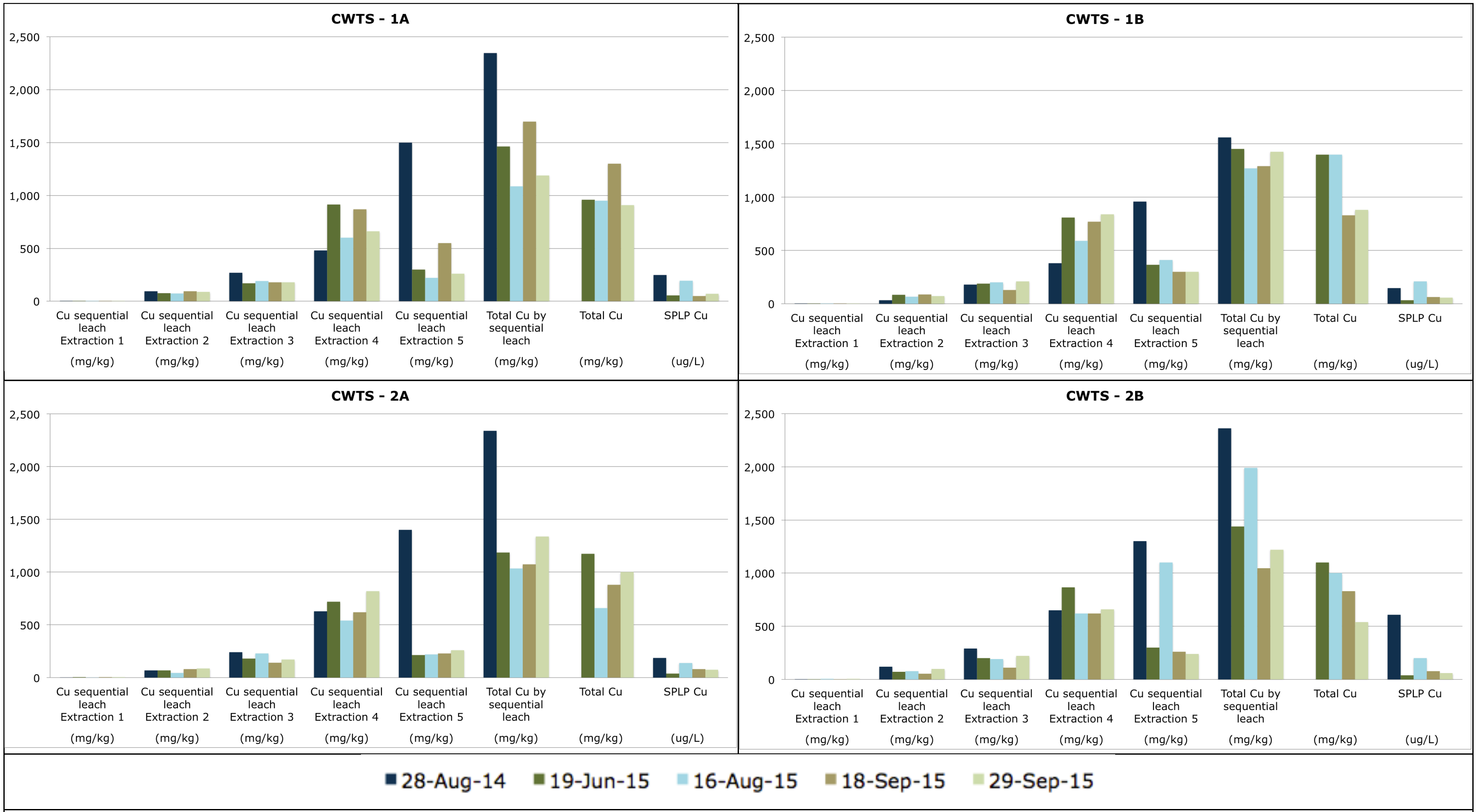

Figure B1 – Copper sequential leach compared to Total copper

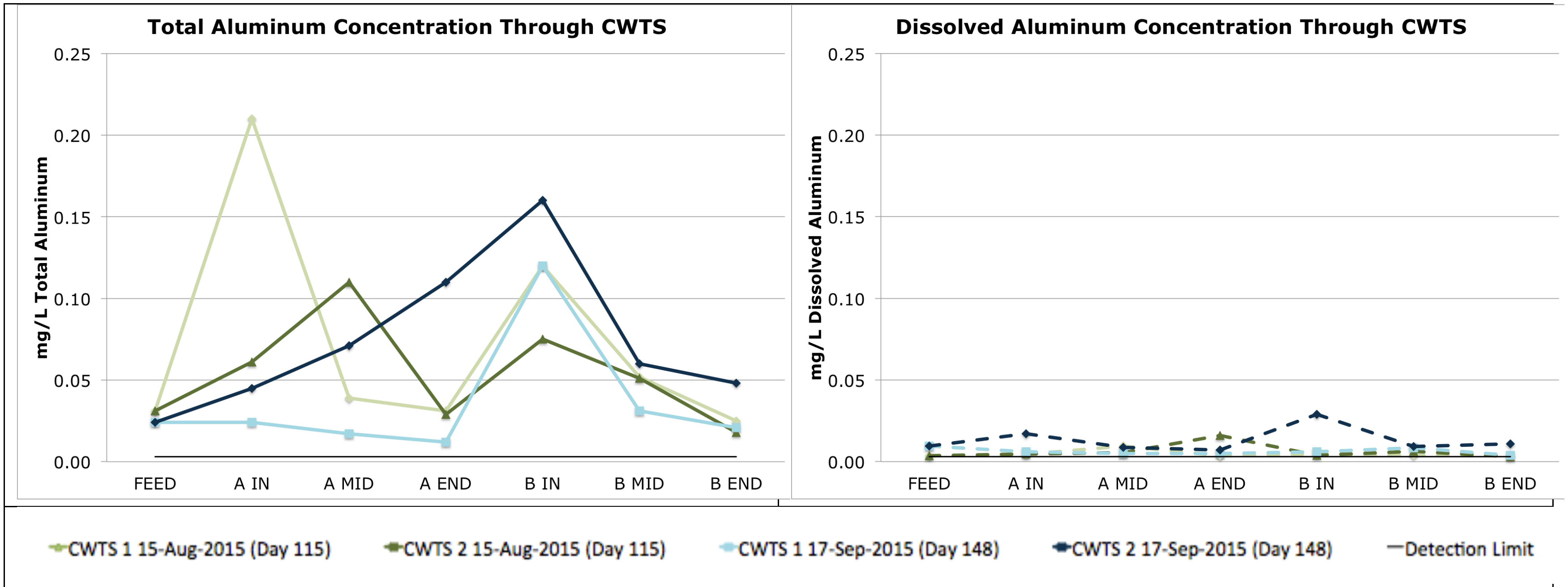

Figure B2 – Concentrations of Aluminum in water through the CWTS.
Water samples were collected from the CWTS feed, and from the beginning, middle, and end of each wetland cell on 2 occasions.

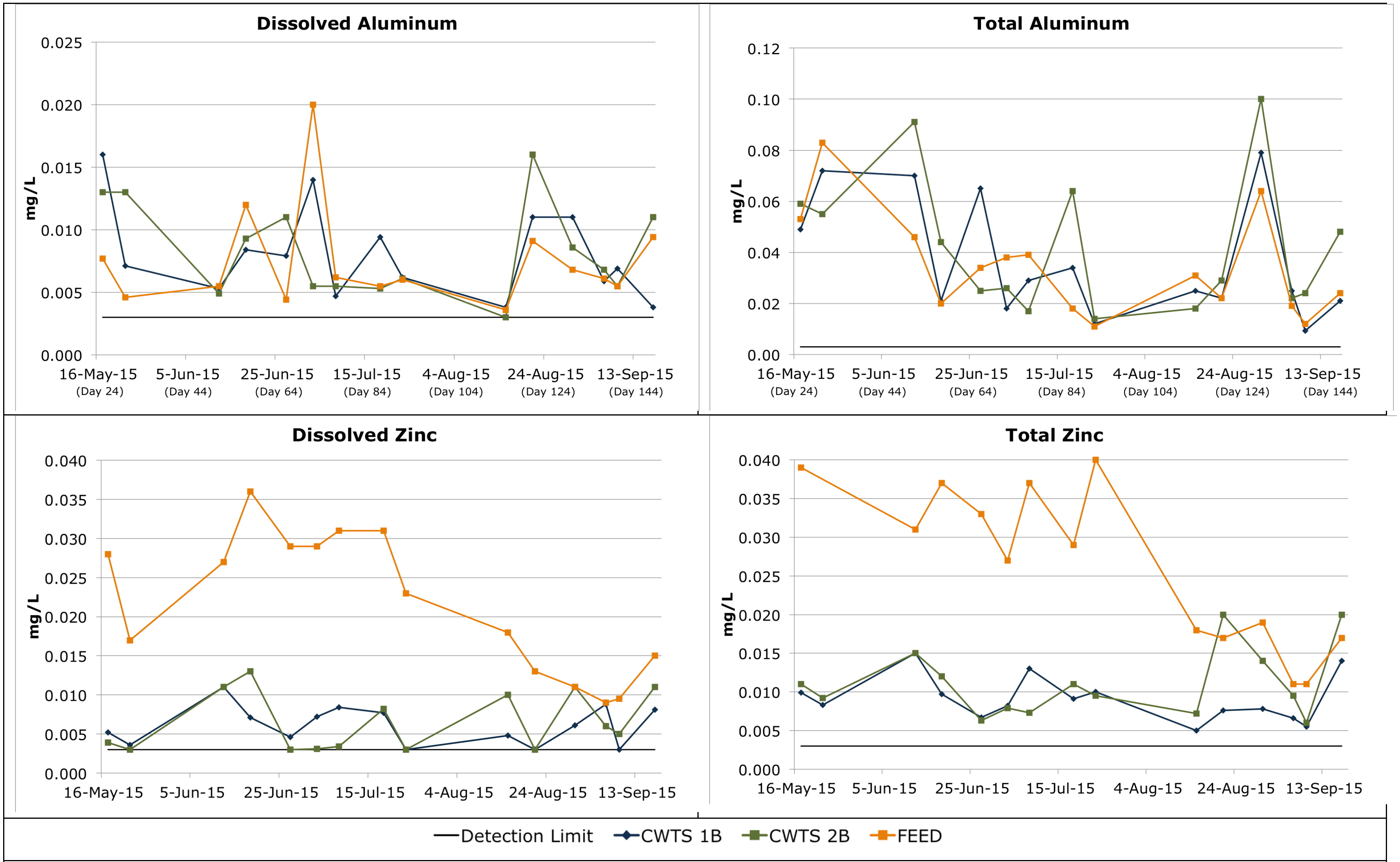

Figure B3 – Aluminum and Zinc concentrations in the demonstration scale wetland from May 17, 2015 to Sept 17, 2015.
The Measurement Uncertainty (MU) for aluminum and zinc is +/- 0.003 mg/L.

Appendix C

Table C1. Schedule of work

Item	Date	Activities	Actual
Construction	June 1-14 2014	Identify potential location for demonstration scale CWTS (CSL site visit – 1 scientist)	Completed
	June - July 2014	Engineering and geotechnical (Minto)	Completed
	July 2014	Construction (Minto)	Completed
	August 2014	Planting and bringing system online (CSL site visit – 1 scientist, 1 technologist), coordinate for local students to assist.	Completed (no students available, brought 2 technologists)
Commissioning	2014	Acclimation and maturation at constant flow rate, ~20 hr HRT	Completed
		September - CSL site visit/checkup (1 technologist, 1 scientist)	Did not occur because construction was last week of August.
	2015	Continued commissioning. Operation at constant flow rate, ~20 hr HRT	Completed (at shorter HRT)
		Spring – CSL site visit/checkup (1 technologist, 1 scientist), includes micro sampling	Completed
		Summer - Increase depth from 10 cm to 20 cm (1 technologist), includes micro sampling	Completed (scientist)
		Fall – CSL site visit/checkup (1 technologist), includes micro sampling	Completed (scientist)
Performance Monitoring	2016	Minto to add sandbags prior to first site visit and begin W15 creek monitoring	Expected May/June 2016
		Spring – CSL site visit (1 scientist, 1 technologist), includes microbial sampling and tasks outlined in Table 7 of report	Expected May/June 2016
		Summer - CSL site visit/checkup (1 scientist, 1 technologist), includes microbial sampling and tasks outlined in Table 7 of report	Expected July/August 2016
		Fall - CSL site visit/checkup (1 technologist), includes microbial sampling and tasks outlined in Table 7 of report	Expected September 2016
	2017*	Continued performance monitoring	*Putative activities, may not be necessary depending on performance and outflow water quality in other years.*
		Possible testing of semi-passive hybrid Bioreactor/CWTS phase. This will involve adding solid organic matter (such as alfalfa hay, straw) to the CWTS cell(s).	
Reporting	2014-2016	Reporting will be performed annually, with verbal and/or emailed interim updates	On Schedule

Appendix A5
Minto Mine Constructed Wetland Treatment Research Program - Demonstration Scale 2016 Update

Minto Mine Constructed Wetland Treatment Research Program – Demonstration Scale 2016 Update

Document – 011_0217_05B

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February 2017

Executive summary

The Minto Mine, operated by Capstone Mining Corp., is located 240 km northwest of Whitehorse on the west side of the Yukon River. In 2013 Contango Strategies Ltd. (Contango) was retained by Capstone Mining Corp. to conduct a phased assessment to determine the feasibility of using passive means to treat water at closure at the Minto Mine. Pilot-scale testing, completed by Contango in July 2014, determined that plants and beneficial microbes found at the Minto site could be used to remediate contaminated mine drainage in a constructed wetland treatment system (CWTS; November, 2014). In August 2014, a demonstration-scale CWTS was implemented at the Minto Mine site. The performance results from the on-site demonstration-scale CWTS confirm that a passive water treatment system can be used to successfully improve mine-impacted waters.

To date, the demonstration-scale CWTS has had 312 operational days (i.e., water flowing), consisting of 24 days in 2014, 137 days in 2015, and 152 days in 2016. Day 248 (July 28, 2016) is when organics were added to the CWTS to aid in treating the additional copper load originating from the soils used as substrate, and marked the end of what we will now be referring to as the period "commissioning-A", and the beginning of period "commissioning-B". The commissioning-B period will continue in 2017 until the demonstration-scale CWTS performance is consistently achieving performance expectations. These commissioning periods are necessary for operational adjustments to be made (e.g., raising water depth, modifying outflow patterns), and for plant and microbial populations to establish and mature to achieve full operational performance of the CWTS. Owing to the types of soils used as substrate in construction (i.e., high concentrations of oxidized copper), commissioning has taken longer than would normally be the case (or would be the case for the full-scale system).

The commissioning period is also being used to collect additional information about the on-site demonstration-scale CWTS that will aid in the final full-scale CWTS design, sizing, and construction. For example, a tracer study was carried out in June 2016 to assess the hydrology and hydraulic retention time (HRT) of the CWTS. Using the data from the tracer study, the pore space involvement of the CWTS substrate was calculated.

Performance continues to be monitored and while full treatment functionality of the demonstration-scale system is not expected during the commissioning period, the information would aid in the development of the full-scale system in the following ways:

- Evaluation of construction effectiveness and potential optimizations.
- Assessment of timelines to reach targeted operational parameters to allow for effective phasing of implementation (e.g., soil redox, percentage and abundance of sulphate reducing bacteria).
- Assessment of the effectiveness of *Carex aquatilis* and aquatic moss transplantation to assess planting density, time period to full density, and if plant propagation and/or a replanting schedule is necessary.

In July 2016 the demonstration-scale system was not achieving stable soil redox values within the targeted range (nor associated performance expectations); therefore, woodchips and straw were added to the demonstration-scale CWTS as sources or organic carbon. Because the demonstration-scale system takes time for plants to mature (and generate organic carbon for the microbes to feed on), the addition of organics early in the operation of the system can supplement the carbon sources needed for beneficial microbes that drive treatment of selenium and other constituents. This will be included in the full-scale system design specifications. The addition of organics marked the end of the commissioning-A period.

Once the commissioning–A period was complete, the commissioning-B period began on July 29 and continued to the end of 2016 operations on September 30, 2016. During the commissioning-B period, the demonstration-scale CWTS achieved on average 64% removal of dissolved cadmium (mean influent 0.0185 µg/L, mean outflow 0.0066 µg/L), 37% removal of dissolved copper (mean influent 46.1 µg/L, mean outflow 28.8 µg/L), a 21% removal of molybdenum (mean influent 7.3 µg/L, mean outflow 5.7 µg/L), a 41% removal of dissolved selenium (mean influent 5.7 µg/L, mean outflow 3.3 µg/L) and a 69% removal of dissolved zinc (mean influent 37.6 µg/L, mean outflow 11.6 µg/L). The percent removal of molybdenum and selenium is notable, as it has increased from 0% removal during commissioning-A, to achieving 21% and 41% removal, respectively during commissioning-B. Monitoring through 2015 and 2016 has indicated that percent removal of elements of concern have been increasing over time. The results of the 2016 on-site demonstration-scale CWTS performance indicate that the CWTS is continuing to mature. Plans for 2017 will focus on testing operations and performance. Flow rates will be set at a constant flow to evaluate the stability of the CWTS performance over one year. A second HRT tracer study will be performed using an updated method based on the findings from the 2016 HRT tracer study. A second evapotranspiration study will also be performed to determine the amount of water that is being lost to evapotranspiration from the CWTS. Weekly monitoring will continue throughout 2017 to evaluate performance of the CWTS.

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Abbreviations and definitions

Acidity – A measure of the capacity of water to neutralize base. Influences pH along with alkalinity.

Alkalinity (Alk) – A measure of the capacity of water to neutralize acids. Influences pH along with acidity.

Amendment – A chemical or organic material added to encourage specific conditions (e.g., aerobic/anaerobic, pH, ORP) or as a source of something that is needed for passive treatment (e.g., nutrients, alkalinity, binding sites, etc).

ANAMMOX – Anaerobic ammonium oxidation; a microbiological process where ammonium and nitrite are converted directly to dinitrogen gas ($NH_4^+ + NO_2^- \rightarrow N_2 + 2H_20$).

Biofilm(s) – A visible and often slimy-looking film (community) of bacteria (may contain other microbes).

Carbon source – A source of carbon (energy/electrons) for microbes (see **electron donors**). Examples include ethanol, methanol, acetate, sugar (glucose), molasses, wood chips, detritus (dead plant matter).

Carex aquatilis – A plant (emergent macrophyte) commonly known as water sedge.

Carex utriculata – A plant (emergent macrophyte) commonly known as Northwest Territory sedge or beaked sedge.

Contango – Contango Strategies Ltd.

Constructed wetland treatment system (CWTS) – Wetlands that are designed and constructed to remove compounds from water, using natural processes to sequester them into the soils rendering them less bioavailable. They are different from wetlands that provide habitat for wildlife.

Denitrification – Where nitrate (NO_3^-) is reduced by microorganisms to form nitrite (NO_2^-), nitric oxide (NO), or nitrous oxide (N_2O), or nitrogen gas (N_2) (see **nitrate reduction**).

Dissolved oxygen (DO) – Diatomic oxygen (O_2) dissolved in water; oxygen can dissolve in water by diffusion from surrounding air, as a product of photosynthesis, or through forced aeration.

Electron donor(s) – A chemical compound that donates electrons to another compound (see **carbon source**). An electron donor is a reducing agent, which that by virtue of it donating electrons, is itself oxidized (see **oxidation** and **reduction**).

Explanatory parameters – Quantifiable parameters that describe how water treatment reactions take place.

Evapotranspiration – The combined effects of open water evaporation and plant transpiration (Beebe *et al*, 2014).

Genetic analysis – Analysis to assess the presence, identity, and diversity of different microbes in a sample.

ICP-MS – Inductively coupled plasma mass spectrometry.

Macrophytes – An aquatic plant, large enough to be seen by eye. Can be emergent, submergent, or floating.

Microbes – Microscopic organisms that can be uni- or multi-cellular. This includes algae, bacteria, fungi, viruses, and yeast.

Most probable number (MPN) – A statistical value representing the viable population of microbes in a sample through use of dilution and multiple inoculations.

Oxidation – The loss of electrons, or increase in valence state, by a molecule, atom, or ion. Can be driven by microbes. Process is complementary to chemical reduction.

Oxidation-reduction potential (ORP) – A measure of the tendency of a chemical species to acquire or donate electrons, thus becoming reduced or oxidized, respectively, measured in millivolts.

Passive or semi-passive treatment system(s) (PTS) – General term used to refer to both passive and semi-passive treatment systems that use processes coupling transformations (e.g., chemical and biogeochemical reactions) with physical transfers (e.g., sorption, filtration) to remove constituents from water, often operationally passive with little long-term management required.

Redox – Oxidation-reduction potential (in sediment), a measure of the tendency of a chemical species acquire or donate electrons, thus becoming reduced or oxidized, measured in millivolts. This measurement is relative to the water ORP.

Reduction – The gain of electrons, or a decrease in valence state, by a molecule, atom, or ion. Can be catalyzed by microbes. Process is complementary to chemical oxidation.

Simultaneously extracted metals (SEM) – Amounts of heavy metals such as Ni, Zn, Cd, Pb, Cu, Hg in sediment, assessed in the context of AVS for excess sulphide. (also see **acid volatile sulphide**)

Sorption – The physical and/or chemical process by which one substance becomes attached to another substance.

Specific conductivity (SPC) – A measurement of electrical conductivity in water that is typically expressed in μs/cm, which has been adjusted for temperature (25°C).

Species (sp.) – One of the basic units of biological classification and a taxonomic rank. Rank in the classification of organisms below genus and above strain. Also can be used to refer to the oxidation state of a mineral (e.g., selenate and selenite are species of selenium).

SPLP – Synthetic precipitation leachate procedure.

Sulphide – An inorganic anion of sulphur that can form stable complexes with metals and make them insoluble in water (remove them from the water).

Sulphide producing bacteria (SPB) – Microbial reduction of sulphur compounds, such as sulphate, sulphite, thiosulphate, and sulphur, which produces sulphides and alkalinity. (see also **SRB**).

Sulphate reducing bacteria (SRB) – A form of sulphide producing bacteria that specifically uses sulphate for reduction (see **sulphide producing bacteria**).

Sulphide production – Microbial reduction of sulphur compounds, such as sulphate, sulphite, thiosulphate, and sulphur, which produces sulphides and alkalinity.

Total dissolved solids (TDS) – A measure of the combined organic and inorganic salts dissolved in water.

Total organic carbon (TOC) – A measurement of the total organic carbons present in water.

Total suspended solids (TSS) – A measurement of all particles in water that are larger than 2 µm (anything smaller than 2 µm considered a dissolved solid).

Transfer – Processes that treat water by transferring a constituent to another location without changing its form. For example: absorption, adsorption, dilution, dispersion, filtration, precipitation (aqueous to solid), and volatilization.

Transform – Processes that change the chemical form or state of a constituent. For example: biodegradation, biotransformation, hydrolysis, ionization, oxidation, photolysis, and reduction.

1. Introduction and background

The Minto Mine, operated by Capstone Mining Corp., is located 240 km northwest of Whitehorse on the west side of the Yukon River. The Minto property lies within the eastern part of the Dawson Range, with elevations from 700 to 1,000 m; the landscape has rounded mountains intersected by broad valleys and drainages that are part of the Yukon River watershed.

The Minto Mine has been in commercial operation since October 2007 and the deposits being mined are copper sulphide mineralized zones. Surface and groundwater water quality is a key consideration in the evaluation of potential effects of mining and mineral development projects and changes to water quality parameters have the potential to affect aquatic and human use of water resources. A Reclamation and Closure Plan (RCP) is required under both the Water License and the Quartz Mining License. The RCP is intended to address the long-term physical and chemical stability of the site and closure of the proposed features and disturbances associated with the mine. As a part of the RCP, a Constructed Wetland Treatment System (CWTS) is being designed, evaluated, and optimized for water treatment at closure through a phased program (Minto Phase V/VI Expansion Project, YOR Project Number 2013-0100).

For CWTSs to be effective, they must be designed, piloted, optimized, implemented, and maintained in a site-specific manner. A scaled approach for CWTS implementation allows for improvement, optimization, and flexibility for modifications along each step. Phases include:

1) site assessment and information gathering,
2) technology selection and conceptual design,
3) pilot-scale testing and optimization (controlled environment),
4) on-site demonstration-scale confirmation and optimization, and
5) full-scale implementation.

Phases 1-3 have been completed (reports 2013-0100-256 and 2013-0100-257 on YESAB registry, and Contango, March 2014; Contango, November 2014) and confirmed plant amenability to transplantation and the CWTS design for further on-site testing. During pilot-scale trials, the selected CWTS design achieved on average 92% removal of cadmium (mean influent 0.336 µg/L, outflow 0.027 µg/L), 92% removal of copper (mean influent 146 µg/L, outflow 11.3 µg/L), 41% removal of selenium (mean influent 10.2 µg/L, outflow 6 µg/L), and 92% removal of zinc (mean influent 40 µg/L, outflow 3.2 µg/L), using synthetic influent designed to mimic the worst-case water chemistry of a long-term closure scenario, but tested under the controlled conditions (e.g., controlled flows, known temperature, etc) of an off-site treatability testing center (Contango, November 2014). It should be noted that lower influent concentrations will have a lower percent removal even when achieving the same final outflow concentrations.

Phase 4 of the project is underway, with the on-site demonstration scale CWTS constructed at the Minto Mine during fall 2014 (Contango, March 2015). The on-site demonstration-scale CWTS operated for 137 days in 2015 and 152 days in 2016 (Table 1). The results of the 2015 and 2016 on-site demonstration-scale CWTS performance indicate that the CWTS is maturing as expected and maturation continued to be monitored in 2016. This document reports on the on-site demonstration scale CWTS data from construction, and through two years of commissioning-A (2015/2016) and into the commissioning-B period (late 2016).

Table 1 – Days of operation of CWTS.

Scale	Year	Days Operated	Date	
			Start	End
Pilot (off-site)[1]	**2013 -2014**	205	Nov 4	May 28
Demonstration (on-site) Commissioning-A	**2014[2]**	23	Aug 27	Sep 19
	2015	137	May 16	Sep 29
	2016	101	May 2	Jul 28
Demonstration (on-site) Commissioning-B	**2016**	51	Jul 29	Sep 30

[1] Pilot-scale system operated from Nov 4, 2013 to July 16, 2014.

[2] The system was constructed in 2014, but no water testing occurred during this first month of commissioning-A.

2. Construction and operation

2.1. System layout and dimensions

The demonstration-scale CWTS includes 2 systems in parallel with 2 cells in each series and a final catchment basin that both systems flow into (Figure 1). Dimensions and construction details are available in the Minto Demonstration Scale Report Document 011_0315_01A (Contango, March 2015). The two parallel systems serve as a replicate for data analysis, and as testing has progressed, the two systems have also allowed for comparison of different management techniques. Dimensions of the systems are provided here in Table 2.

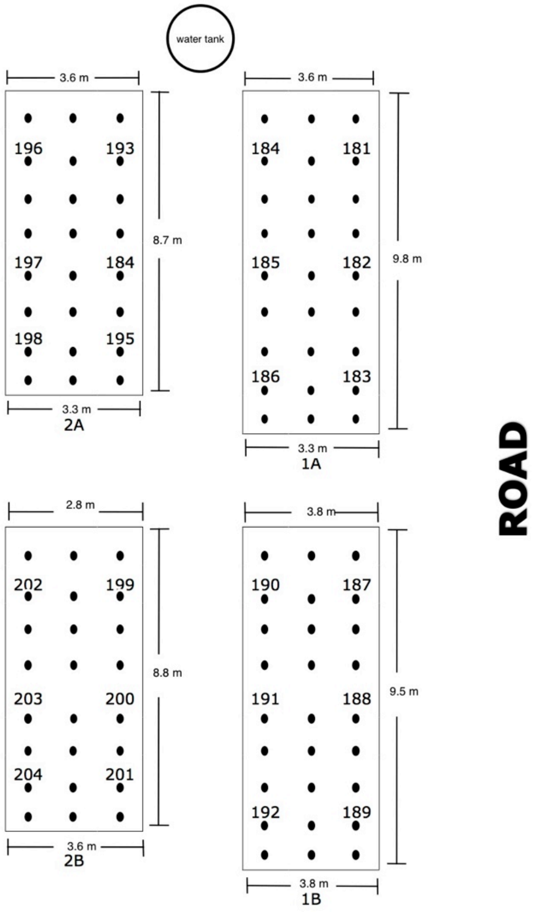


Figure 1 – Diagram of demonstration-scale CWTS.
Dimension measurements are indicated at soil surface. Black dots indicate initial construction grid marked by moss stakes, and locations of soil redox probes with identifying numbers.

Table 2 – Dimensions of demonstration-scale CWTS cells at soil surface and resultant areas of treatment systems.

Measurement		Series 1		Series 2	
		1A	1B	2A	2B
Width (m)	Inflow	3.6	3.8	3.6	2.8
	Outflow	3.3	3.8	3.3	3.6
Length (m)		9.8	9.5	8.7	8.8
Approximate surface area at soil (m^2)		33.8	36.1	30.0	28.2
Total area of system at soil (m^2)		69.9		58.2	

2.2. Substrate soils used in construction

Soils used to construct the CWTS are described in the initial report that outlines construction (Contango, March 2015). In brief, the recommended soil for the CWTS was sand, with 2-7% by volume as organic material (e.g., woodchips, peat). In the pilot-scale systems, this resulted in a total organic carbon (TOC) content by weight of 0.2-0.6% (the sand itself was at 0.1% TOC prior to adding amendment). Ideally, this percentage could be higher, approximately 2-10% by weight to stimulate the desired reducing conditions. For the demonstration-scale system, the soil added to each of the 4 cells during construction was from a local borrow site. As is expected in a mining area, the soils are likely mineralized. Although a potential borrow source was tested prior to construction ("Tested Soil"; Table 3), a different borrow source was available upon construction of the demonstration-scale wetland ("Soil used"; Table 3). The material used in the construction of the demonstration-scale wetland was an organic peat, and analyses received after construction indicated an elevated concentration of leachable copper (Table 3). It should be noted that in a full-scale system, the variability in soil substrate would be normalized by the larger volume of soil used. The substrate in the wetland (composed of the organic peat soil, wood chips, and straw) had a TOC content of 1.8-3.1%. The implications of this are discussed in section 6.1 of this report.

Table 3 – Comparison of copper concentrations in soils of pilot- and demonstration-scale CWTS.

Test method	Pilot-scale	Demonstration-scale	
	Initial soil	Tested soil (June, 2014)	Soil used (August, 2014)
SPLP Copper (mg/L)[1]	-	0.00546-0.0296[2]	0.148-0.608
Total Copper (mg/kg)	5.3-5.5	210-1400[2]	960-1400[3]

[1] SPLP - Synthetic Precipitation Leaching Procedure

[2] For the June 2014 samples, the soil with the highest total copper concentration also had the lowest leachable copper concentration, and was therefore deemed acceptable for use.

[3] Total copper value for soils used was taken in June 2015 (no data for August 2014).

2.3. Vegetation used in planting

The demonstration-scale CWTS was planted with *Carex aquatilis* (aquatic sedge) and aquatic mosses from the W10 area of the Minto Site. The plant selection and borrow source was previously determined through the site assessment (reports 2013-0100-256 and 2013-0100-257 on the YESAB registry) and pilot-scale testing (Contango, November 2014). Five *C. aquatilis* plants were planted per square meter, with moss tied to stakes that outlined the 1 m x 1 m grid for planting (details provided in Contango, March 2015).

2.4. Water source and flow

Water from the W36 area receiving seepage from the toe of the Mill Valley Fill Extension (MVFE) was selected for the demonstration-scale CWTS testing as the leachate is similar to that expected upon closure in the MVFE area. The chemistry of this water at the time of bringing the demonstration-scale CWTS online (September 18, 2014) is provided in Contango, March 2015. In 2015 the water for the CWTS was pumped out of the sump at the toe of the MVFE. The Mill Valley Fill Extension Stage 2 (MVFE2) collection sump (W62 sump) was constructed from November 9, 2015 to February 7, 2016. The sump was constructed as a replacement for the sump used in 2015. The W36 sump was decommissioned in February, 2016 as part of the MVFE2 construction. The new sump approximately 30m downslope was the supply water for the CWTS for the summer of 2016 (Figure 2).

Figure 2 – Water source for the demonstration-scale CWTS in 2016.

After construction in 2014 and in early 2015, the flow rates for the systems were planned to be set to have a 10 day nominal hydraulic retention time (HRT), meaning water entering the wetland takes 10 days to exit. This is referred to as a nominal HRT because it is a calculation based on the size of the wetland and the amount of water entering, and not confirmed empirically using tracing dyes. This HRT is much longer than what is necessary to achieve treatment based on the pilot-scale systems (~3 days), and was chosen to facilitate plant establishment and maturation. However, due to the leachable copper concentrations in the soils used for construction, it was instead decided to run the systems at a faster flow to wash as much leachable copper from the soils as possible. As such, a shorter nominal HRT of ~20 hrs (Figure 3) was used as a starting point (HRT calculated using measured water depths of approximately 15 cm and negligible pore water involvement [30cm of soil at 10% pore volume] due to peat soils). Despite the shorter HRT resulting from the faster flow of water, the systems have acclimated and matured as was expected for the longer HRT. Because the sizes of the CWTS systems are slightly different, Series 1 (closer to the road) and Series 2 (further from road) are set with flow rates to result in similar HRTs in each system. Flow rates were monitored and adjusted throughout 2015 based on CWTS establishment and maturation (further information in sections 3 and 4).

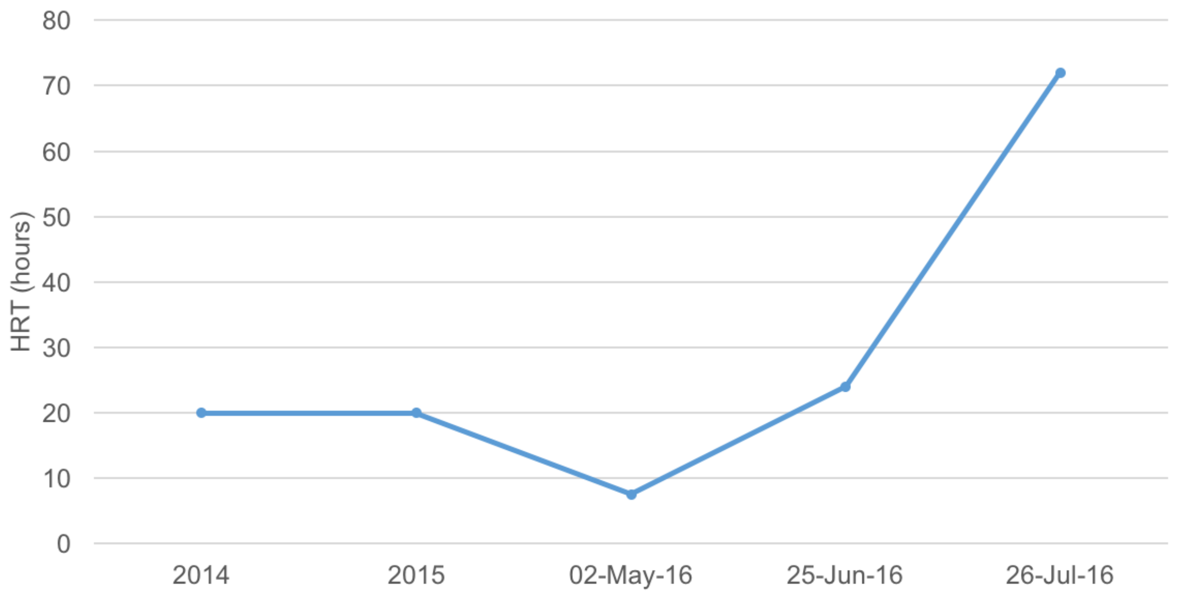


Figure 3 – Demonstration-scale CWTS targeted hydraulic retention time from construction to present.

Three flow rates were used during operation of the CWTS in 2016. At start up in May 2016 the nominal HRT was set to ~7.5 hours to further attempt to flush copper out of the soil (further enhancing the 2015 EDTA trials conducted in System 2 (section 6.3)). In early June, HRT was increased to ~24 hours to allow for a tracer study to be conducted during a 2-day site visit in attempt to determine the actual HRT (vs nominal, calculated HRT) of the CWTS (section 7). At the end of June, the HRT was lengthened to a calculated ~72 hours (3 days) for performance testing and remained at this HRT until the end of operations in September 2016. Due to pump and flow meter issues the actual flow rates varied from the target flow rates throughout 2016 operations. Table 5 outlines known pump and flow meter issues that occurred in 2016, and Figure 4 shows the fluctuation in actual vs targeted flow rates throughout the 2016 operations.

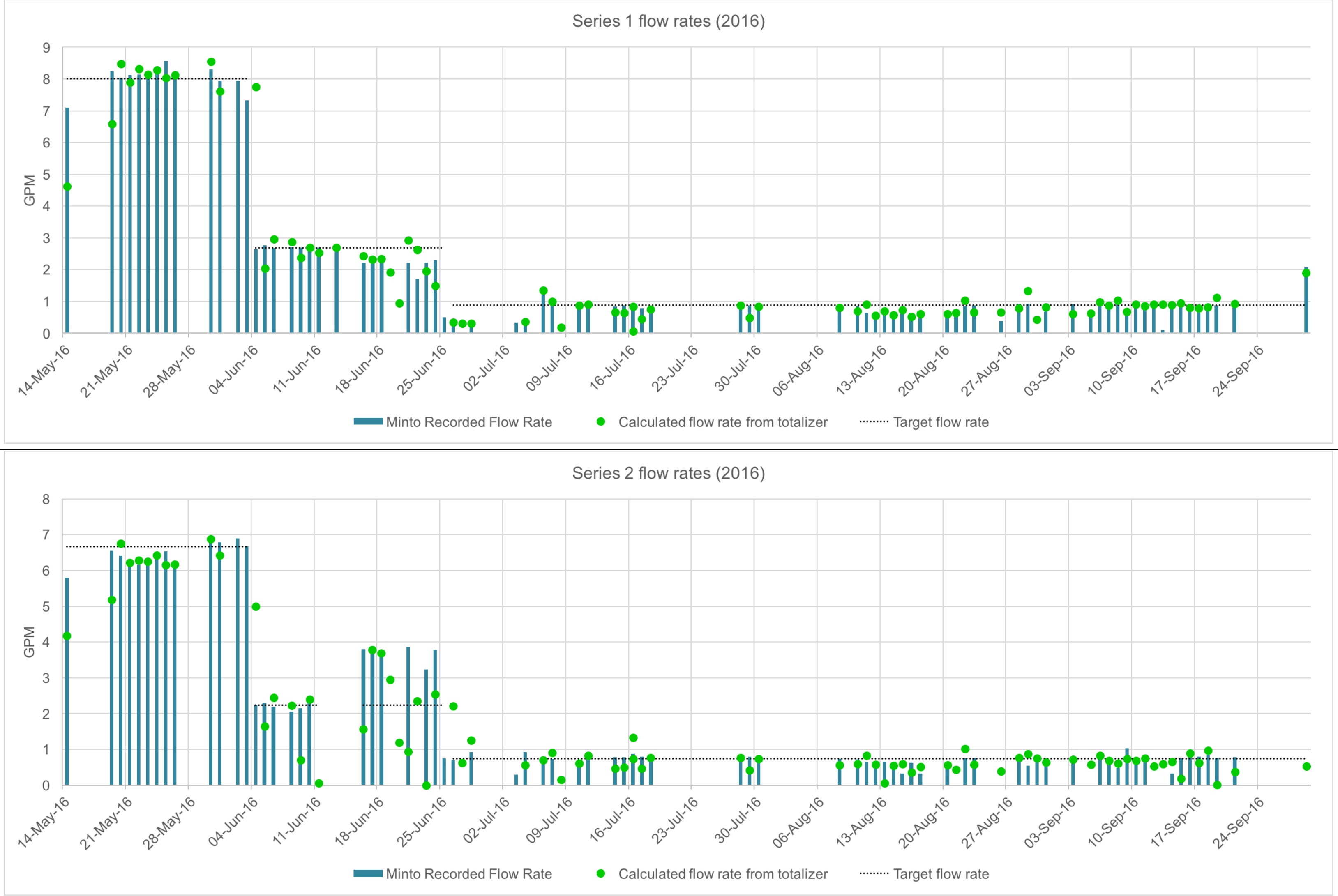


Figure 4 – Flow rates during CWTS operations in 2016.
Blue bars indicate flow rates displayed on meter, while green dots are flow rates calculated from the totalizer values (values from meter were recorded by Minto personnel. The totalizer value is the cumulative volume of water passing through the flow meter between two measurement dates. Areas with no blue bars or green dots are time periods where flow rates and totalizer values were not recorded.

3. Commissioning

The period between the construction of the CWTS and achieving the expected treatment performance is referred to as the commissioning period. During this period, the plant and microbial populations establish and mature, and construction effectiveness and optimization opportunities are evaluated to make operational adjustments (e.g., raising water depth, modifying outflow patterns) and inform on the full-scale system (Table 4). For the demonstration-scale CWTS the commissioning period was divided into two periods, commissioning-A, and commissioning-B. The end of the commissioning-A period and the beginning of the commissioning-B period was marked by the addition of organics on July 28, 2016.

Performance continues to be monitored and while full treatment functionality of the demonstration-scale system is not expected during the commissioning period, the information will aid in the development of the full-scale system in the following ways:

- Evaluation of construction effectiveness and potential optimizations.
- Assessment of timelines to reach targeted operational parameters to allow for effective phasing of implementation (e.g., soil redox, percentage and abundance of sulphate reducing bacteria).
- Assessment of the effectiveness of *Carex aquatilis* and aquatic moss transplantation to assess planting density, time period to full density, and if plant propagation and/or a replanting schedule is necessary.

However, there are aspects of the demonstration-scale CWTS that are not directly transferrable to the planned construction of the full-scale CWTS. Notably, the demonstration-scale CWTS was built with a different soil type and chemistry than recommended for the full-scale system. Therefore; it is taking a longer time to commission the demonstration-scale system as the copper in the soils needs to be treated in addition to the copper and other constituents in the water.

Based on pilot-scale testing (Contango, November 2014), the estimated commissioning period for the Minto demonstration-scale CWTS was 4 months of operation (i.e., period when water is flowing). In 2014, the demonstration-scale CWTS operated for less than one month prior to freezing, and was restarted along with spring thaw (freshet) in mid-May 2015. Based on these timelines, September 2015 was month 4 of commissioning, and the demonstration-scale system was trending towards performance as expected during the commissioning period (Contango, March 2016). However, as discussed further in sections 2.2 and 6.1, the soil used in the CWTS had high concentrations of leachable copper, and therefore optimization opportunities were evaluated throughout 2015, and adjustments were implemented in 2015 and 2016. The last operational adjustment during the commissioning period was the addition of organic material in 2016, which marked the end of the commissioning-A period and the beginning of the commissioning-B period. Organic material will also be added during construction of the full-scale design to enhance desired reducing conditions to establish in the CWTS until vegetation is sufficient to provide for this required component.

Table 4 – Operational adjustments made to the demonstration-scale wetland.

Year	Activity	Purpose
2014	Construction	Construction
2015	Increasing water depth	Plant acclimation and establishment
	Adding more aquatic moss	Increase moss density
	Modifying inflow and outflow distribution areas	Promote uniform flow field
	Removing *Carex utriculata*	Was erroneously planted
	Wrapping inflow tank	Prevent algal growth
	Fe-EDTA test on CWTS series 2	To test if non-invasive treatments could be used to further leach the metals and improve soil quality
2016	Adding sandbags to the perimeter of the CWTS	Promote uniform flow field and prevent short circuiting of water around perimeter
	Perform tracer study	Determine the actual hydraulic retention time (HRT) of the CWTS
	Increase water depth of Series 1	Bring to desired specification depth
	Evapotranspiration study	Determine the amount of water loss occurring (and therefore concentration of elements)
	Setting flow rates at a 3 day calculated HRT (compared to 20 hrs previously used)	Continue commissioning period and develop rate kinetics
	Adding organics (woodchips and straw)[1]	Enhance desired reducing conditions (will be added to full-scale design specifications)

[1] This marked the end of the commissioning-A period and the beginning of the commissioning-B period.

4. Timeline and sampling schedule

Major events and operational adjustments are listed in Table 5. The actual dates as well as relative days of operation are provided, which adjusts for time that the CWTS was not receiving water when it was frozen. The relative days of operation allows for comparison to expected timelines from the pilot-scale testing, and for planning and scheduling to be done for full-scale construction and commissioning in the context of mine closure planning.

The sampling schedules for 2015 and 2016 were conceptually developed prior to beginning construction of the demonstration-scale CWTS (Appendix A). Actual dates of sampling were dependent on timing of spring thaw and winter freeze-up, and the associated ability to have the pumps operating at the W62 sump to supply water to the demonstration-scale CWTS.

Table 5 – Events and sampling activities since construction.

Event	Key Activity	Flow Rate Setting m^3/day (gal/min)		Calendar Date	Day(s) of Operation
		CWTS Series 1	CWTS Series 2		
CWTS constructed and planted	First sampling, water started.	-	-	August 27 – 31, 2014	0-4
Freeze up for winter	Feed water pumps turned off.	-	-	September 19, 2014	23
Winter 2014/2015					
Start up for 2015	Feed water pumps turned on.	14.17 (2.60)	11.61 (2.13)	May 16, 2015	24
Contango Site Visit #1	Microbiology, soils, water tested. *Carex* stem counts. Added more aquatic moss. Put black wrap on water tank to prevent algal growth. Water depth adjusted with sandbags.			June 18, 2015	57
Flow rate increased	Flow rates increased.	17.44 (3.20)	15.81 (2.90)	July 13, 2015	82
Contango Site Visit #2	Microbiology, soils, water tested. Added more aquatic moss.			August 16, 2015	116
Contango Site Visit #3	Water tested. Started Fe-EDTA test on System 2.			September 17, 2015	148
	Microbiology, soils, plants, water tested.			September 18, 2015	149
Fe-EDTA Testing	Daily total and dissolved copper analysis conducted at Minto.			September 19 – 26, 2015	150-157
Freeze up for Winter	Feed water pumps turned off.	-	-	September 29, 2015	160
Winter 2015/2016					
Flow meters installed and pumps turned on	Flush copper leaching from soil (associated with 2015 EDTA test).	44.10 (8.09)	38.10 (6.99)	May 2, 2016	161
Start up for 2016	Feed water pumps turned on.			May 13, 2016	172
Pump problems	Getting proper pumps installed at new sump location.			May 13-17, 2016	172-176
Flow rate decreased	HRT increased to 24 hours.	14.39 (2.68)	12.26 (2.24)	June 4, 2016	194
Added sandbags	Added sandbags to perimeter of CWTS.			June 7, 2016	197
Contango Site Visit #4	Microbiology, soils, water tested.			June 13 – 15, 2016	203-205
	Tracer test for HRT.			June 13 – 17, 2016	203 - 207

Table 5 – Continued.

Event	Key Activity	Flow Rate Setting m^3/day (gal/min)		Calendar Date	Day(s) of Operation
		CWTS Series 1	CWTS Series 1		
Inconsistent flow	Flow rates in series 2 inconsistent and above targeted flow rate.	14.39 (2.68)	20.71 (3.80)	June 16 - 24, 2016	206-214
Flow rate decreased	HRT increased to 72 hours.	2.73 (0.89)	4.09 (0.75)	June 25, 2016	215
Flow meter switched on series 1	Max flow on new flow meter is lower than targeted flow rate due to flow meter being installed backwards.	Unknown		June 25 – July 4, 2016	215-224
Flow meter for series 1 was on backwards resulting in unknown flow rates	Installed the flow meter correctly and reset flow rate to meet targeted HRT range of 72 hrs.	(0.89)		July 4, 2016	224
Evaporation Study	Flow stopped.	-	-	July 18 – 26, 2016	238-246
End of evaporation study	Flow turned back on.	2.73 (0.89)	4.09 (0.75)	July 26, 2016	246
Contango Site Visit #5	Microbiology and water tested.			July 27 - 28, 2016	247-248
	Added organic material (straw and woodchips)			July 28, 2016	248
Flow interruptions	Flow meters plugged.			August 15 –18 2016	266-268
Contango Site Visit #6	Microbiology, soils, water, and plants tested.			September 7 – 8, 2016	289-290
Freeze up for Winter	Feed water pumps turned off.	-	-	September 30, 2016	312

5. Monitoring explanatory parameters

Explanatory parameters are quantifiable aspects of a CWTS environment that can be used to assess feasibility of treatment for a range of constituents, and therefore 'explain' the performance of a CWTS. These parameters, which often include acidity, alkalinity, conductivity, dissolved oxygen (DO), pH, oxidation reduction potential (ORP), ion balance, available electrons donors (e.g., organic carbon, reduced elements), and temperature, can be used to predict, promote, and/or optimize the ability of the system to treat different constituents (Haakensen et al., 2015). A YSI ProPlus meter was used in the field to test for water temperature, DO, conductivity (and specific conductivity; SPC), pH, and ORP.

Average water temperature of the demonstration-scale CWTS in 2015 was 12.9°C, ranging from 0.5°C to 25°C, and in 2016 was 10.2°C, ranging from 0.8°C to 23.2°C. As would be expected, both the month of testing and time of day were found to affect temperature variation (section 7). DO concentrations in the CWTS cells were on average 10 mg/L in 2015, 15.9 mg/L in 2016 prior to commissioning being complete, and 8.4 mg/L in 2016 after commissioning was complete, which is higher than the pilot-scale systems (average 4.8 mg/L). This higher DO concentration makes the system more oxidizing and therefore more difficult to carry out nitrate and selenium treatment, and produce sulphides for copper and cadmium treatment. However, the conductivity, pH and ORP of the demonstration-scale CWTS cells are all very similar to the pilot-scale systems (Table 6).

Table 6 – Average in situ measurements from the pilot scale and demonstration-scale system.

Testing Period		DO (mg/L)	SPC (µS/cm)	pH	ORP (mV)	Soil redox (mV)
Pilot 2014[1]		5.73	990.0	7.71	159	-185
Demonstration-scale 2015		10	817.9	8.11	147.9	-52
Demonstration-scale 2016	commissioning-A[2]	15.9	890.9	7.79	143.7	-85
	commissioning-B[3]	8.4	1020	7.59	157.6	-89

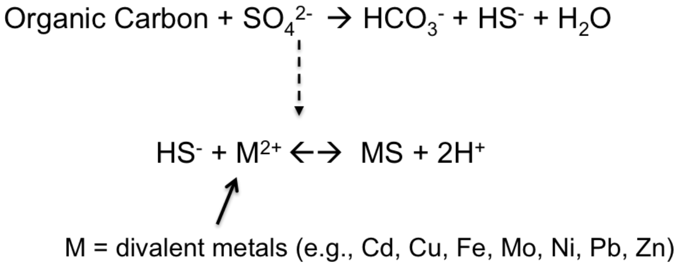
[1] Pilot system data is from the low N system with moss and *Carex*. This was the system that was used as the foundational design.

[2] Data for commissioning-A period is from May 2-July 28, 2016.

[3] Data for commissioning-B period is from July 29-September 30, 2016.

An additional explanatory parameter that can be used to monitor maturation of the wetland during the commissioning period is the soil redox potential, which is measured using platinum tip probes (in soil) and Calomel electrodes (in water). This measurement offers insight into the direction of electron flux between the sediment/soil/pore water and overlying water column (Faulkner et al., 1989; Huddleston & Rodgers, 2008), and can be used to confirm reducing conditions in the soil. Based on the information gathered in pilot-scale testing, the targeted soil redox for the demonstration-scale CWTS is between -100 and -250 mV. In these redox ranges, bacterial sulphide-production through reduction of sulphur compounds (e.g., sulphate) is expected. Sulphide production directly results in metals and metalloid treatment for elements such as cadmium, copper, molybdenum, nickel, lead, and zinc by precipitation as metal sulphides (Figure 5).

This maturation period is necessary for sufficient quantities of microbes to populate the wetland and become active in decomposing organic material. It is the electrons produced by the decomposition of organic material that is reported by the soil redox measurements. The decomposition of organic material then feeds the sulphate-reducing bacteria the type of energy they need to produce the sulphides that remove the copper, cadmium, molybdenum, and zinc from the water. The microbial activity of the system is discussed further in Section 10.3.



$$\text{Organic Carbon} + SO_4^{2-} \rightarrow HCO_3^{-} + HS^{-} + H_2O$$

$$HS^{-} + M^{2+} \leftrightarrow MS + 2H^{+}$$

Figure 5 – Example equation of sulphate reduction and resultant metals mineralization and treatment.

Equation is not balanced; demonstrates sulphate reduction with creation of alkalinity and sulphides, which can then form metal sulphide complexes.

As expected from the pilot-scale testing, the soil redox in all the demonstration-scale CWTS cells has decreased over time, indicating maturation of the system (Figure 6). At the end of 2015, only Series 1 had begun to achieve targeted soil redox values that are conducive to sulphide production (ahead of anticipated schedule). It is possible that Series 1 had more organic material in the soils than Series 2, because of how construction occurred and this wasn’t reflected in the small sample size sent for analytical testing.

Some soil redox probes were reporting negative values in the targeted range by July 18, 2015 (87 days); however, in general the CWTS took approximately 4 months of operation to establish generally reducing conditions. By September 17, 2015 (day 148), most of the soil redox probes within Series 1 were reporting redox values within the targeted range, with Series 2 still trending downwards but not yet within the targeted range. In comparison, the pilot-scale systems were stable and reducing within approximately 4 months of construction (Figure 6). In early 2016, the soil redox in both series was not being maintained within the targeted range, which indicated that additional organics may be needed in the CWTS to enhance maturation.

5.1.Addition of organics

Since the demonstration-scale system was not achieving stable redox values (nor associated performance expectations) within the targeted range, woodchips and straw were added to the demonstration-scale CWTS on July 28, 2016. Because the demonstration-scale system takes time for plants to mature (and generate organic carbon for the microbes to feed on), the addition of organics early in the operation of the system can supplement the carbon sources needed for sulphate-reducing bacteria, and produce the desired sulphur- and selenium-reducing conditions (section 10.3). This will be included in the full-scale system design specifications.

One compressed 20-liter pail of woodchips was spread across the surface of each of the four CWTS cells (Figure 7). The A cells also each received one 0.16 m^3 bale of straw while the B cells received half of a straw bale of the same size. In the A cells, the straw was added along the inflow, outflow and along the sides of the cell in between the sand bags. In the B cells, straw was added at the inflow before and after the sand bags, and along the sides in between the sand bags (Figure 7).

By September 8, 2016 (final redox readings of 2016) redox values for cell 2B were consistently within the targeted range, and the redox values for series 1 were achieving targeted ranges 50% of the time (3 of the 6 in situ probes were reading within the targeted range). It is anticipated that the addition of organics will continue to provide the necessary carbon source to stimulate desired reducing conditions in 2017.

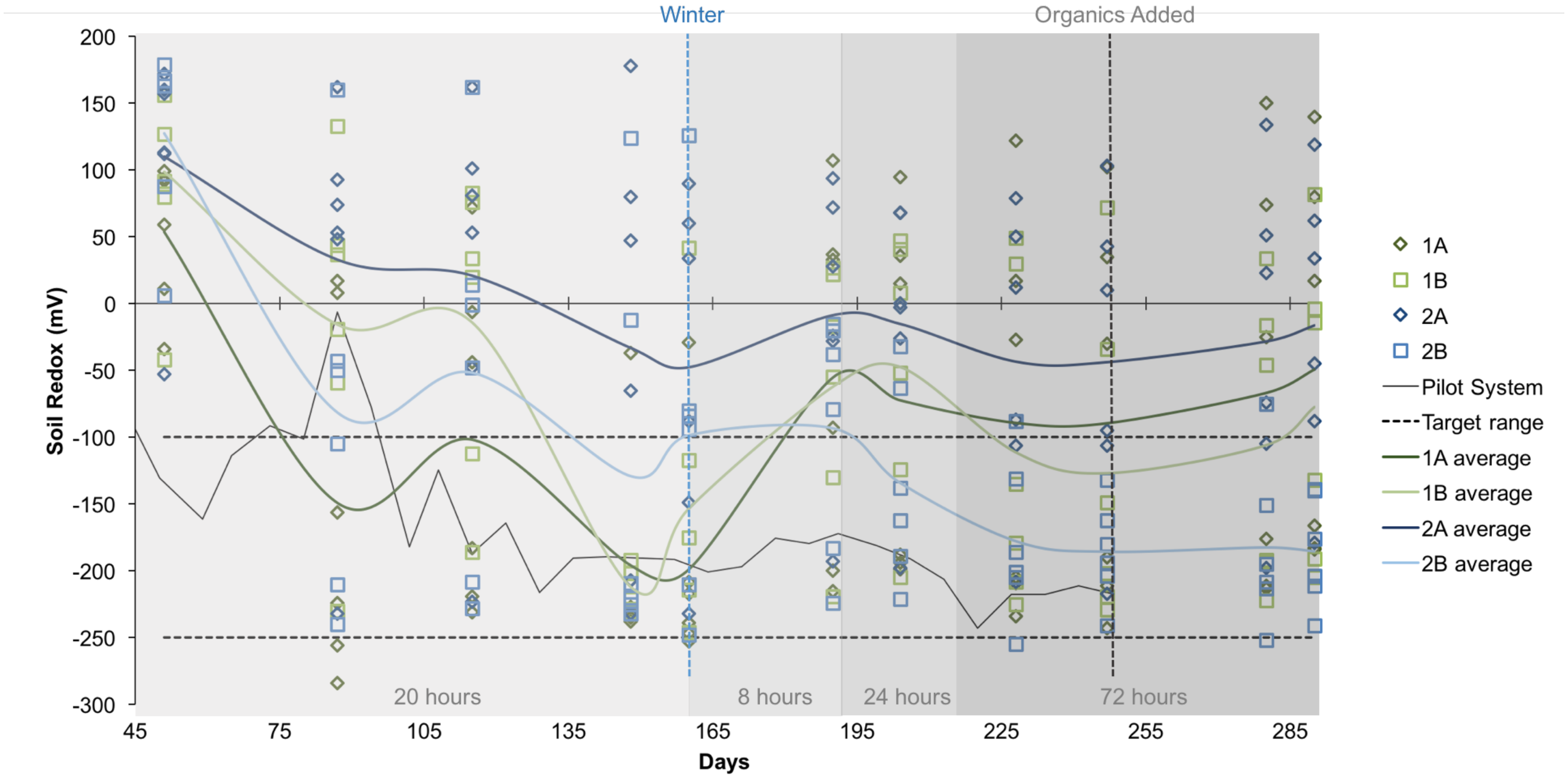


Figure 6 – Soil redox potential of each CWTS cell over time.
All demonstration-scale CWTS soil redox measurements are plotted, along with the average soil redox of the pilot-scale systems. Targeted soil redox values based on pilot-scale testing are indicated with dotted lines. The blue dotted line indicates break in measurements for winter 2015. Hours and associated grey shading indicate the HRT.

Figure 7 – Addition of organics on July 28, 2016.
Top picture shows cell 1A with woodchips that were added (floating on water surface). Bottom picture shows cell 2A with straw that was added after woodchips.

6. Performance progress during commissioning period and early operation

6.1. Soils

6.1.1. Methods

Although unintentional, the use of soils in the CWTS with high initial leachable copper concentrations (Table 3) allowed for additional types of testing to be carried out on these systems. Because the soil substrates used for construction of the CWTS were from overburden sources, the copper was not in a mineral form that would typically be found in a reducing CWTS (i.e., negative relative soil redox). Therefore, there has been some initial leaching of copper (and other elements, such as aluminum) from the soils into the water (Table 8, Figure 10, and Figure 12).

To assess the effect of the elevated metals (aluminum and copper) in the soils used in construction on CWTS functionality, four soil analytical test methods were used:

- Total concentration of elements in the soils by ICP,
- In 2015, leachable concentrations of elements in the soils by Synthetic Precipitation Leaching Procedure (SPLP), which is a method to assess the mobility of elements in soils at the pH of rain water (i.e., if the wetland were to entirely dry out, then be subjected to leaching by rain water) (EPA Method 1312/6010B)
- In 2016 a leach method was used. This analysis was carried out using a leaching procedure which involved the gentle tumbling of a sample in a specified leaching solution (water from the CWTS) for 2 hours. The resulting extract is then analyzed by inductively coupled plasma – optical emission spectrophotometry (EPA method 6010A). This method was selected in 2016 to determine the concentration of metals that are being released from the soil into the overlying water column.
- Sequential extraction procedure for the speciation of particulate trace metals (Tessier *et al*, 1979, EPA 6020A) to assess the stability and form of elements in soils (Table 7).

Table 7 – Summary of extractable fractions from sequential extraction procedure for the speciation of particulate trace metals[1].

Fraction	Description	Elements unstable when
1	Exchangeable fraction for adsorbed minerals	Readily released (i.e., soluble and exchangeable)
2	Mineral fraction bound to carbonates	Decreased pH
3	Mineral fraction bound to Fe-Mn oxides	Reducing conditions
4	Mineral fraction bound to organic matter and sulphides	Oxidizing conditions
5	Residual mineral fraction (primary and secondary minerals)	Not expected to be released in solution over time under conditions normally encountered in nature

[1] Method based on Tessier *et al.,* 1979.

6.1.2. Soil Aging

While the total copper concentrations have increased over time (with the addition of mineralized copper from the water), the leachable copper (measured by SPLP) in 2015 decreased over time. By day 58 of operation, the top 5 cm of soil was decreased to only 10-20% of the initial leachable copper concentration, and the lower 10-20 cm layers reached similar concentrations by day 149 (Table 8). In 2016 a new leach method was used to determine the concentration of metals that are being released from the soil into the overlying water column, rather than using the SPLP method which assumes leaching at rain water pH. The main difference between these methods is that the SPLP method uses laboratory water at the pH of rain water, while the new leach method uses a sample of the overlaying water in the CWTS. Therefore, the leach method is more representative of actual potential leachability of the soils into the wetland than is the SPLP method. In 2016 there was an overall decrease in leachable aluminum and copper from a depth of 0-10 cm (Table 8 and Appendix D). The B cells experienced a significant decrease of leachable copper of approximately 80% between June 15 and September 7, 2016. Cell 1A decreased 53%, and cell 2A had very little change in leachable copper. Cells 1A, 2A, and 2B experienced a similar decrease of leachable aluminum between 70% and 77%. Cell 1B experienced a decrease of leachable aluminum of 54%.

In 2016 there was an overall increase in leachable copper from a depth of 10-20 cm: cell 1A increased by 25%, cell 1B increased by 32%, cell 2A increased by 46%, and cell 2B increased by 7% (Table 8). In 2016 there was a decrease in leachable aluminum from 28% to 58% at a depth of 10-20 cm in cell 1A, 1B, and 2A. Cell 2B increased in leachable aluminum by 49% (appendix D).

Analysis of the soils by ICP-MS with sequentially extracted acid analysis shows that despite elevated initial leachable copper concentrations, the soils have become more stable (less leachable) over time in the wetland setting as the soils have aged (Figure 8). This beneficial aging of soils to a less soluble mineralized form of sulphide is expected for this type of treatment wetland design. It should be noted that due to the starting soil substrate containing leachable copper and other metals such as aluminum (Appendix B) that these elements are leaching from the substrate into the water, putting additional treatment demands on the systems.

The evapotranspiration study also confirmed that due to copper, metals, and metalloids in the initial substrates placed in the soils, constituents continue to leach from the substrate as these constituents shift from oxidized fractions 2 and 3 to reduced fraction 4 (Appendix B). Copper concentrations in the CWTS increased on average from 58 µg/L in in 2016 prior to evaporation study, to an average 80 µg/L during the evapotranspiration study. Additionally, aluminum concentrations in the CWTS in 2016 increased on average from 10.9 µg/L prior to evaporation study, to an average 32 µg/L during the evapotranspiration study. Molybdenum, selenium, and zinc all decreased in concentrations during the evapotranspiration study compared to the average concentration prior to the study in 2016. Molybdenum decreased from ~7.5 µg/L to ~6.0 µg/L, selenium decreased from ~3.3 µg/L to ~1.3 µg/L, and zinc decreased from ~52 µg/L to ~28 µg/L. Cadmium concentrations were so low that there was not a notable change in concentration during the evaporation study.

It is noted that the increase in copper concentration during the evapotranspiration trial is not representative of what would occur during periods with no flow in a full-scale system, where soils with minimal leachable copper are used and copper is deposited in sulphide form (fraction 4) by the biogeochemical activity of the CWTS. Rather, enhanced removal of constituents such as copper and selenium is expected during these periods as the system becomes more reducing with no flow. In the case of the demonstration-scale wetland, due to the elements switching from oxidized to reduced forms in the soils, the increased concentration of some constituents is seen despite a substantial decrease of sulphate. That is, there are more metals switching from oxidized to reduced forms, than sulphides being produced during this time based on available organic carbon to produce the sulphides (sulphate decreased from ~134 mg/L to ~104 mg/L). This was one of the pieces of data that prompted the addition of carbon sources to the wetland to initiate commissioning-B and address these remaining oxidized metals in the CWTS. If metals continue to leach in 2017, flows could be stopped temporarily to promote this shift from oxidized to reduced forms, with the additional carbon sources of straw and wood chips now available for the bacteria to use to produce more sulphides for metals treatment.

For the CWTS to treat the copper from the soils, additional organic carbon is needed beyond that necessary for the waters alone. Organic carbon is contributed to the CWTS through decomposition of plant material as the wetland matures. However, in 2015 the CWTS did not host enough plants that would decompose and contribute organic carbon in 2016 to the wetland, as plants were still establishing. Therefore, in 2016 additional carbon was added to the wetland in the form of woodchips and straw (Section 5.1). Organic carbon is used as food by the microbes, which in turn produce sulphides which drive metals treatment through mineralization by coupled biogeochemical processes. Presently, as there are excess copper forms transitioning from oxidized to reduced in the soils, these will bind to the sulphides, transforming them to the sulphide bound fraction 4 (Table 7). This in turn impacts the ability to treat water, as it uses the available electrons and results in insufficient sulphides to treat metals in the water. When the mineral fractions of the soils have completed transforming the oxidized copper in the soils to a sulphide bound fraction 4 mineral, the soils will no longer be sulphide hungry, allowing for the soil-produced sulphides to be utilized for metals treatment in the water. This progress can be followed by the Tessier extractions, and also by the appearance of acid volatile sulphides (AVS) in the soils. AVS was tested for in 2016 prior to adding the straw and wood chips and was non-detectable (hence, the decision to add the straw and wood chips). The appearance of measurable AVS over time will indicate that the microbes in the soil have worked through the additional copper and the wetland should start performing the way it should have had soils with high leachable copper not been used. In 2017 an AVS soil test should be conducted to determine if the soils have completed the transition to fraction 4.

It is recommended that for construction of the full-scale systems, soils with low total and leachable copper concentrations should be used. Additionally, to supplement carbon until the vegetation has fully established, solid phase organic carbon (e.g., straw, woodchips) should be mixed into the soils. After plants have begun to grow, but are not yet fully mature and able to provide enough annual carbon to the wetland through their growth, solid phase organic carbon can also be added into the wetland in the same way as was done in the demonstration-scale CWTS in 2017.

Table 8 – Total and leachable soil copper concentrations in first year of operations.

CWTS Cell	Sampling Date	Days in Operation	Sample Depth (cm)	Total Cu (mg/kg)	SPLP Cu (mg/L)	Leachable Cu (mg/kg)
1A	28-Aug-14	1	Initial Composite	-	0.298 (0.148-0.608)	-
	19-Jun-15	58	0-5	960	0.055[1]	-
	16-Aug-15	116	10-20	950	0.187	-
	18-Sep-15	149	10-20	1300	0.049	-
	29-Sep-15	160	10-20	910	0.069	-
	15-Jun-16	194	0-10	1440	-	0.953
	15-Jun-16	194	10-20	1210	-	0.66
	8-Jul-16	217	0-10	1430	-	0.603
	8-Jul-16	217	10-20	1730	-	0.832
	7-Sep-16	247	0-10	1290	-	0.449
1B	28-Aug-14	1	Initial Composite	-	0.298 (0.148-0.608)	-
	19-Jun-15	58	0-5	1400	0.033[1]	-
	16-Aug-15	116	10-20	1400	0.209	-
	18-Sep-15	149	10-20	830	0.065	-
	29-Sep-15	160	10-20	880	0.059	-
	15-Jun-16	194	0-10	1130	-	1.01
	15-Jun-16	194	10-20	1240	-	0.822
	8-Jul-16	217	0-10	1250	-	1.11
	8-Jul-16	217	10-20	1620	-	1.21
	7-Sep-16	247	0-10	1190	-	0.197
2A	28-Aug-14	1	Initial Composite	-	0.298 (0.148-0.608)	-
	19-Jun-15	58	0-5	1175	0.037[1]	-
	16-Aug-15	116	10-20	660	0.139	-
	18-Sep-15	149	10-20	880	0.081	-
	29-Sep-15	160	10-20	1000	0.073	-
	15-Jun-16	194	0-10	1100	-	0.823
	15-Jun-16	194	10-20	1280	-	0.900
	8-Jul-16	217	0-10	1450	-	0.963
	8-Jul-16	217	10-20	1150	-	1.68
	7-Sep-16	247	0-10	1290		0.838

Table 8 – Continued.

CWTS Cell	Sampling Date	Days in Operation	Sample Depth (cm)	Total Cu (mg/kg)	SPLP Cu (mg/L)	Leachable Cu (mg/kg)
2B	28-Aug-14	1	Initial Composite	-	0.298 (0.148-0.608)	-
	19-Jun-15	58	0-5	1100	0.039[1]	-
	16-Aug-15	116	10-20	1000	0.201	-
	18-Sep-15	149	10-20	830	0.078	-
	29-Sep-15	160	10-20	540	0.059	-
	15-Jun-16	194	0-10	1040	-	0.771
	15-Jun-16	194	10-20	1310	-	1.16
	8-Jul-16	217	0-10	1070	-	1.38
	8-Jul-16	217	10-20	1180	-	1.25
	7-Sep-16	247	0-10	1520	-	0.123

[1] Samples collected in June 2015 were at a shallow depth (0-5 cm) and copper content had therefore likely already been removed by washing from the faster flows of the CWTS system. The aging of the deeper (10-20 cm) soil copper concentrations over time to a less soluble form is shown in Figure 8.

The blue shading indicated samples that were taken from a shallower depth.

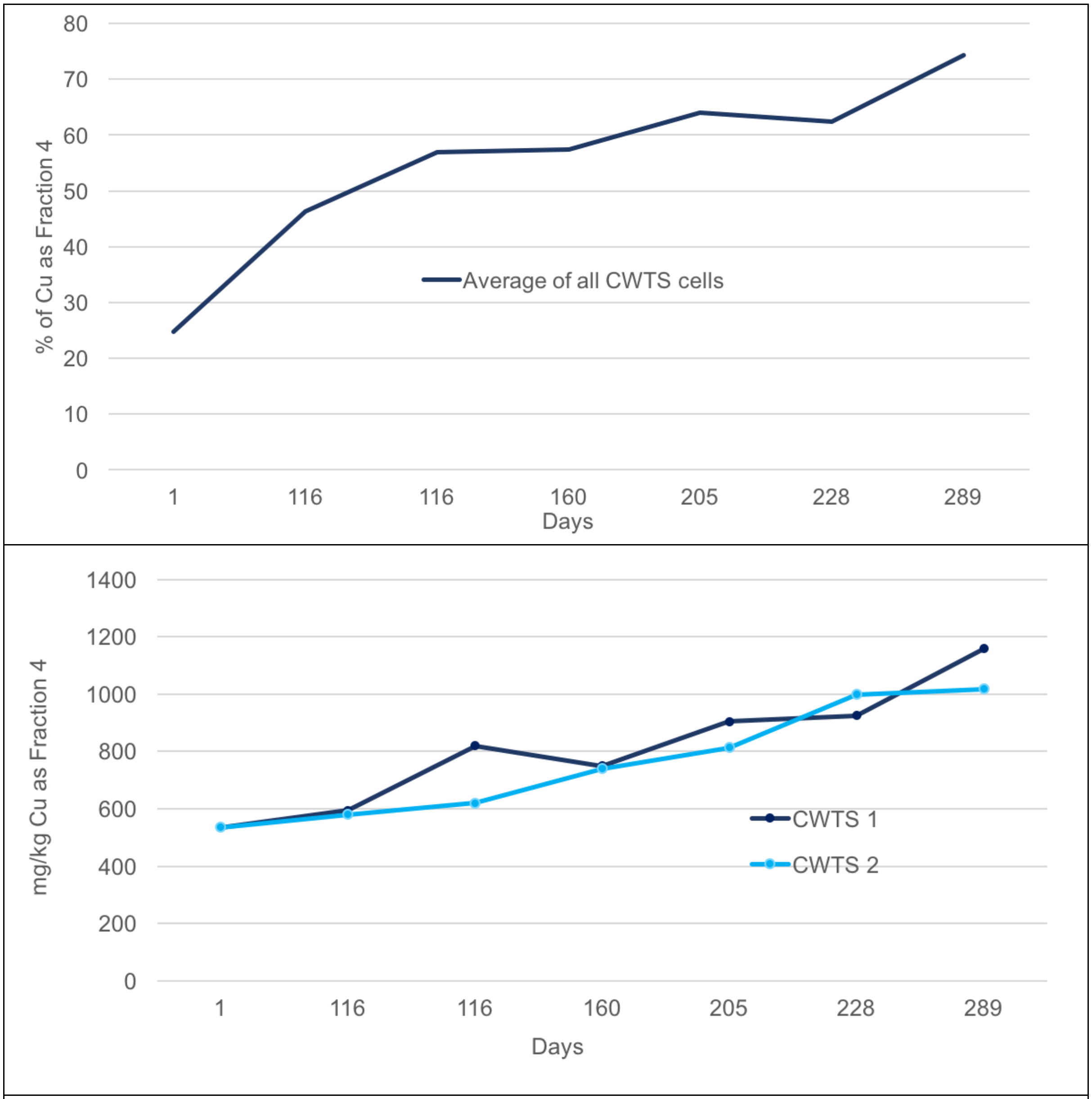


Figure 8 – Copper as sequential leach fraction 4 over time.
Copper in the form of the targeted Fraction 4 (sulphide mineral form and bound to organics), increased in the CWTS over time as the soils matured. Additional information in Appendix B.

6.2.Water

6.2.1. Pilot-scale testing performance

Pilot-scale testing was performed with water that mimicked the worst-case long-term post-closure water chemistry (mean influent concentrations of 146 µg/L copper and 10.2 µg/L selenium). In contrast, the on-site demonstration-scale system uses water from the sump downslope of the dry stack tailings facility and the MVFE (W36 or W62) and therefore has inflow concentrations that are currently occurring during operations (mean influent concentrations of 58 µg/L copper and 6 µg/L selenium). Because of this, a lower percent removal will achieve the same extent of removal and associated outflow concentrations than was required in the pilot-scale systems. For example, the pilot-scale system achieved on average 92% removal of copper (mean outflow of 11.3 µg/L) and 41% removal of selenium (mean outflow of 6 µg/L). To achieve these same outflow concentrations with the demonstration-scale system, 80% removal of copper and minimal (or no) removal of selenium would be needed.

6.2.2. Demonstration-scale metal leaching from soils

The treatment of copper has been improving through commissioning as the system has matured (Figure 16). However, as shown in Figure 10 and Figure 12 several elements are being released through the wetland by the soils, such as aluminum, and copper (as discussed in Section 6.1). Because of this, negative percent removals of copper have been observed, especially in early operations (Appendix B). It was initially theorized that this was occurring when the May and June 2015 data reported outflow concentrations higher than the influent. This paired with the soils data (Section 6.1 and Appendix A) led to the design of a new sampling scheme to determine whether detectable levels of metals were being released from the soils within the wetland (2015) and to monitor this (2016). For two timepoints in 2015 (August 15, 2015 and September 17, 2015) and 2 timepoints in 2016 (June 14, 2016 and September 7, 2016), water was sampled not only at the feed and the outflow of each cell, but also through the cell. Beginning at the outflow of cell B and working upwards towards the feed, samples were taken at the B cell outflow, B cell mid-point, and B cell inflow, and then the same 3 points for the A cell (Figure 9). In each case, the sample was taken from within a reaching distance of the side shore to ensure that sediments were not suspended in sampling.

Since the beginning of operations of the demonstration-scale CWTS, significant concentrations of copper have been leaching from the wetlands soils of all cells (Figure 12). Moreover, metal types and concentrations (e.g., Aluminum, Appendix B) that could not be accounted for by the influent water chemistry were elevated at random points within the wetland. This suggested that because of metals leaching from the soils, the treatment occurring within the wetlands was far greater than what was being observed by simply measuring the inflow and outflow points (Figure 16). For example, in August of 2015, influent copper concentrations were measured as 50 µg/L, but within the first meter of cell 1A increased to 100 µg/L, and by the outflow of cell 1A, down to 42 µg/L (58 µg/L decrease), they then increased to 70 µg/L at the beginning of cell B, and again were treated to a final outflow concentration of 40 µg/L (30 µg/L decrease) for a total of at least 88 µg/L removed by Series 1 of the treatment wetland. This suggested the wetland is achieving much greater copper treatment (88 µg/L removed), than would be suggested by only measuring the inflow and outflow of the system (suggests 10 µg/L removed). Similar leaching was observed through the wetland during testing in September 2015.

When the flow through the wetland was tested for metals leaching from soils in September 2016, influent copper concentrations were measured as 51 µg/L, but within the first meter of cell 1A increased to 74 µg/L, and by the midpoint of cell 1A they decreased to 36 µg/L and at the outflow of cell 1A, increased to 40 µg/L (i.e., a net 39 µg/L decrease, although only appearing as 14 µg/L compared to inflow). Copper concentrations were 34 µg/L at the beginning of cell B, and again were treated to a final outflow concentration of 28 µg/L (6 µg/L decrease) for a total of at least 45 µg/L removed by cells A and B of Series 1 of the treatment wetland. This suggests the wetland is achieving much greater copper treatment (45 µg/L removed), than would be suggested by only measuring the inflow and outflow of the system (suggests 23 µg/L removed). Copper continues to leach from the wetland soils, however the amount of leaching has decreased in 2016, with an 80% decrease in leachable copper from the soil in B cells, and 50% decrease in leachable copper in cell 1A, and cell 2A has become more stable with little change in leachable copper through 2016 (Figure 12).

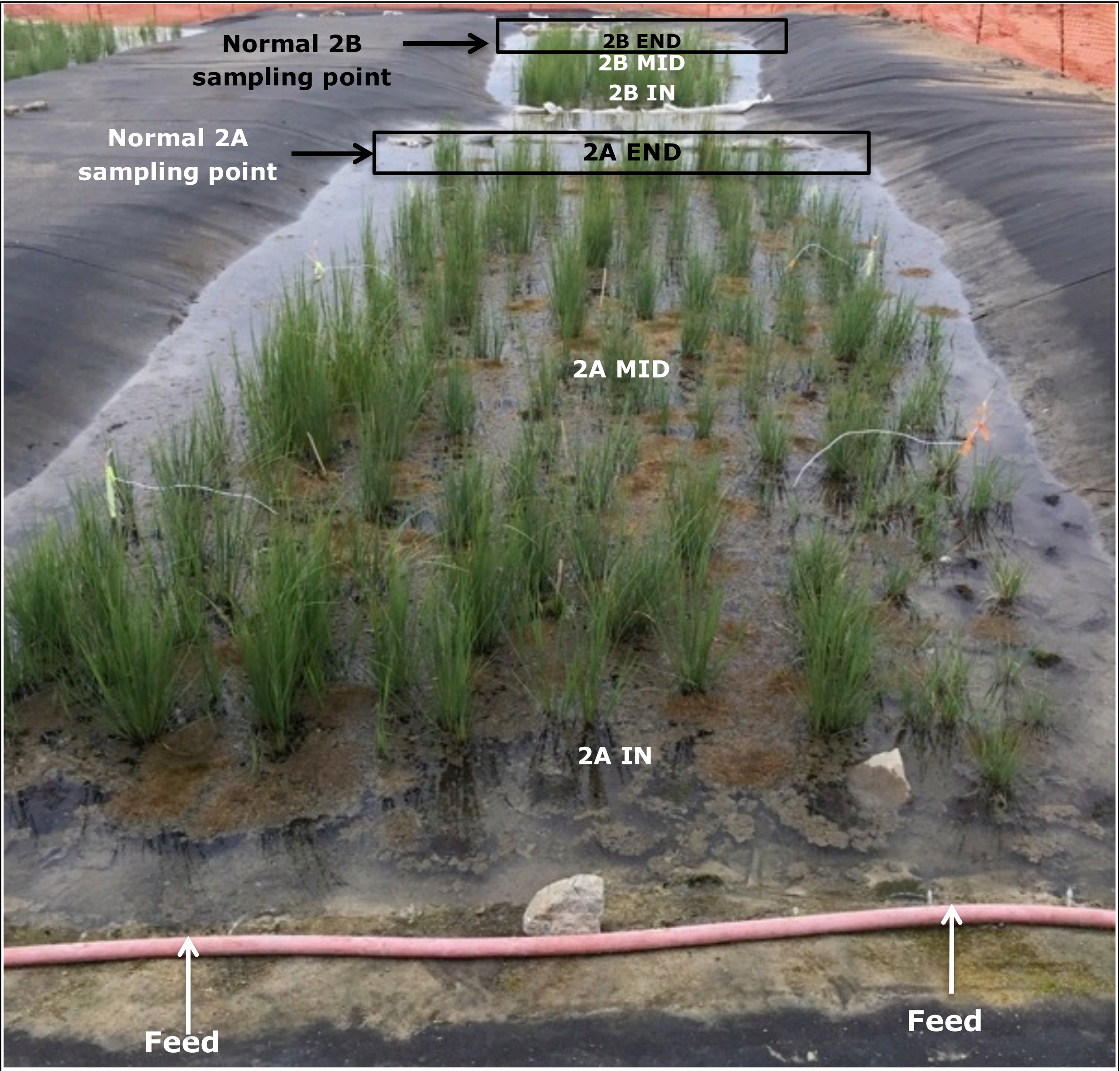


Figure 9 – Sampling points through the CWTS (Photo taken August 16, 2015).

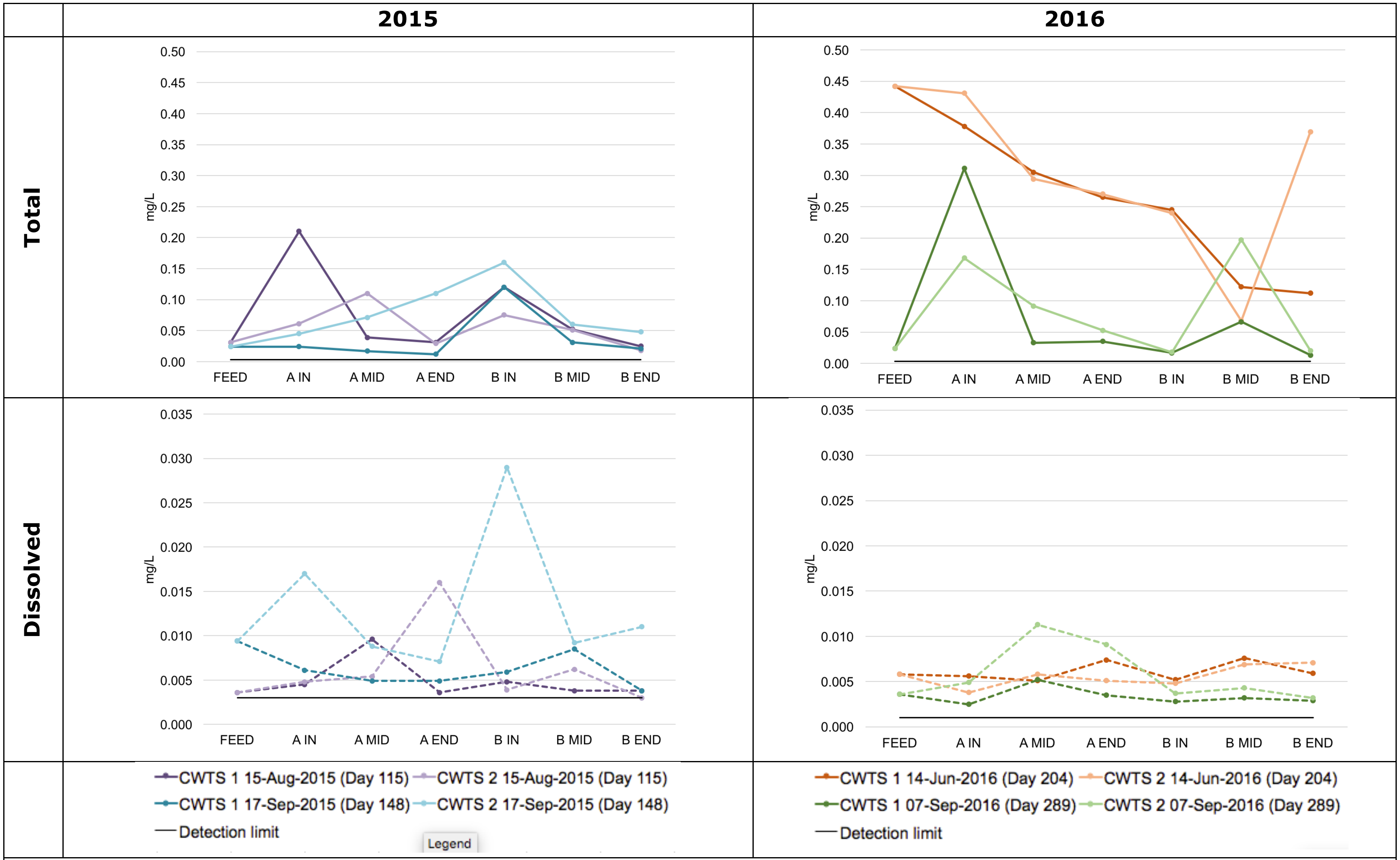


Figure 10 – Aluminum concentrations through the CWTS.
Left is 2015, right is 2016, top graphs are total concentrations and bottom graphs are dissolved concentrations. Data shown for four timepoints, where water was sampled at 7 locations through the flow path of the CWTS to assess for treatment fronts within the wetland, or possible leaching of elements from the soils into the CWTS. Y-axes are set to be the same for total and the same for dissolved. The Maxxam (2015 results) detection limits for aluminum are 0.0030 mg/L. The ALS (2016 results) dissolved aluminum detection limit is 0.0010 mg/L, and the total aluminum detection limit is 0.0030 mg/L.

Figure 11 – Cadmium concentrations through the CWTS.
Left is 2015, right is 2016, top graphs are total concentrations and bottom graphs are dissolved concentrations. Data shown for four timepoints, where water was sampled at 7 locations through the flow path of the CWTS to assess for treatment fronts within the wetland, or possible leaching of elements from the soils into the CWTS. Y-axes are set to be the same for total and the same for dissolved. The Maxxam (2015 results) detection limits for cadmium are 0.020 µg/L. The ALS (2016 results) detection limits are 0.005 µg/L.

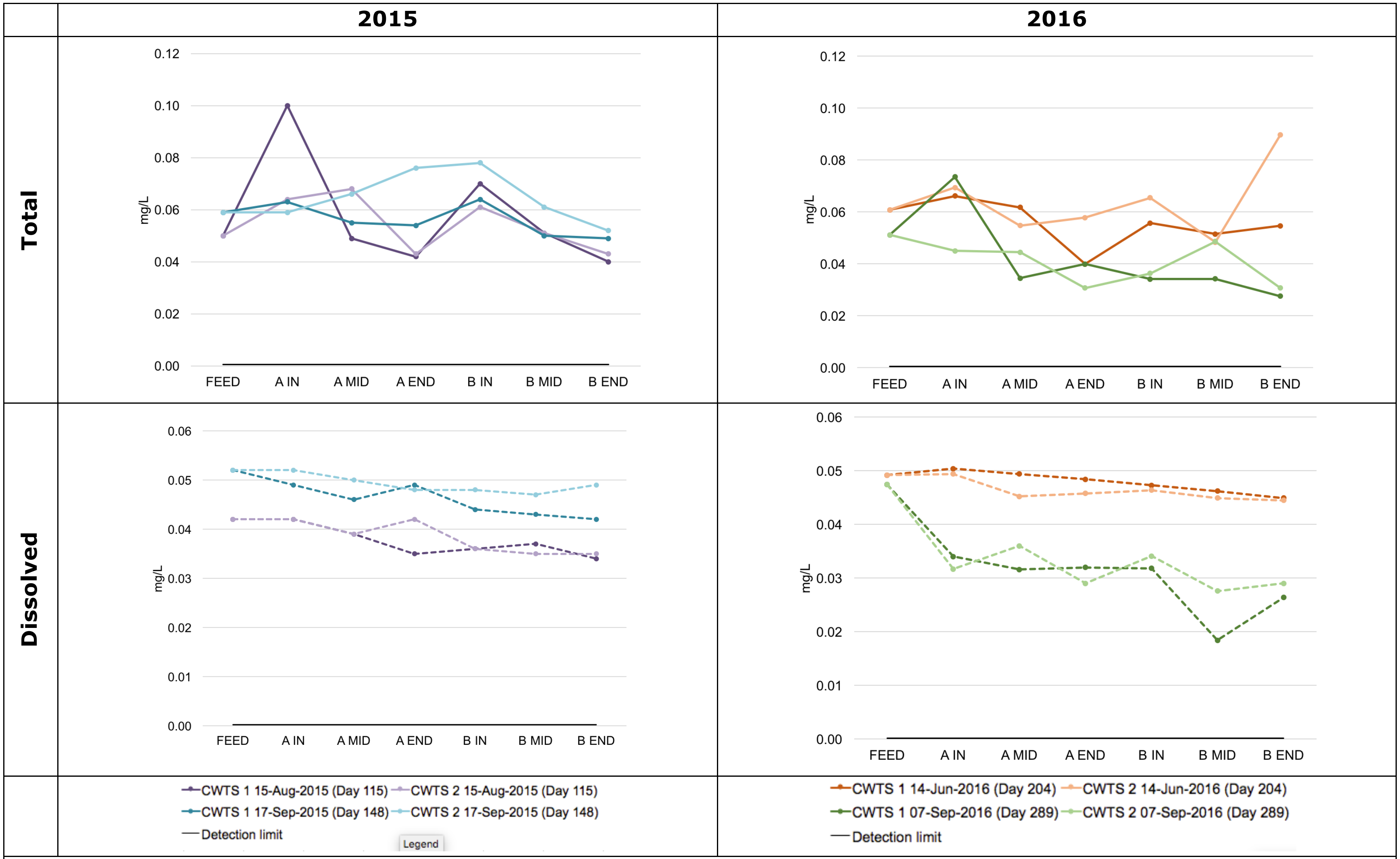


Figure 12 – Copper concentrations through the CWTS.
Left is 2015, right is 2016, top graphs are total concentrations and bottom graphs are dissolved concentrations. Data shown for four timepoints, where water was sampled at 7 locations through the flow path of the CWTS to assess for treatment fronts within the wetland, or possible leaching of elements from the soils into the CWTS. The Maxxam (2015 results) detection limits for copper are 0.0002 mg/L. The ALS (2016 results) detection limits for copper are 0.0005 mg/L.

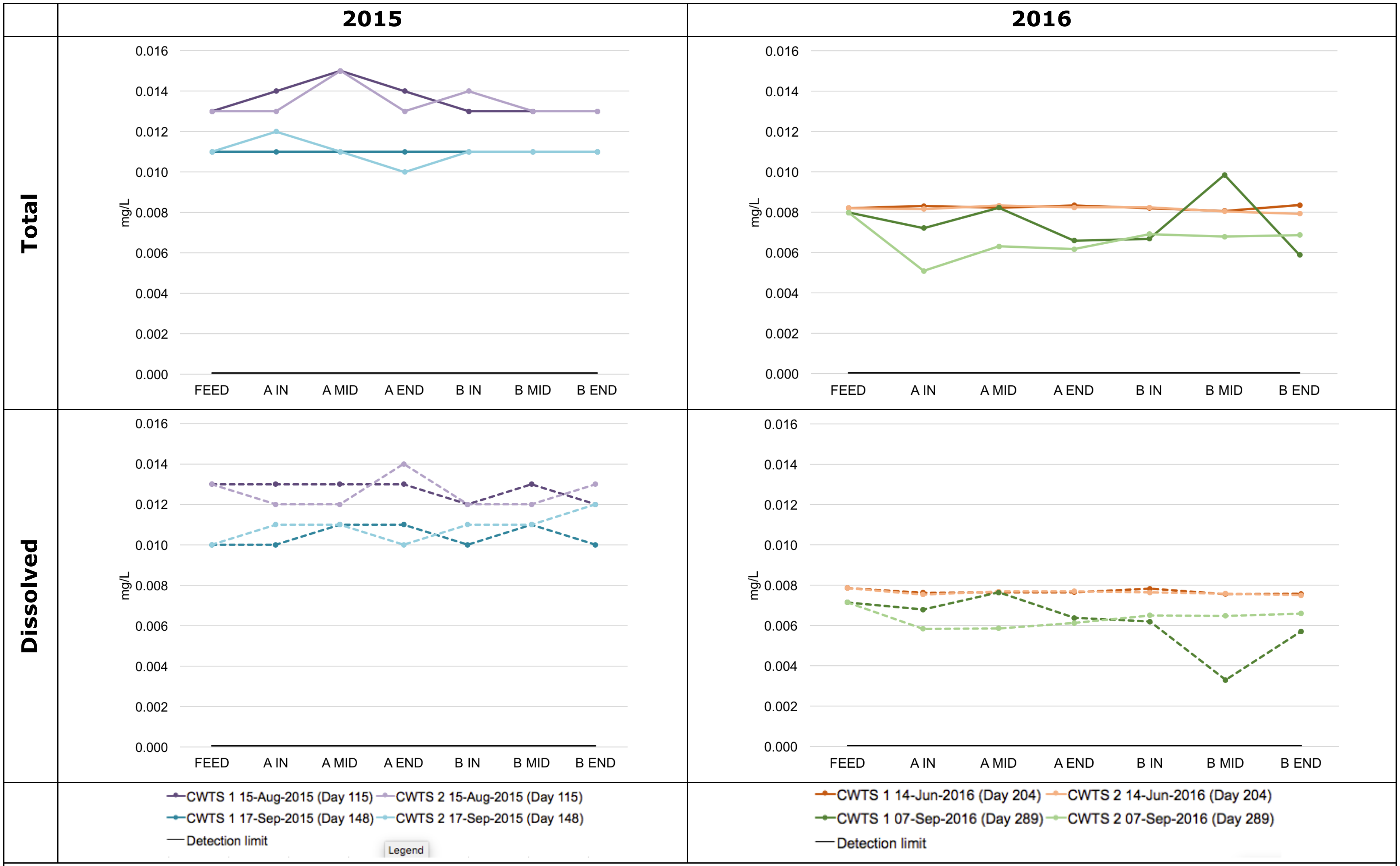


Figure 13 – Molybdenum concentrations through the CWTS.

Left is 2015, right is 2016, top graphs are total concentrations and bottom graphs are dissolved concentrations. Data shown for four timepoints, where water was sampled at 7 locations through the flow path of the CWTS to assess for treatment fronts within the wetland, or possible leaching of elements from the soils into the CWTS. Y-axes are set to be the same for total and dissolved. The Maxxam (2015 results) detection limits for molybdenum are 0.0002 mg/L. The ALS (2016 results) detection limits are 0.000050 mg/L.

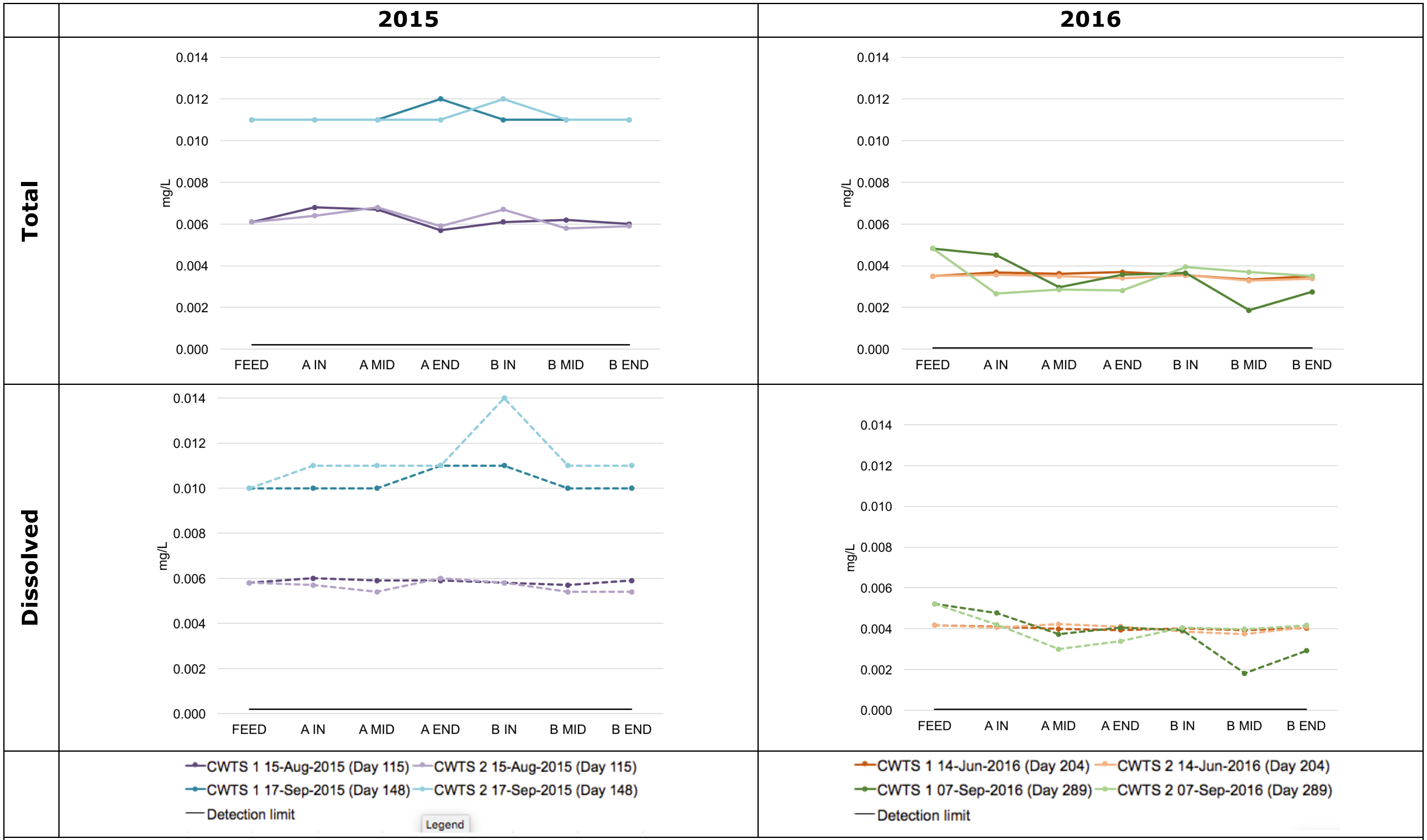


Figure 14 – Selenium concentrations through the CWTS.
Left is 2015, right is 2016, top graphs are total concentrations and bottom graphs are dissolved concentrations. Data shown for four timepoints, where water was sampled at 7 locations through the flow path of the CWTS to assess for treatment fronts within the wetland, or possible leaching of elements from the soils into the CWTS. Y-axes are set to be the same for total and dissolved. The Maxxam (2015 results) detection limit for selenium is 0.0002 mg/L. The ALS (2016 results) detection limit is 0.000050 mg/L.

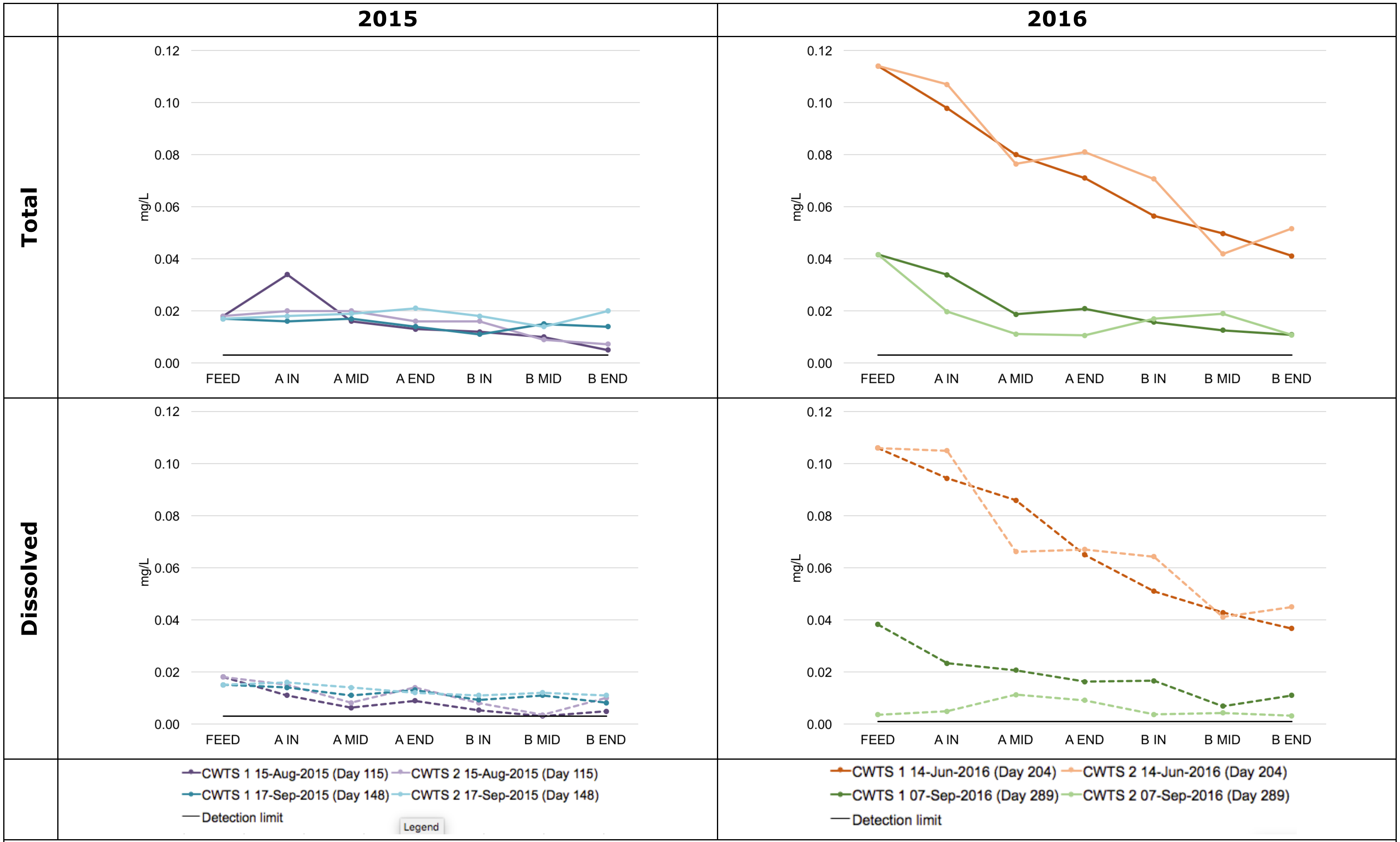


Figure 15 – Zinc concentrations through the CWTS.
Left is 2015, right is 2016, top graphs are total concentrations and bottom graphs are dissolved concentrations. Data shown for four timepoints, where water was sampled at 7 locations through the flow path of the CWTS to assess for treatment fronts within the wetland, or possible leaching of elements from the soils into the CWTS. Y-axis is set to be the same for total and dissolved. The Maxxam (2015 results) detection limit for zinc is 0.0030 mg/L. The ALS (2016 results) detection limit is 0.0010 mg/L.

6.2.3. *Demonstration-scale performance during commissioning-A*

By the end of 2015 the outflow concentration for dissolved cadmium, was on average 49% lower than influent concentrations, with average influent concentrations of 0.0505 µg/L decreasing to an average outflow concentration of 0.0248 µg/L. During commissioning-A in 2016 treatment decreased to an average removal of 40%, with average influent concentrations of 0.0240 µg/L decreasing to an average outflow concentration of 0.0142 µg/L. Dissolved copper also experienced the same trend with an average outflow concentration 17% lower than influent concentrations at the end of 2015, with average influent concentrations of 54.5 µg/L decreasing to an average outflow concentration of 45.0 µg/L. During commissioning-A in 2016, treatment decreased to an average removal of 8%, with average influent concentrations of 61.6 µg/L decreasing to an average outflow concentration of 56.7 µg/L. Molybdenum experienced no treatment through commissioning-A in 2015 and 2016, with average outflow concentrations being very similar to average influent concentrations. Dissolved selenium also experienced no treatment through commissioning-A in 2015, however by the end of commissioning-A in 2016 dissolved selenium was on average 8% lower than influent concentrations, with average influent concentrations of 3.7 µg/L decreasing to an average outflow concentration of 3.4 µg/L. By the end of 2015 the outflow concentration for dissolved zinc, was on average 42% lower than influent concentrations, with average influent concentrations of 12.3 µg/L decreasing to an average outflow concentration of 6.8 µg/L. During commissioning-A in 2016 treatment increased to an average removal of 47%, with average influent concentrations of 92.8 µg/L decreasing to an average outflow concentration of 49.0 µg/L lower than influent concentrations.

6.2.4. *Elevated zinc in influent in 2016*

The concertation of zinc in the influent to the CWTS increased significantly in 2016 compared to 2015 concentrations (Table 9, Figure 15, and Figure 20). It is uncertain whether the increase in zinc is a result of the change in sump source water location at the toe of the MVFE, where a metal culvert was installed at the beginning of operations in 2016 (Section 2.4), or if this is a result of seasonal variation.

6.2.5. *Demonstration-scale performance during commissioning-B*

After commissioning-A was complete at the end of July 2016, cadmium, copper, molybdenum, selenium, and zinc were being treated by the CWTS (Figure 16 to Figure 21 and Appendix B), while other metals/metalloids of potential concern as outlined in the Adaptive Management Plan (AMP) (Minto, 2016) were below the non- degradation central tendency water quality objectives (NDCT-WQO) for the Lower Minto Creek (W2) area.

Dissolved cadmium treatment improved through the commissioning-A period in 2016 to achieve on average 64% removal during the commissioning-B period from July 29 to September 30, 2016, with average influent concentrations of 0.0185 µg/L decreasing to an average outflow concentration of 0.0066 µg/L (Table 9, Figure 16 and Appendix B) Copper, and zinc experienced the same trends with treatment improving through the commissioning-A period in 2016 to achieve on average 37% and 69% removal during the commissioning-B period from July 29 to September 30, 2016 (Table 9, Figure 17, Figure 20, and Appendix B). During the commissioning-B period, the average influent concentrations for copper (46.1 µg/L) decreased to an average outflow concentration of 28.8 µg/L. During the same time period the average influent concentrations for zinc (37.6 µg/L) decreased to an average outflow concentration of 11.6 µg/L. The treatment of molybdenum and selenium in 2016 is notable as there was minimal treatment in 2015, improving through 2016 to achieve on average 21% and 41% removal during the commissioning-B period from July 29 to September 30, 2016 (Table 9, Figure 18, Figure 19, and Appendix B). This suggests that not only is the wetland maturing as expected, creating reducing sulphide-producing conditions, but that it is already performing far beyond what was anticipated from the design, sequestering orders of magnitude more copper than would be apparent by looking at the influent water alone (i.e., is also removing copper that has leached from the soils over time). All constituents of concern have percent removal rates that continue to trend upward and are becoming more stable as the wetland matures.

Table 9 – Percent removal of constituents in the demonstration-scale CWTS.

Element (µg/L)		**Pilot-scale[1]**	**Demonstration-scale**			
		2013	**2014**	**2015[2]**	**2016 [3]**	**2016[4]**
Cd	In	0.336	NA	0.0505	0.0240	0.0185
	Out	0.027	NA	0.0248	0.0142	0.0066
	%	**92**	NA	**49**	**40**	**64**
Cu	In	146	NA	54.5	61.6	46.1
	Out	11.3	NA	45.0	56.7	28.8
	%	**92**	NA	**17**	**8**	**37**
Mo	In	13.0	NA	11.0	7.6	7.3
	Out	10.4	NA	11.3	7.6	5.7
	%	**20**	NA	**0**	**0**	**21**
Se	In	10.2	NA	11.0	3.7	5.7
	Out	6	NA	11.3	3.4	3.3
	%	**41**	NA	**0**	**8**	**41**
Zn	In	40	NA	12.3	92.8	37.6
	Out	3.2	NA	6.8	49.0	11.6
	%	**92**	NA	**42**	**47**	**69**

[1] The pilot-scale system operated from Nov 4, 2013 to July 16, 2014. The data used in this table is from the low N period in the *carex* and moss system which operated from April 13, 2014 to May 28, 2014.

[2] Values calculated from end last two sampling event in 2015 before the addition of EDTA (September 9 and 17, 2015).

[3] Commissioning-A (May 2, 2016 to July 28, 2016).

[4] Commissioning-B (July 29, 2016 to September 30, 2016).

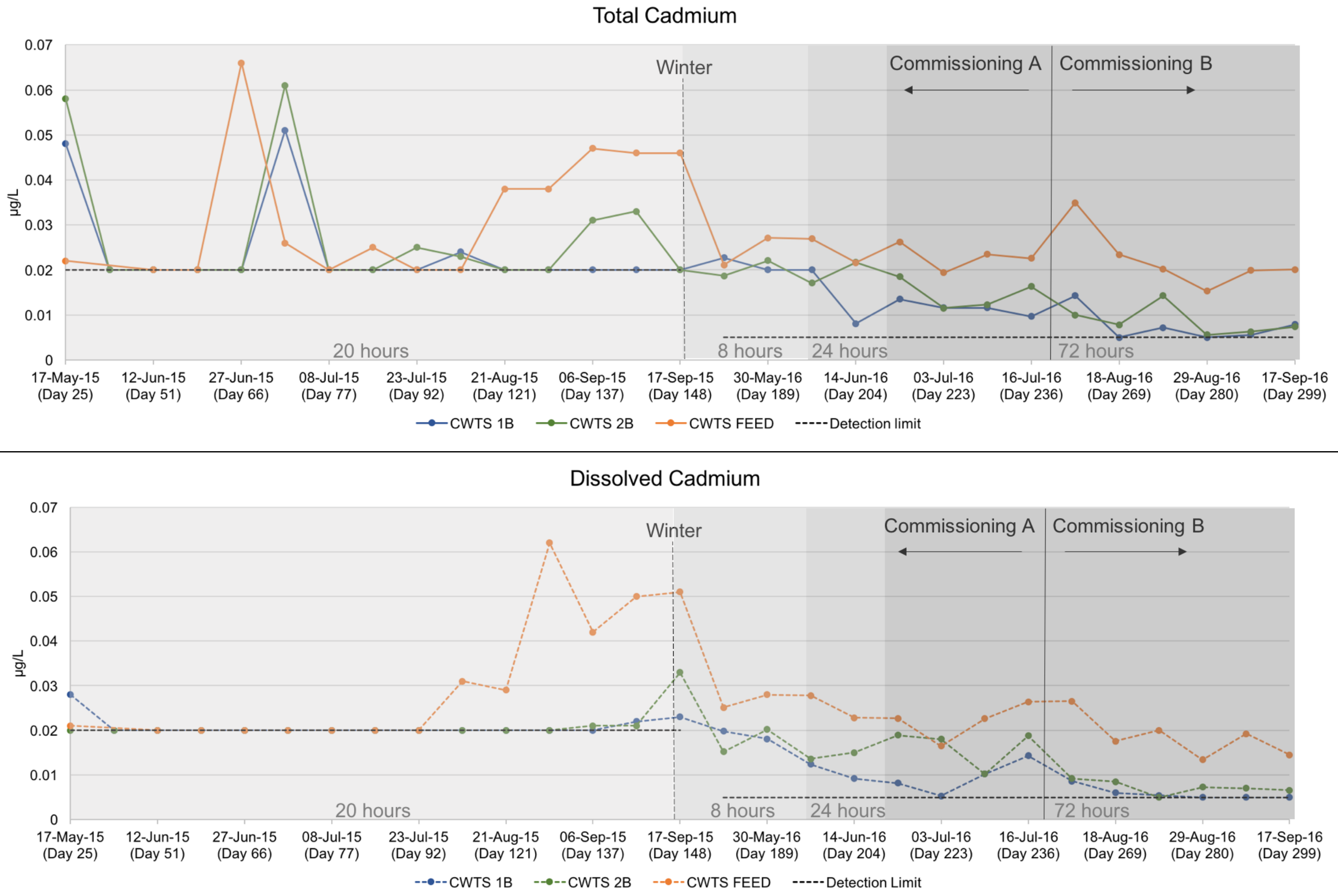


Figure 16 – Cadmium concentrations in the demonstration scale wetland.
The HRT is indicated by grey shading and the duration in hours. The Maxxam (2015 results) measurement uncertainty (MU) for cadmium is +/- 0.020 µg/L. The ALS (2016 results) MU is +/- 0.005 µg/L. Timepoints where the dissolved concentration is higher than the total concentration are within the limit of uncertainty.

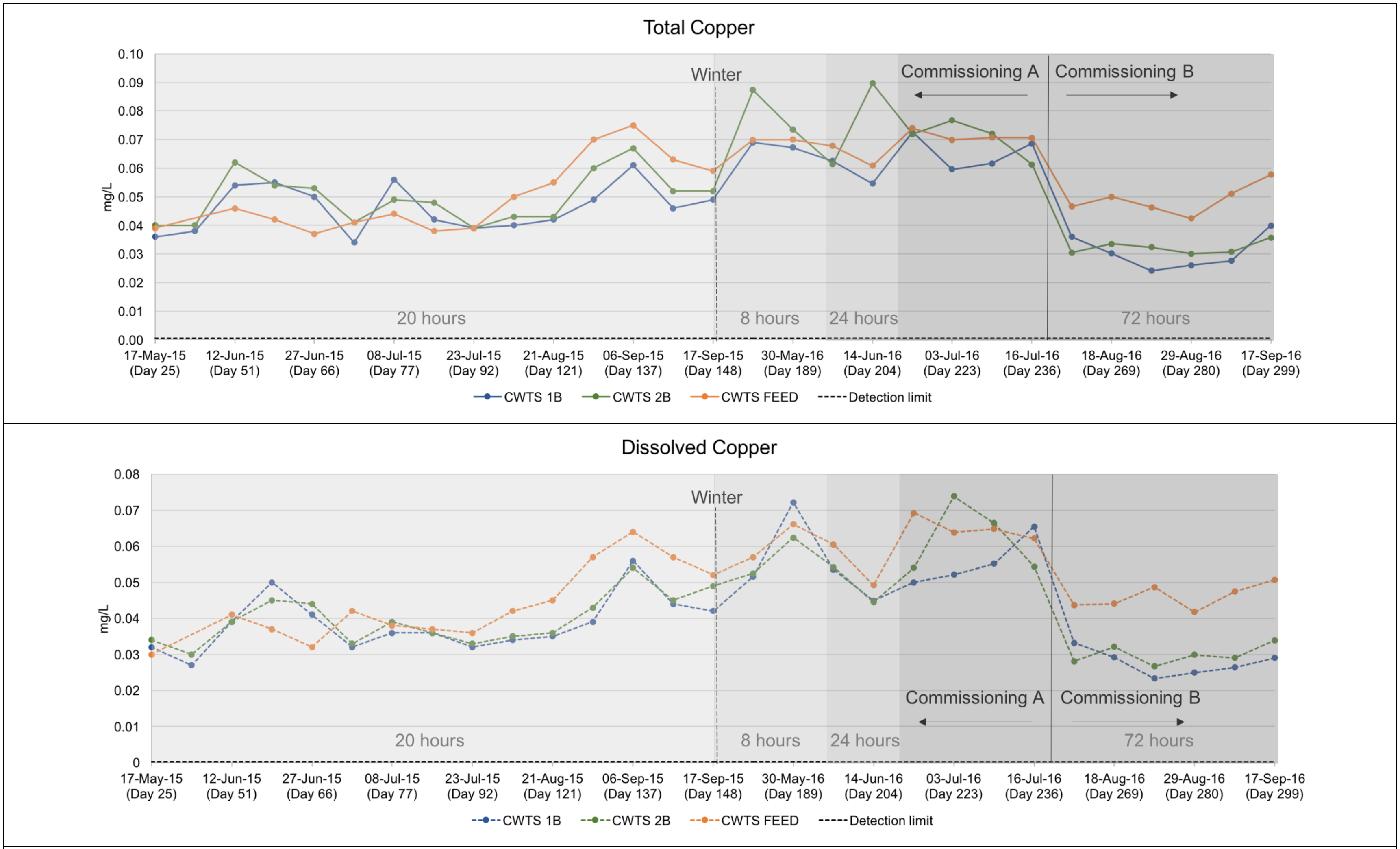


Figure 17 – Copper concentrations in the demonstration scale wetland.
The HRT is indicated by grey shading and the duration in hours. The Maxxam (2015 results) and The ALS (2016 results) measurement uncertainty (MU) for copper is +/- 0.0002 mg/L. Timepoints where the dissolved concentration is higher than the total concentration are within the limit of uncertainty.

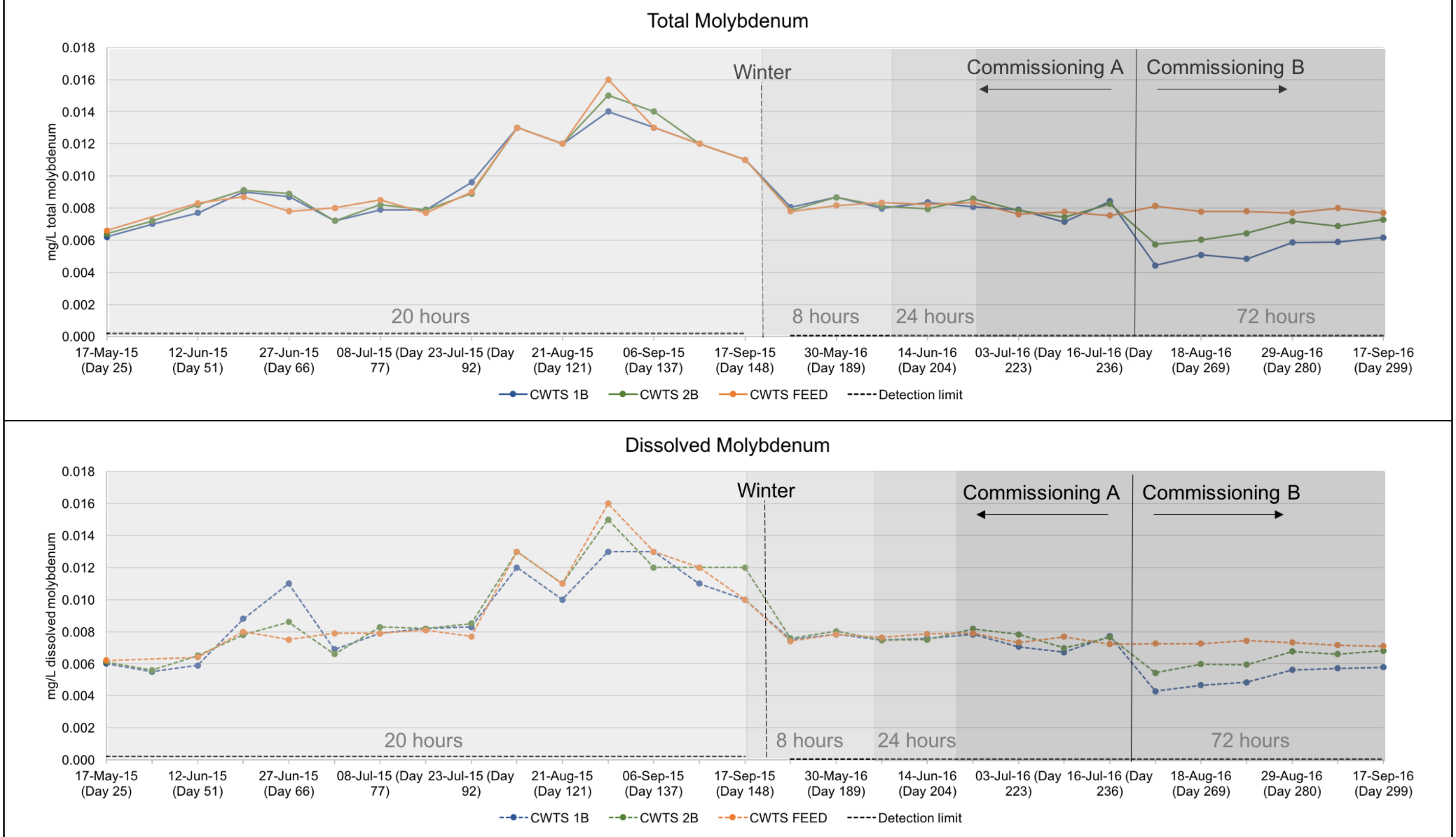
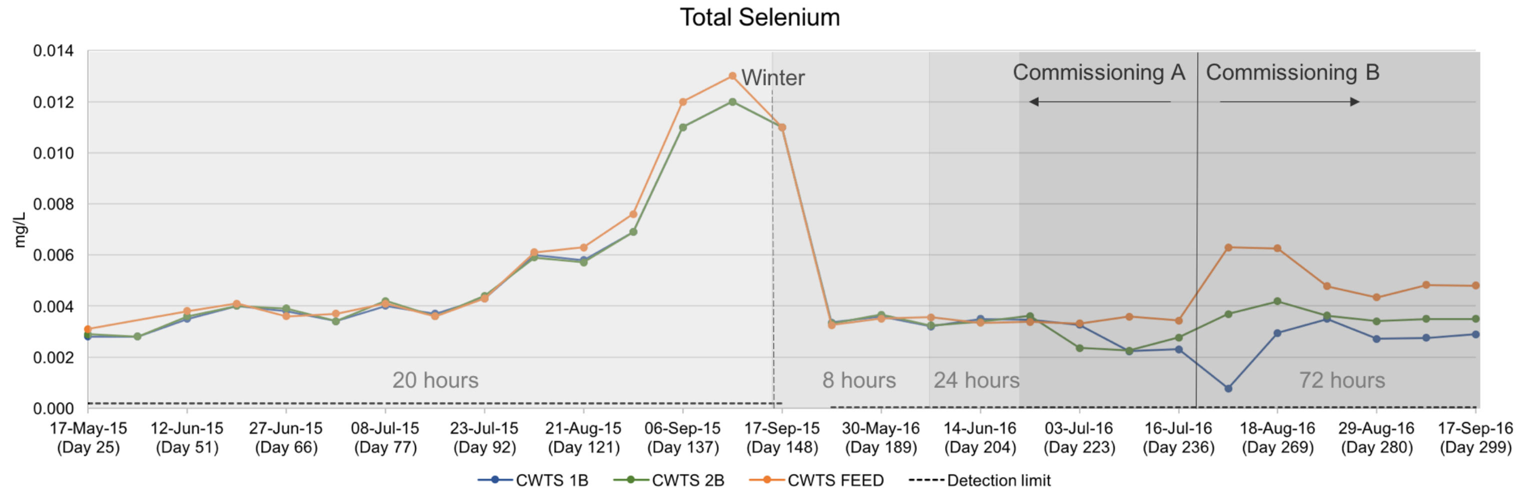


Figure 18 – Molybdenum concentrations in the demonstration scale wetland.
The HRT is indicated by grey shading and the duration in hours. The Maxxam (2015 results) measurement uncertainty (MU) for molybdenum is +/- 0.0002 mg/L. The ALS (2016 results) MU is +/- 0.000050 mg/L. Timepoints where the dissolved concentration is higher than the total concentration are within the limit of uncertainty.



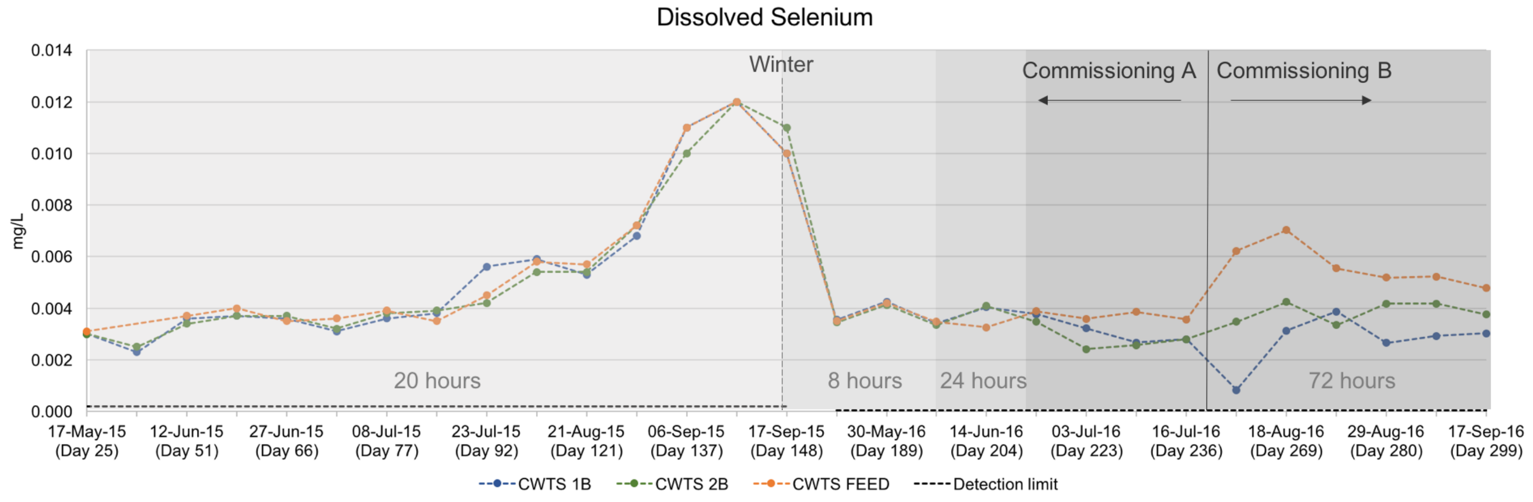


Figure 19 – Selenium concentrations in the demonstration scale wetland.
The HRT is indicated by grey shading and the duration in hours. The Maxxam (2015 results) measurement uncertainty (MU) for selenium is +/- 0.0002 mg/L. The ALS (2016 results) MU is +/- 0.000050 mg/L. Timepoints where the dissolved concentration is higher than the total concentration are within the limit of uncertainty.

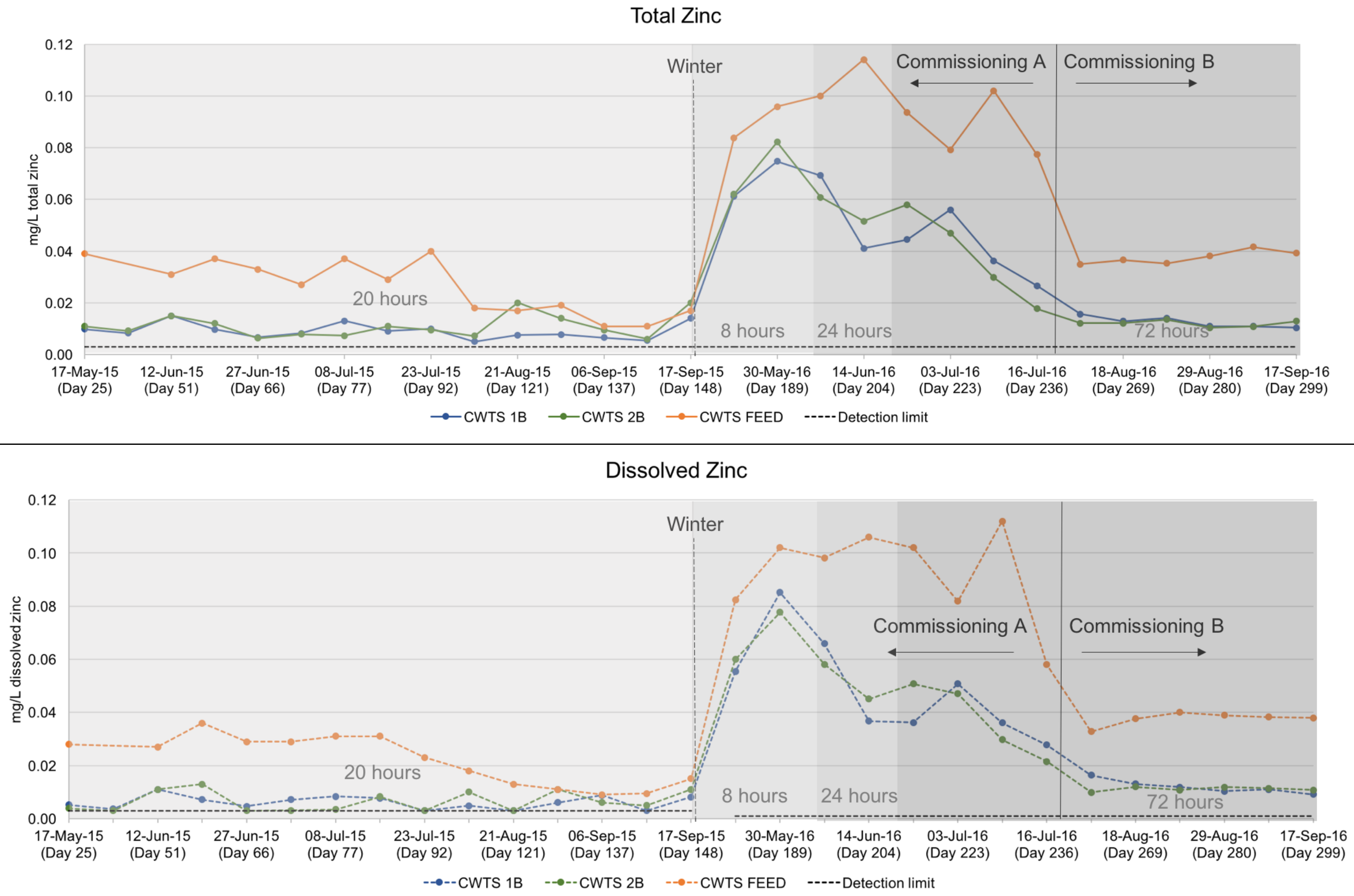


Figure 20 – Zinc concentrations in the demonstration scale wetland.
The HRT is indicated by grey shading and the duration in hours. The Maxxam (2015 results) measurement uncertainty (MU) for zinc is +/- 0.0030 mg/L. The ALS (2016 results) MU is +/- 0.0010 mg/L. Timepoints where the dissolved concentration is higher than the total concentration are within the limit of uncertainty.

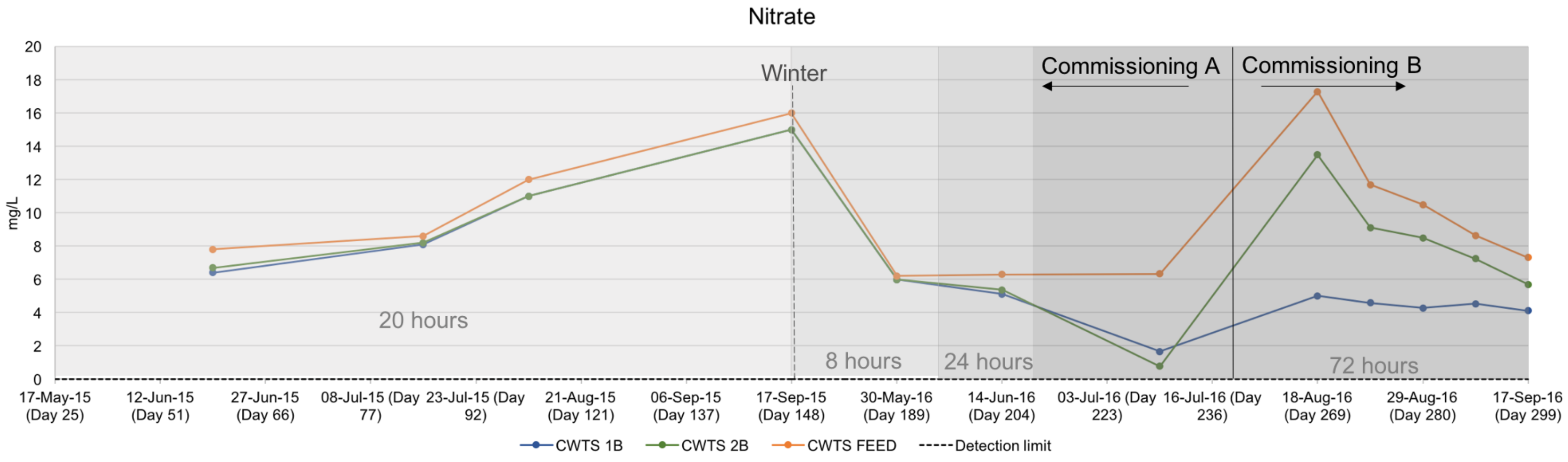


Figure 21 – Nitrite as N (NO_2) and Nitrate as N (NO_3) concentrations in the demonstration scale wetland. The HRT is indicated by grey shading and the duration in hours. The Maxxam (2015 results) measured uncertainty (MU) for nitrite is +/- 0.010 mg/L. The ALS (2016 results) MU is +/- 0.0010 mg/L. The Maxxam (2015 results) measured uncertainty for nitrate is +/- 0.010 mg/L. The ALS (2016 results) MU is +/- 0.0050 mg/L.

6.3.Chelated iron (fertilizer micronutrient) treatment

Because elevated metals were present in the soils used for construction, there was an opportunity to assess whether non-invasive treatments could be used to further leach the metals and improve soil quality. A chelated iron (Fe-EDTA) product was added to the Series 2 wetland on September 17, 2015. The Fe-EDTA treatment was performed on Series 2, with Series 1 remaining untreated for comparison purposes. Increases in copper concentrations were observed in the outflow from both cells in CWTS Series 2 after the addition of Fe-EDTA. In the 10 days following the addition of Fe-EDTA, approximately 75 g of copper was removed from the wetland Series 2. This is approximately 1.25 g of copper per m^2 of wetland. Elevated flow rates were selected for CWTS start up in 2016 to flush copper leaching from soil (associated with 2015 EDTA test).

7. Hydraulic retention time tracer study

A tracer study was conducted from June 13-15, 2016 on cell 1A of the CWTS with a flow rate of 2.43 GPM (13.25 m^3/day). The purpose of the tracer study was to determine the actual hydraulic retention time, and the flow path of water through the CWTS. Salt (NaCl) was used as the tracer in this study. By adding a salt solution at the inflow of the wetland, and placing a YSI meter at the outflow of the wetland, it can be determined how long it takes for the salt to pass through the wetland by monitoring the specific conductance (SPC) in situ (as salt raises the SPC). The HRT of the CWTS can be determined through a calculation using the volume and concentration of salt solution added at the inflow of the wetland and the time over which the specific conductance remains elevated above background levels at the outflow.

The HRT tracer study used 1.87 kg of salt dissolved into 480L of water. The 480 L of water was gradually removed from the end of the CWTS, 20 liters at a time, dosed with salt, and added at the front of the CWTS. This method took 50 minutes to dose in the 480 liters of salt solution into the CWTS and was selected as it did not affect the total volume of water in the CWTS during the HRT tracer study. The volume of water and weight of salt was calculated based on the amount required to increase the specific conductance (SPC) of cell 1A to at least twice its background level (i.e., from 850 µs/cm, to 1700 µs/cm) (Oakton Instruments, 1997). The volume of water used was then selected to ensure the concentration of the salt solution was sufficiently diluted and would mix with the water of the CWTS (i.e., wasn’t so dense that it would stratify and sink to the bottom of the CWTS).

In situ monitoring of the HRT tracer study was carried out from June 13, 2016 at 14:52 until June 15 at 12:12. This time period was selected because Contango was on site for 2 days to conduct the HRT tracer study and to collect data. Also the battery life of the YSI unit was approximately 2 days, and at the time, it was not feasible to implement dosing pumps and in situ monitoring (data logging) for a longer period of time. The YSI unit was placed in the wetland for approximately 20 mins prior to starting the HRT tracer study to record background levels before dosing of the salt solution into the CWTS. The background SPC prior to commencing the HRT tracer study was approximately 900 µS/cm. During the tracer study, there were two tracer breakthroughs. The first breakthrough was at 1.03 days (24.72 hours), with peak SPC at 2228 µS/cm. The second breakthrough was at 0.75 days (18 hours), with a peak SPC of 1928 µS/cm. Based on the results of the two breakthroughs in the HRT tracer study, it is possible that there are two flow paths through the wetland, however, this may also be due to how the salt solution was added to the CWTS.

In 2017 it is recommended that another 1 m^3 tank be added to the CWTS area, and another HRT tracer study be conducted. The second 1m^3 tank could provide a way to mix a lower concentration salt solution, and dose it into the CWTS over a longer period at a constant flow using a metering pump. This would allow the flow rate to be calculated for the duration of time the salt solution is dosed into the CWTS. To conduct the HRT tracer study over a longer period, the YSI unit would need to be connected to a power source due to a limited battery life. By conducting the tracer study in 2017 as described above it is anticipated that only one breakthrough would occur, providing more accurate results.

The data from the 2016 HRT tracer study suggests that the HRT of cell 1A is 0.89 days (21.36 hours), the average of the two breakthroughs. It is possible that not all the tracer salt had yet flowed through the wetland, as SPC had not yet reached original background levels, and so the average HRT may be longer slightly than the 0.89 days observed here. By comparison, the calculated HRT was 0.53 days (12.82 hours), therefore the actual HRT was approximately 40% slower than the calculated HRT. Most of this difference in calculated vs tracer study HRT is owing to the exclusion of pore water involvement in the calculated HRT (because of the soil type used, it was an unknown factor that could not be inferred from the off-site pilot-scale trials). However, part of this difference can also be attributed to loss of water through evapotranspiration (Section 9) which results in a lower flow and therefore longer HRT.

Based on the results of the HRT tracer study, the depth of cell 1A including pore water involvement was able to be calculated following Equation 1. The actual HRT of 0.89 days (21.36 hours) was used to solve Equation 1, resulting in a total depth of 0.35 meters. The measured depth of water in cell 1A was then subtracted from total depth (0.35 meters – 0.16 meters), to obtain a pore water involvement of 0.19 meters. The measured depth of cell 1A was obtained from the depth sticks that were installed in the CWTS in June 2016 (Figure 23).

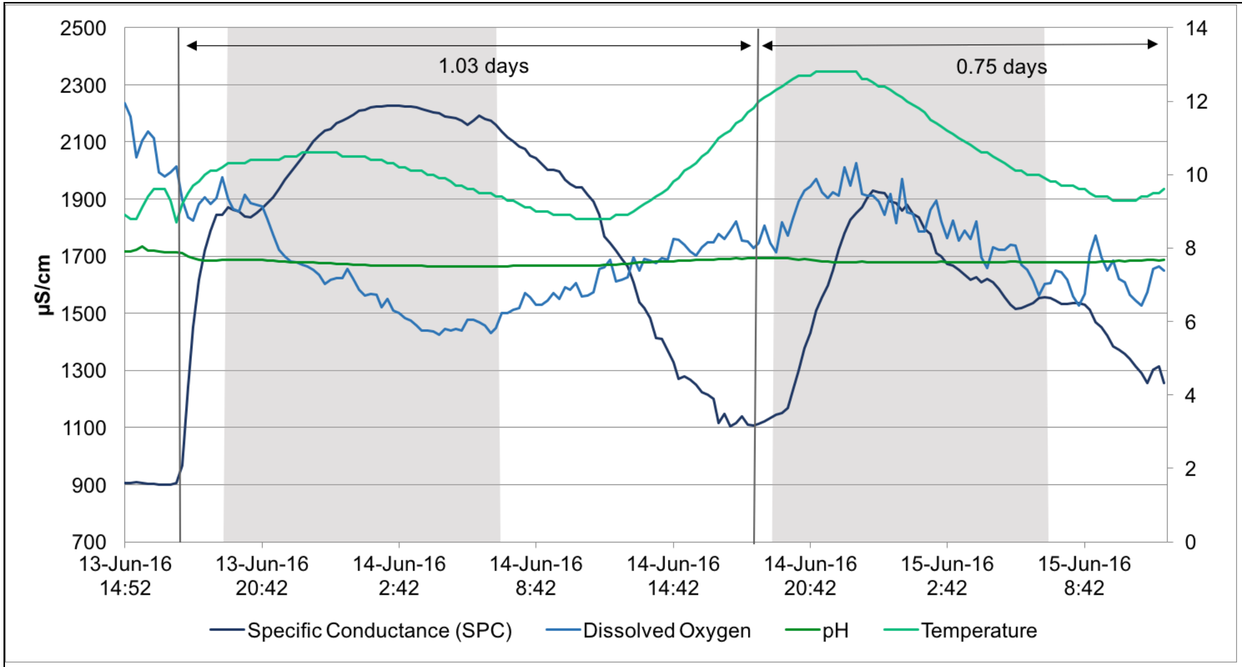


Figure 22 – Tracer study results.
SPC (µS/cm) on primary y-axis. Dissolved oxygen (mg/L), pH, and temperature (°C) on secondary y-axis. The grey shading indicated a 12-hour night period from 7am to 7 pm. The vertical black lines indicate the beginning and end of the tracer breakthrough.

$$\text{Depth} = \left({}^{\text{Q}}\!/_{length * width}\right) * \text{ HRT}$$

Equation 1 – Equation for calculation of the CWTS depth including pore water involvement.
Q is the flow rate.

8. Calculations of rate coefficients (*k*)

8.1. Rate coefficients

An important factor for CWTS design is the rate of treatment, also known as the treatment (or removal) rate coefficient (*k*). The rate coefficient is based on the treatability of a specific compound and the hydraulic retention time of the system, both of which are site-specific based on water chemistry, wetland designs, and characteristics of the system. A treatment rate coefficient (*k*) was applied for cadmium, copper, molybdenum, selenium and zinc, to develop a conceptual size for the Minto CWTSs and determine which elements and load sources were key for treatment (Table 10). Based on pilot-scale testing for the Minto CWTS, in this site-specific situation, the treatment rate coefficient (*k*) for selenium follows a zero-order reaction kinetic, while the rate coefficients for cadmium, copper, molybdenum, and zinc follow first-order kinetics.

In Equations 2-3, *Cf* is final concentration, *Ci* is initial concentration, and *HRT* is *the* hydraulic retention (Equation 4) time calculated using the CWTS depth result of the tracer study (Equation 1). The HRT was calculated using the volume of each CWTS series including the pore water involvement calculated from the results of the tracer study (Equation 1), and the flow rate from during the time period that *k* was calculated for in 2016 (from August 10 – September 17, 2016) to obtain the HRT.

Using the removal rate coefficients (*k*) in Table 10 and Equations 2-4, parameters can be rearranged to solve for those of interest, such as the volume needed, that in turn determines the area of wetland required which is dependent upon the design. Analytical results from August 10 – September 17, 2016 were chosen to calculate *k* because this is the period after the final operational adjustment were completed in 2016 (addition of organics) and flow rates were stable and at targeted values. The treatment rate coefficients applied here are intended to be a conservative estimate for conceptual sizing purposes, and will need to be refined through further demonstration-scale (on site) testing.

$$k = \frac{-\ln\left(\frac{Cf}{Ci}\right)}{\mathrm{HRT}}$$

Equation 2 – Equation for calculation of first-order removal rate coefficient.
k is the removal rate coefficient, *Cf* is the final concentration, *Ci* is the initial concentration, and HRT is the hydraulic retention time.

$$k = \frac{(Ci - Cf)}{\mathrm{HRT}}$$

Equation 3 – Equation for calculation of zero-order removal rate coefficient.
k is the removal rate coefficient, *Cf* is the final concentration, *Ci* is the initial concentration, and HRT is the hydraulic retention time.

$$HRT = {}^{V}\!/_{Q}$$

Equation 4 – Equation for calculation of hydraulic retention time.
HRT is the hydraulic retention time, V is the volume of the wetland, and Q is the flow rate.

Table 10 – Rate coefficients (*k*) for elements in exceedance of proposed WQO's[1].

Element[2]	Pilot k*hour^{-1}	Demonstration[6] k*hour^{-1}				Demonstration[6] k*day[1]			
		Series 1		Series 2		Series 1		Series 2	
	Total	Dissolved	Total	Dissolved	Total	Dissolved	Total	Dissolved	Total
First order removal rate coefficients									
Cd	0.0476[4]	0.00817	0.00803	0.00610	0.00640	0.196	0.193	0.147	0.154
Cu[3]	0.0497[5]	0.00365[3]	0.00341[3]	0.00283[3]	0.00276[3]	0.0876[3]	0.0819[3]	0.0680[3]	0.0661[3]
Mo	0.0042[4]	0.00248	0.00273	0.000989	0.00117	0.0594	0.0655	0.0237	0.0280
Zn	0.0477[4]	0.00824	0.00790	0.00799	0.00752	0.198	0.190	0.192	0.181
Nitrate	0.0380[4]	N/A	0.00610	N/A	0.00149	N/A	0.147	N/A	0.0358
Zero order removal rate coefficients									
Se	7	0.0000179	0.0000160	0.0000118	0.0000103	0.000430	0.000385	0.000284	0.000246

[1] Non- degradation central tendency water quality objectives (NDCT-WQO) for the Lower Minto Creek (W2) area from the Adaptive Management Plan (Minto, 2016).

[2] All treatment rate coefficients are for first-order reaction kinetics except for selenium which is a zero-order reaction rate kinetic.

[3] Rate coefficients for copper in demonstration scale system are artificially lower than actual due to leaching of copper into water from soils, which increases outflow copper concentrations and affects the *k* calculation (Section 6.2.2).

[4] Values calculated from data in Table 8 of the pilot-scale report (Contango, November 2014).

[5] Value retrieved from Table 10 of the pilot-scale report (Contango, November 2014).

[6] Analytical results from August 10 – September 17, 2016 were used to calculate *k.*

9. Evapotranspiration study

An evapotranspiration study was conducted in a controlled greenhouse at Contango in April 2016 using the same general summer temperatures and vegetation types as the Minto CWTS. Total evapotranspiration from the system is the combined effects of open water evaporation and plant transpiration (Beebe *et al*, 2014). The purpose of calculating the evapotranspiration of a system is to understand the amount of water lost, which in turn concentrates elements and should be considered in the context of the difference of decrease in outflow concentration (or not) and outflow load reduction. The findings of the controlled environment (off site) evapotranspiration study suggested that on average 15.53 L/m^2/day would be lost from a CWTS design such as that at Minto through evapotranspiration. This would result in an equivalent concentration of elements (the actual percentage concentration being dependent on the amount of water in the system).

An evapotranspiration study was then performed on site July 18-25, 2016. The flow to the CWTS was shut off on July 18, 2016 and depth measuring sticks were installed at each end of the wetland to record the amount the water level decreases due to evapotranspiration (Figure 23). However, this time period experienced rain, and also the Minto weather station was not functional at this time, and therefore the evapotranspiration rates of the on-site wetland could not be determined and it is recommended this study should be repeated in 2017.

Applying the findings of the off-site evapotranspiration study to the demonstration-scale CWTS, series 1 could lose 1,085 L/day and series 2 could lose 903 L/day in dry periods. Using the 3 different HRT under which the demonstration-scale CWTS was operated in 2016, evapotranspiration loss could result in a concentration of elements in the outflow water from 3 – 31 % (Table 11), meaning the actual load removed is this much greater than would be appreciated by looking at the concentrations alone. An on-site evaporation trial in 2017 can determine if these findings are accurate for the Minto CWTS. Evapotranspiration must be accounted for in sizing of a full-scale wetland.

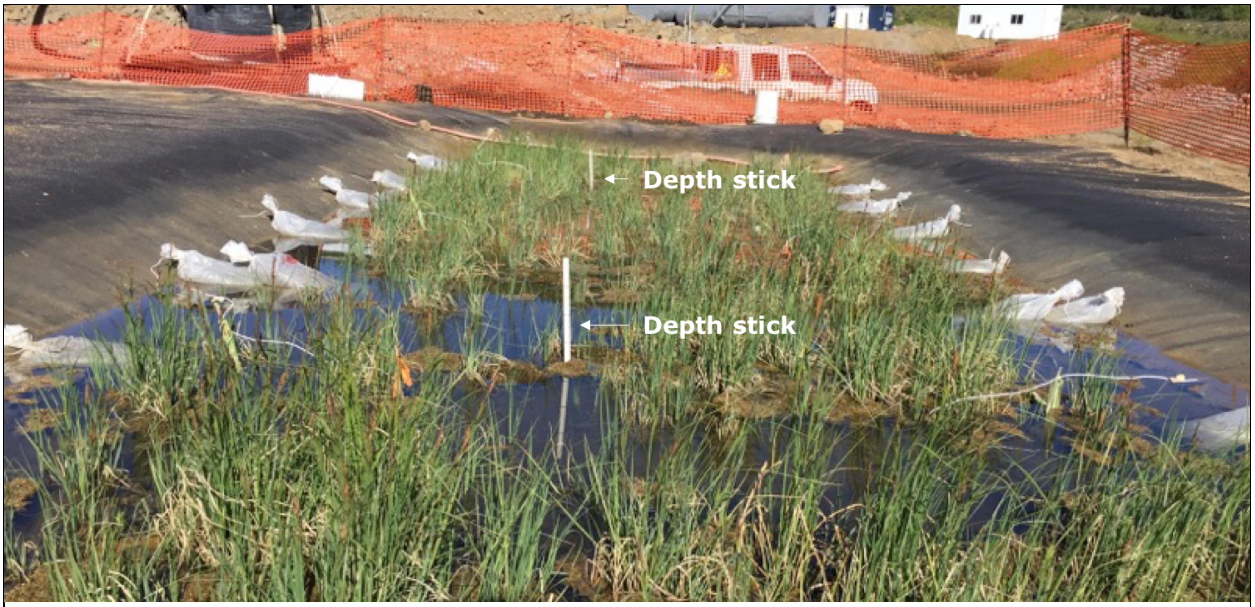


Figure 23 – Depth sticks installed in CWTS to record evapotranspiration.

Table 11 – Potential loss of water through evapotranspiration in the CWTS .

HRT (days)	L/day through series		L/day lost		% Lost /day
	Series 1	Series 2	Series 1	Series 2	
0.3	34,998	28,638	1,085	904	3
1	10,510	8,600			10
3	3,503	2,867			31

10.Vegetation

10.1. Health and establishment

10.1.1. Carex aquatilis

During the commissioning period, plants establish and mature, with density expected to increase over time. When counted at the first site visit in June 2015, >95% of the plants were found to have survived their first winter. This survival rate is impressive considering the late fall planting of August 28, 2014 and suggests the *C. aquatilis* are very robust and reaffirms they are a good candidate for use in the full-scale CWTS at Minto. Additionally, there was a greater than 20% increase in total stems in the short growing season up to June 2015 (as counted by new shoots/runners). By the second site visit in August 2015, the plants were too dense to count stems, and therefore the survival and establishment was considered a success and no longer monitored by counting (Figure 26). By the second site visit in 2016 (July) the CWTS cells hosted a dense monoculture of *C. aquatilis* that continued to thrive until the end of operations in 2016.

Pilot-scale testing suggested that *C. aquatilis* would increase more quickly the number of stems once the maximum plant height was achieved, and that maximum plant height is dependent upon water depth (with deeper water resulting in taller plants). This was also seen in the demonstration-scale wetland on site, with the density of plants filling in greatly through July and August 2015 and throughout 2016 (Figure 26).

Of note, it was observed that during the last site visit of the year by Contango (September 17-18th, 2015), the *C. aquatilis* in the demonstration-scale CWTS were still predominantly green, while other plants in the area had turned brown. This suggests that the CWTSs may have a longer range of activity than natural systems in the area, possibly due to liners and separation from colder ground water.

10.1.1.1. Aphids

Aphids were observed in all CWTS cells in July 2016 (Figure 28), and had originally been noticed in cell 2A in August 2015. Aphids occur naturally in the area and have been observed during site visits and background sampling in the Yukon and Northwest Territories on *Carex* and *Typha*. The effects of aphids on a CWTS are not expected to be pronounced unless it has a large buffer zone between it and other insect habitat (e.g., forest, prairie, etc), which prevents predator insects from also colonizing and keeping the aphids at a lower population density. At Minto, there is a large buffer area (MVFE) around the demonstration-scale CWTS, and as such, the aphids may colonize more robustly than anticipated in the full-scale CWTS at site, which would not have the same buffer zone. The aphids will continue to be watched in 2017, and other background areas (e.g., W10 and W15) compared to see if increases in aphid populations are specific to the CWTS, or general in the area.

10.1.2. Moss

Despite several mosses drying out during the winter of 2015 after planting, there was 100% survival and establishment. However, their growth was much slower than the sedge and therefore they were supplemented with additional aquatic moss (harvested from the same W10 area as the original plants for the CWTS) in June and August 2015 to augment their general abundance and bring the CWTS through commissioning more quickly (Figure 24). Mosses continued to mature and expand in size through 2016. The mature mosses are beginning to show characteristics of the desired coupled transfer (sorption, filtration) and transformation (mineralization, reduction) processes, with the top of the moss growing and producing new biomass (i.e., is green new growth; transfer sites), and the older bottom of the moss turning black (i.e., beginning to decompose producing sulphidic reducing zones; transformation reactions) (Figure 24).

10.2. Metals uptake

Concentrations of various elements in *C. aquatilis* and moss from the demonstration-scale systems were compared to those from pilot-scale testing. It is expected that the concentrations would be higher in the demonstration-scale system as the CWTS is not yet fully functional (i.e., elements are in greater bioavailability when in dissolved form) and also due to the composition of the soils used for construction.

C. aquatilis and moss in the demonstration-scale system had higher copper concentrations than the pilot systems. However, concentration of copper in the *C. aquatilis* at the end of 2015 was not significantly different than that of the plants borrowed from the W10 area for planting of the systems in 2014. Concentration of copper in the *C. aquatilis* in series 1 at the end of 2016 were comparable to the 2015 concentrations, however the concentration of copper in series 2 was higher (Figure 30). This is possibly due to the increased soluble (i.e., bioavailable) copper in series 2 after the addition of Fe-EDTA in September 2015. The moss had higher copper concentrations compared to the initial moss sample in all cells in 2015, and increased to nearly double the 2015 values by the end of 2016 (Figure 30). Mosses remove metals from water through sorption, which is different than the plant uptake that occurs in macrophytes such as *Carex* (and therefore, expected to release copper when exposed to EDTA, rather than have an increased uptake). Additionally, because the mosses were being added through 2015 (from the W10 source), it is expected that mosses would have lower metals concentrations (of any element) in 2015 compared to 2016 as they were not exposed to the CWTS water chemistry for the full year. It should be noted that over time, the mosses convert the sorbed elements to reduced minerals, rendering them lower bioavailability (Section 10.1.2.). As mosses are not a significant food source for any fauna, this is a safe mechanism to transfer elements from water eventually into stable mineral forms in the wetland soils and substrate.

Cadmium concentrations were either below or close to the detection limit in *Carex* in 2015 and 2016 (Figure 29). Additionally, cadmium concentrations in moss and selenium concentrations in both plant types tested were lower in the demonstration-scale (2015 and

2016) compared to pilot-scale. This result was presumably due to lower concentrations of both cadmium and selenium in the water of the demonstration-scale system than pilot scale. In 2016 molybdenum concentrations in *Carex* tissue were higher than the pilot-scale system, but lower than the 2015 CWTS concentrations. In 2016 zinc concentrations in *Carex* tissue has increased compared to the pilot-scale system and the 2015 demonstration-scale system concentrations. This could be attributed to the increase in zinc in the feed water in 2016 (Figure 20). Additionally, in 2016 molybdenum, selenium, and zinc concentrations in moss increased compared to the 2015 concentrations, which suggests that as mosses are continuing to grow and fill in the wetland. Selenium treatment performance is increasing as mosses are a source of sorption, and also harbor a high abundance of selenate-reducing microorganisms (see Section 10.3.2).

Figure 24 – Moss maturation in CWTS.

Figure 25 – Moss top, bottom, and side view June 2016.

Figure 26 – Maturation of the CWTS from construction to year-end 2016.
Top left picture is of cell 1A, top right picture is of cell 2B, bottom left picture is of cell 1B, and the bottom right picture is of cells 2A and 2B. Continued next page

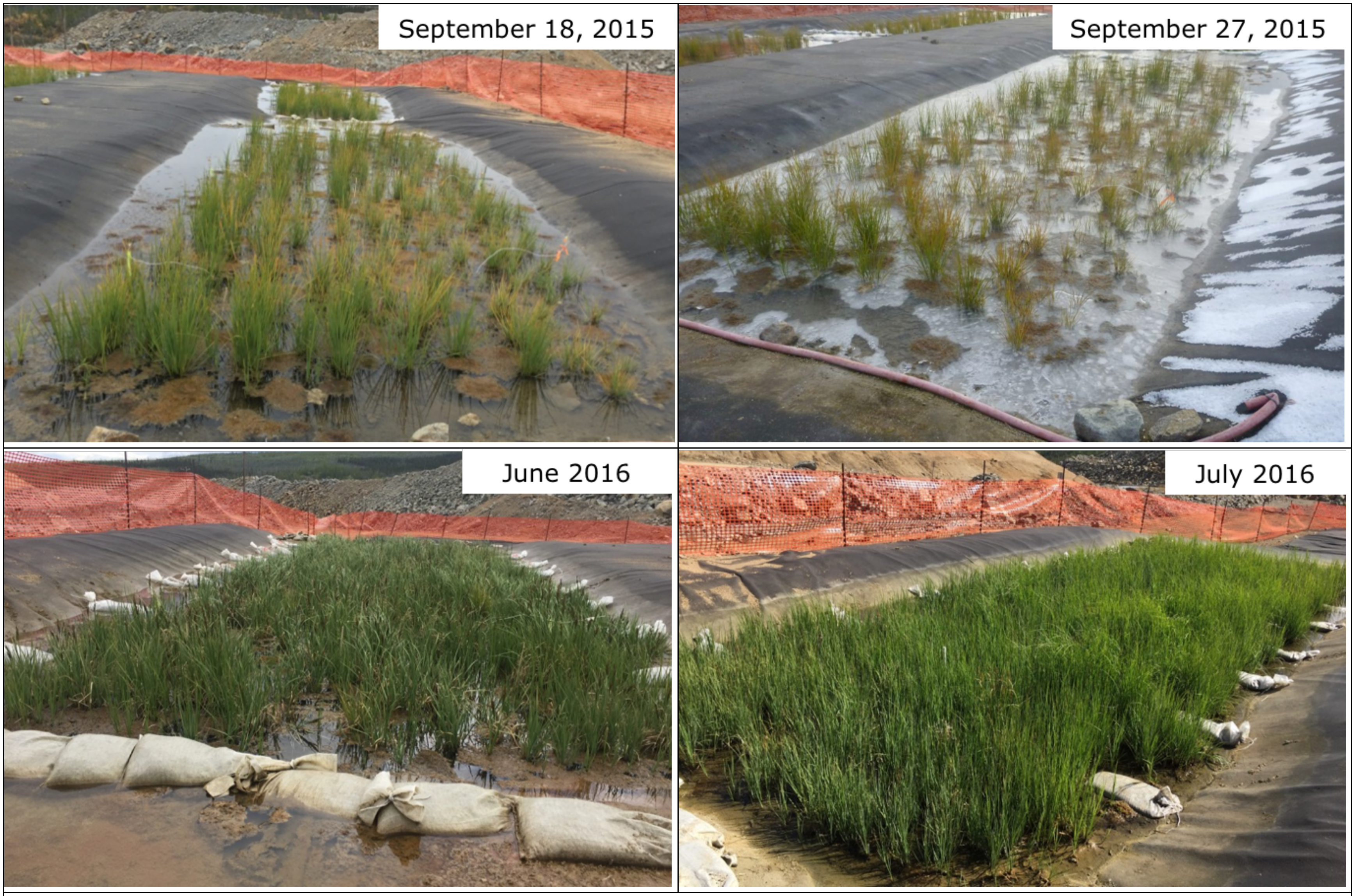


Figure 26 – Continued.
Top pictures are of cell 2A, and bottom picutes are of cell 1B.

September 7, 2016

September 30, 2016

Figure 26 – Continued.
Pictures are of cell 1B.

Figure 27 – Aphids observed in cell 1A and 2A.
Left picture is of cell 1A. Right picture is of cell 2A. Note the increased yellowing in cell 2A due to a denser aphid population.

Figure 28 – Aphids observed on Carex (September 8, 2016).
The top picture is of cell 2A, the bottom picture is of cell 1B. Note cell 2A has more yellowing due to larger aphid population.

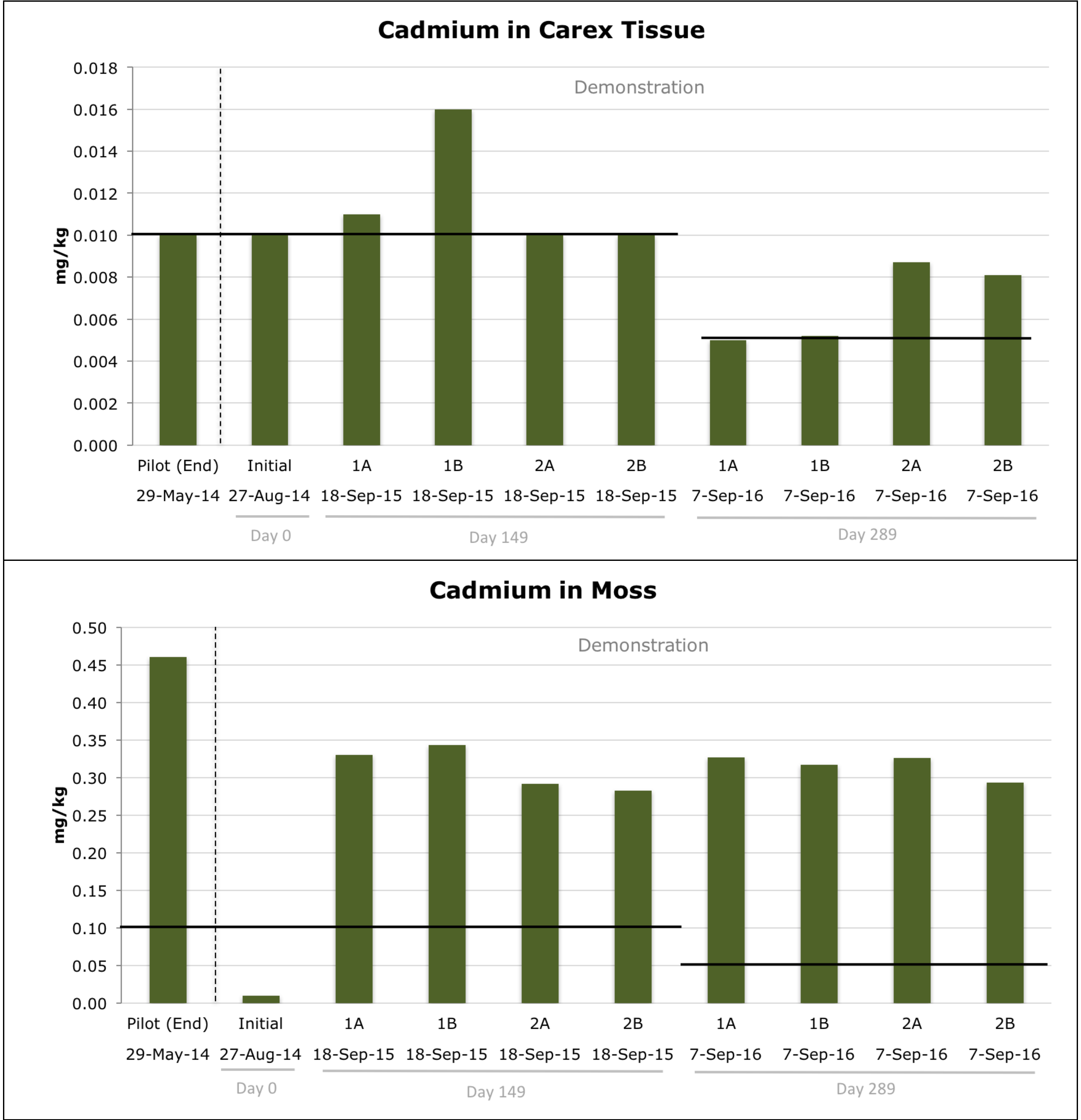


Figure 29 – Cadmium concentrations in plant tissue.
The 2014 and 2015 DL for Cadmium is 0.10 mg/kg. The initial data set is the average value of CWTS 1A-2B. The error bars indicate the minimum and maximum values in that data set.

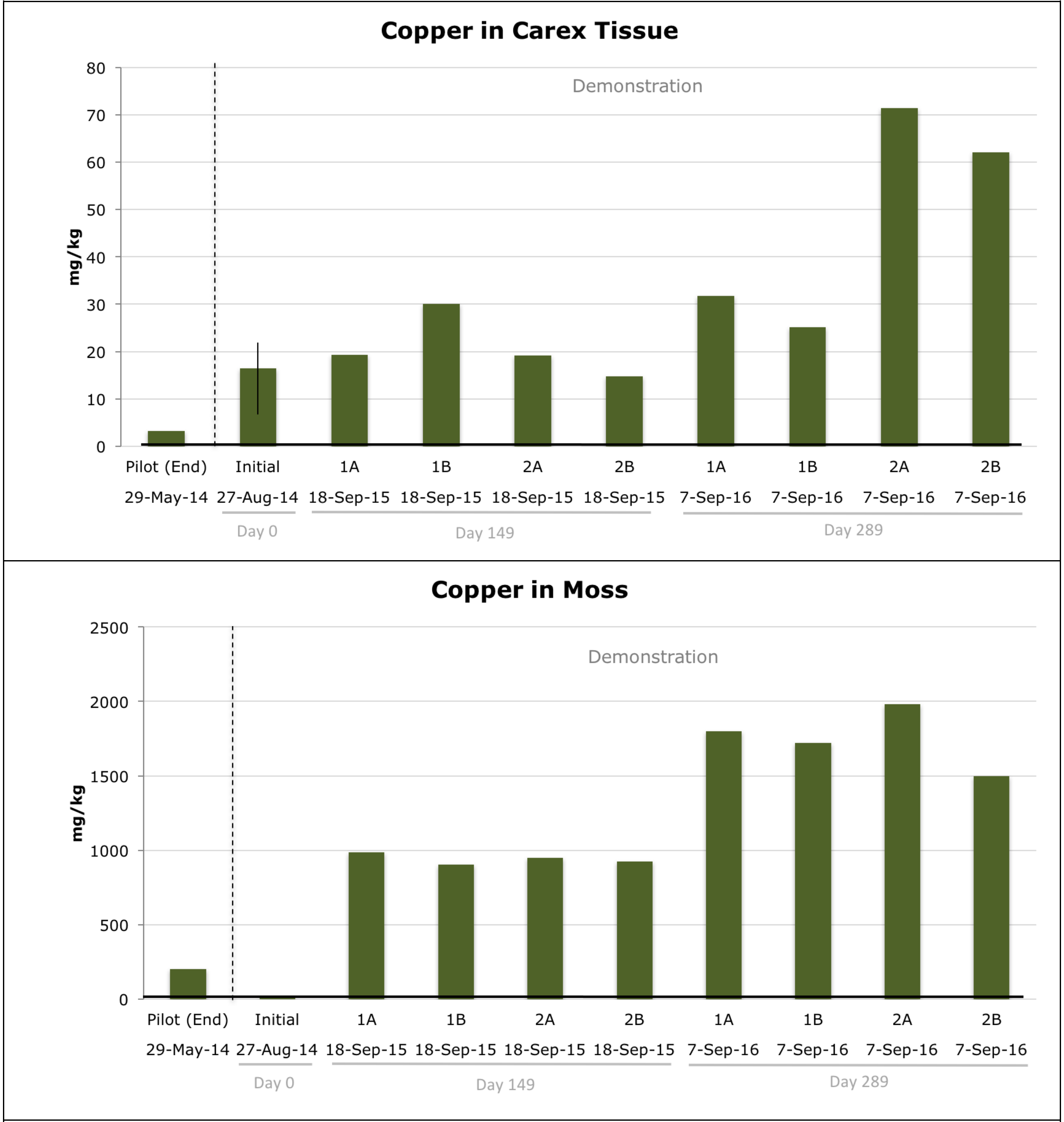


Figure 30 – Copper concentrations in plant tissue.
The 2014 DL for Copper is 0.5 mg/kg, the 2015 DL is 0.1 mg/kg, and the 2016 DL is 0.05 mg/kg. The initial data set is the average value of CWTS 1A-2B. The error bars indicate the minimum and maximum values in that data set.

Figure 31 – Molybdenum concentrations in plant tissue.
The 2014 and 2015 DL for Molybdenum is 0.05 mg/kg, the 2016 DL is 0.020 mg/kg. The initial data set is the average value of CWTS 1A-2B. The error bars indicate the minimum and maximum values in that data set.

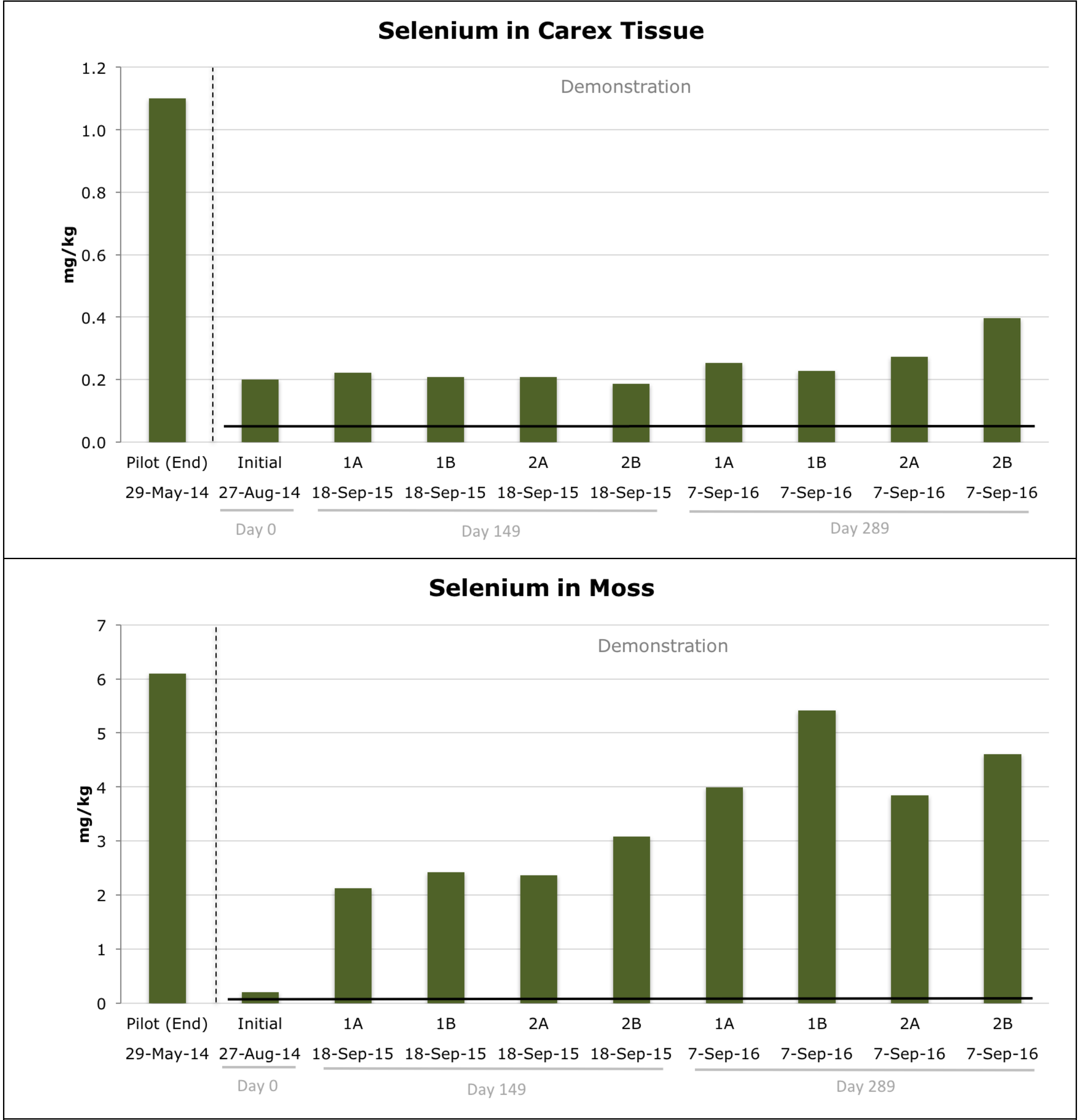


Figure 32 – Selenium concentrations in plant tissue.
The method detection limit for Selenium is 0.2 mg/kg. Initial data set is the average value of replacates used for planting of all CWTS cells. Error bars indicate the minimum and maximum values in that data set.

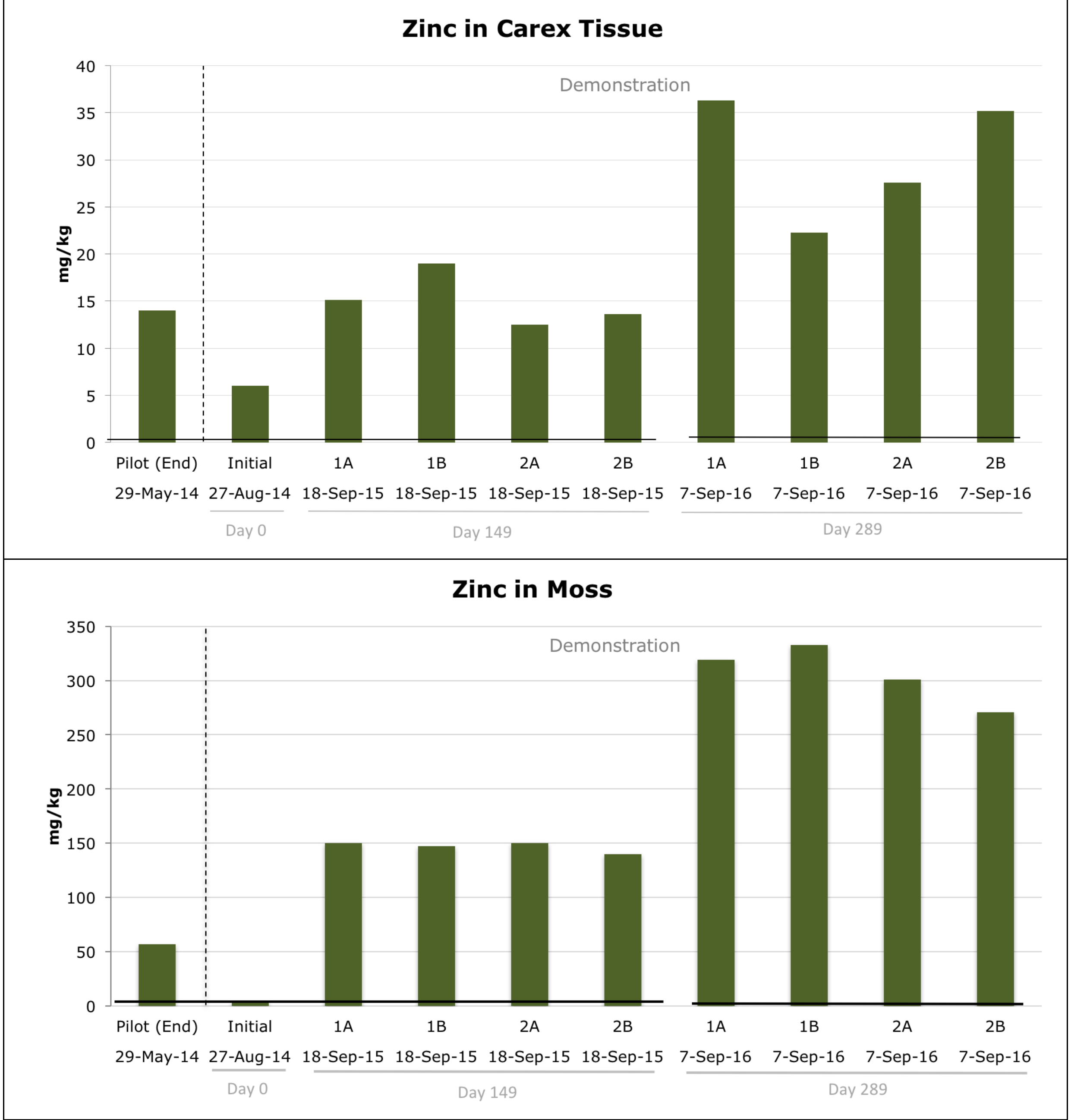


Figure 33 – Zinc concentrations in plant tissue.
The 2014 DL for Zinc is 2.0 mg/kg, the 2015 DL is 0.002 mg/kg, and the 2016 DL is 0.5 mg/kg. The initial data set is the average value of CWTS 1A-2B. The error bars indicate the minimum and maximum values in that data set.

10.3. Beneficial microbes

Microbes are the driving force of many treatment pathways that are targeted in CWTSs. The beneficial microbes in these systems catalyze biogeochemical cycles for remediation of specific constituents of concern. Careful design of CWTSs can create the environmental conditions needed to enhance the abundance and metabolic activity of these beneficial microbes. Accordingly, complimentary methods of genetic and growth-based testing were used to characterize the microbial populations associated with a range of microbial habitats in the demonstration-scale CWTS (e.g., soils, sediment, biofilms, aquatic mosses, and plant roots).

In the context of the Minto Mine CWTS, beneficial microbes include those that are involved in the reduction of selenium (selenate and selenite), nitrate, and sulphur compounds (which in turn can treat copper, cadmium, molybdenum, and zinc). Information on each of these mechanisms and the associated microbial populations in the demonstration-scale system is outlined in the following sections.

10.3.1. Sulphide-producing bacteria

Treatment is achieved by targeting the lithic biogeochemical sequestration of divalent metals through sulfide (i.e., S^{2-}, HS^{-}) precipitation as mineralized species (e.g., chalcocite [CuS], covellite [Cu_2S]). These sulfide bound species are relatively insoluble (CuS; $K_{sp}=10^{-16}$; Stumm and Morgan 1996), and are transferred from the water column into the CWTS soil as non-bioavailable fractions (Murray-Gulde et al., 2003; Huddleston et al., 2008). Moreover, similar reactions occur with cadmium and zinc, rending them non-bioavailable. As such, sulphide production is a key biogeochemical treatment mechanism for water treatment at Minto Mine. Sulphides can be created by beneficial microorganisms through the reduction of sulphur-containing compounds, such as sulphate, sulphite, thiosulphate, and elemental sulphur.

Based on the information gathered in pilot-scale testing, the targeted soil redox for the demonstration-scale CWTS is between -100 and -250 mV. This is in agreement with literature that indicates anaerobic conditions with relatively low ORP (-250 to -100 mV) are necessary for promoting anaerobic metabolisms in bacteria which oxidize organic matter, producing electrons which reduce sulfate to hydrogen sulfide (H_2S) and other reduced sulfide species (i.e. bisulfide ion (HS^{-}), sulfide ion [S^{2-}]; Mitsch and Gosselink 2007). In these redox ranges, bacterial sulphide-production through reduction of sulphur compounds is expected, alongside increases in the proportion (percentage) and abundance of these microbes.

As expected, the proportion of sulphide-producing bacteria increased as the soil redox decreased in the demonstration-scale system through commissioning (Figure 34). The *C. aquatilis* roots were found to harbor high proportions of beneficial sulphide-producing bacteria (SPB), as well as a diversity of SPB (Table 12) which were different types than those found in the soil (Figure 34). This is good as it increases the diversity of bacteria in the CWTS that can carry out the beneficial reaction under a wider range of conditions than a small diversity of organisms could. Mosses, algae, and biofilms were typically associated with low proportions of sulphide-producing bacteria (data not shown), as would be expected in these photosynthetic and oxidizing environments.

Table 12 – Average number of different types of sulphide-producing bacteria in different sample types.

Sample Type	Before organics (all cells)	A cells post organic	B cells post organic
algae/biofilm	2	NT	NT
detritus	NT	6	8
moss	5	4	5
root	9	8	15
soil	7	11	15

NT – not tested. Post organic addition are samples collected in September 2016. The number of different types is based on counting the number of operational taxonomic units (clustered at 97% identity) that are classified as known sulphide-producing bacteria.

In addition to assessing the proportion of the community that are SPB, the inferred abundance of SPB was analyzed for all sample types (Figure 35). Soil and root samples were found to have the highest inferred abundances of sulphide-producing bacteria per gram of sample, while mosses typically had lower abundances. The black bottom part of the moss had ~100x more sulphide-producing bacteria per gram than the top part of the moss collected from the same location (Figure 24). This is desired as the mature mosses begin to show characteristics of the desired coupled transfer and transformation processes (with new biomass, and decomposition of older bottom; Section 10.1.2).

The overall abundance of sulphide-producing bacteria in the B cells have also increased in the soil and *C. aquatilis* root samples of the CWTSs over time, particularly in series 1 after the addition of organics (Figure 35). There was also an increase in the average number of different types of sulphide-producing bacteria in samples after the addition of organics (Table 12, Figure 34). The addition of organics was done to provide carbon sources needed by sulphide-producing bacteria and to provide the desired sulphur- and selenium-reducing conditions. It is anticipated the addition of organics will continue to provide the necessary carbon source to stimulate desired reducing conditions and microbial populations in 2017, and until the vegetation has established sufficiently to provide this carbon source annually going forward.

The microbial analysis of various sample types in the CWTS has therefore confirmed that the commissioning period is proceeding as expected, with beneficial sulphide-producing bacterial populations establishing in the soils alongside reducing conditions, which will continue to be monitored for stability or further improvement in 2017.

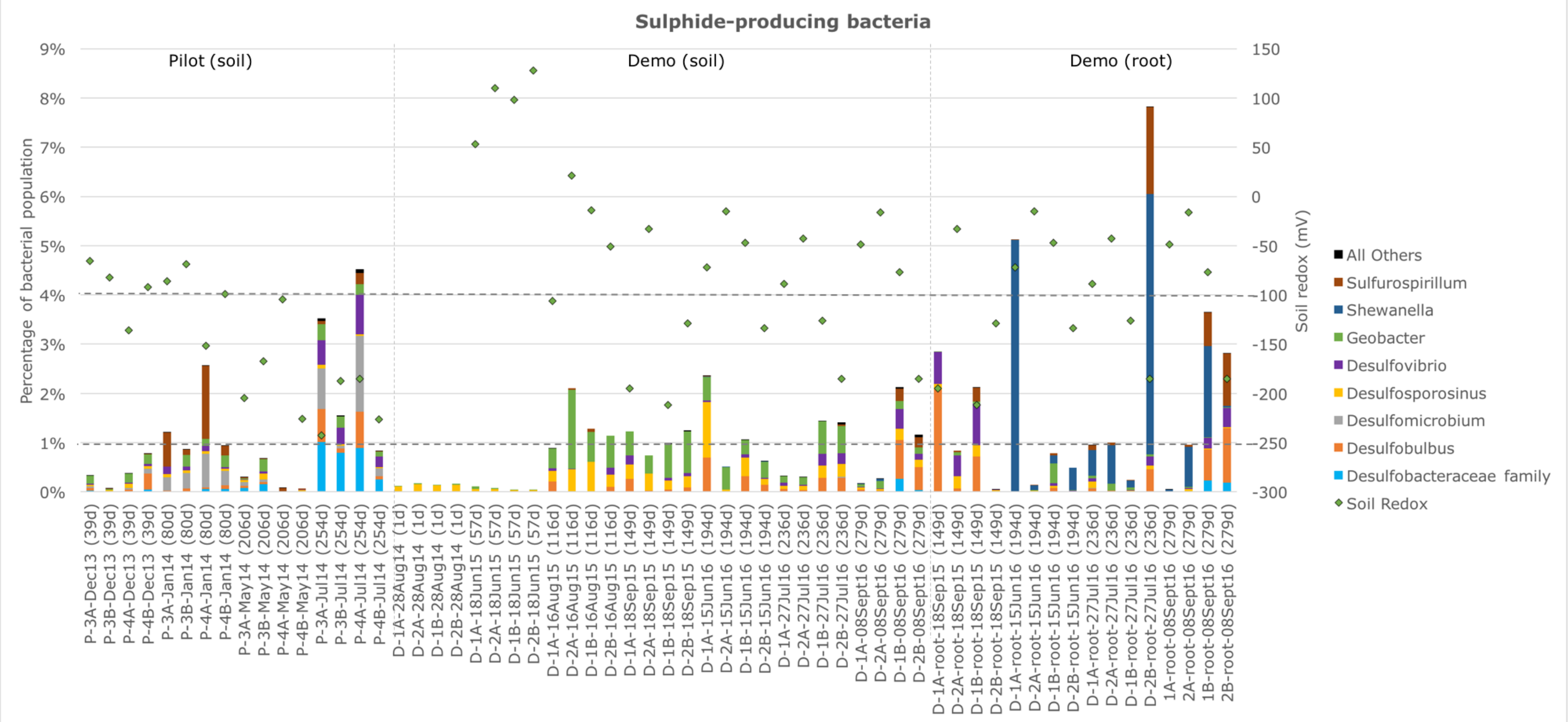


Figure 34 – Percentage and identity of sulphide-producing bacteria in soil of the pilot-scale and demonstration-scale CWTSs.

The vertical dashed lines separate the pilot-scale system data from the demonstration-scale system 1 and system 2 data. The horizontal dashed lines indicate the targeted soil redox range. Organism classifications and data analysis methods have been updated from Contango (March 2016).

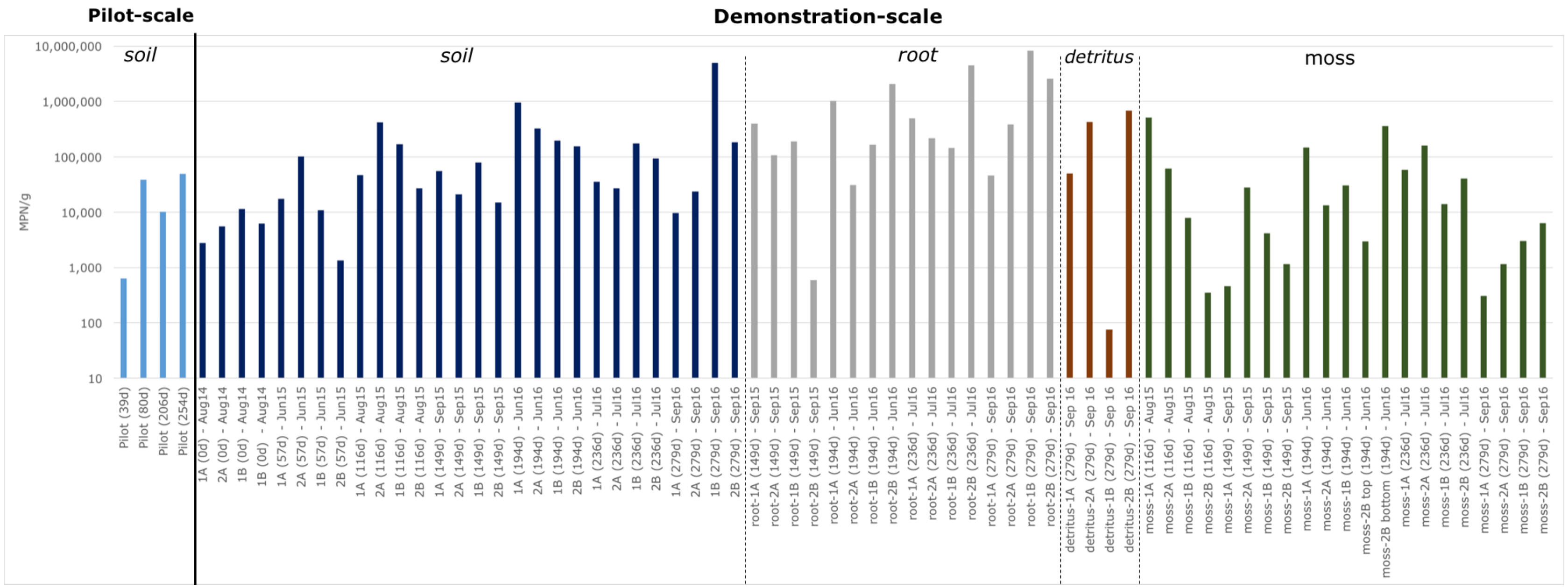


Figure 35 – Inferred abundance of sulphide-producing bacteria in soil of the pilot- and demonstration-scale CWTSs.

Inferred abundance is calculated based on a combination of genetic and growth-based data.

Shallow soil (0-5 cm); deep soil (10-20 cm); soil at 0d was that used for construction of wetland.

10.3.2. Selenium-reducing bacteria

The targeted selenium treatment pathways in the Minto CWTS include sorption to moss and soils, and subsequent microbial reduction of soluble (sorbed) selenate (Se(VI)) and selenite (Se(IV)) to insoluble elemental selenium (Se(0)). This reductive process can also be achieved directly in the water column, but is more effective associated with mosses and biofilms due to their sorptive properties that bring the selenium in contact with beneficial selenium-reducing bacteria. This is achieved within the range of soil redox conditions targeted for sulphate-reduction as suggested by pilot-scale testing and literature (see Section 5).

Selenite-reducing organisms are ubiquitous in nature and as expected, were detected in all sample types, including algae, biofilm, moss, soil, sediment, roots, and detritus. Although organisms that reduce selenate to elemental selenium (rather than intermediary selenium compounds) are generally less abundant in the environment, they were found associated with all sample types, indicating that the conditions conducive to their proliferation have been created within the CWTS. Moreover, the abundance of selenite- and selenate-reducing organisms increased over time in the demonstration-scale system during the commissioning period (Figure 36). Aquatic mosses were found to initially host the highest abundances of both selenate- and selenite- reducing organisms, affirming the importance of the inclusion of moss in the CWTS. Over time, as the vegetation has established, selenium-reducing bacteria have increased in abundance on the roots of *C. aquatilis,* and were also found associated with the added organic material once it began decomposing (Figure 36

These findings indicate the demonstration-scale CWTS has established beneficial selenium-reducing microbes in several areas of the wetland, which would be involved in selenium removal in the CWTS (either by reducing selenium that has been sorbed to moss or detritus, or by interacting directly with selenium in water that has been drawn into the root zone by plants). Their abundance is similar to what was found during pilot-scale testing in the soil, indicating they have established as expected. Selenium-reducing microorganisms will continue to be monitored in 2017, alongside performance testing.

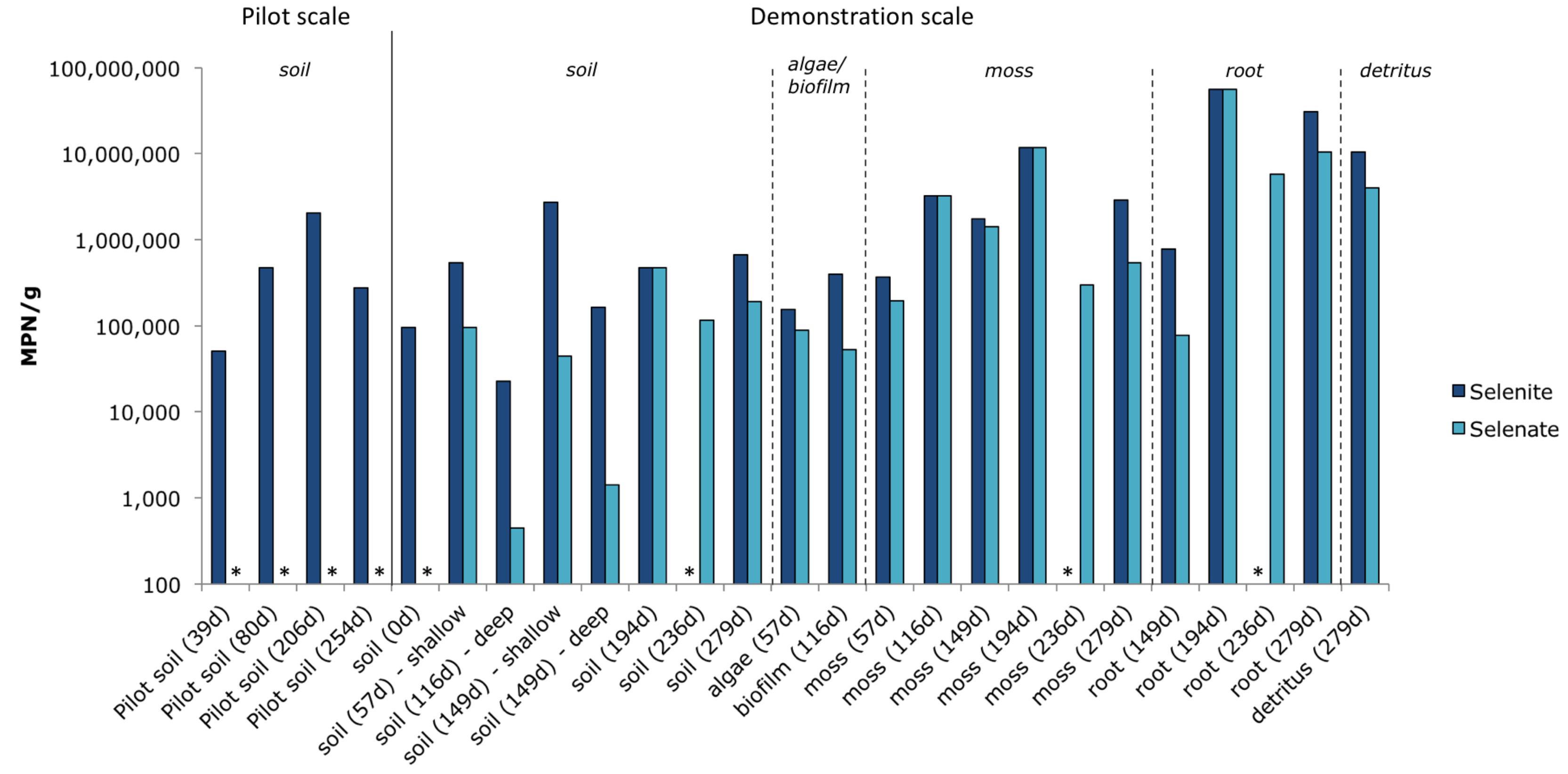


Figure 36 – Abundance of selenite- and selenate-reducing organisms in various CWTS sample types over time.
* Selenite or selenate not tested at this timepoint
Shallow soil (0-5 cm); deep soil (10-20 cm); soil at 0d was that used for construction of wetland. Organics material was added to the wetland after day 236.

10.1. Nitrate-reducing bacteria

Nitrate is sometimes a constituent of concern during operations and early closure owing to residuals from blasting activities. Even if not in exceedance of water quality guidelines in terms of receiving environment objectives, nitrate often requires attention to achieve treatment of other constituents. The presence of nitrate can interfere with the treatment of certain elements in water (such as selenium). Nitrate can be removed from water by different types of microbes, including nitrate reducing bacteria which can reduce nitrate (NO_3) to nitrite (NO_2), and also denitrifying organisms that are capable of fully reducing nitrate to nitric oxide (NO), nitrous oxide (N_2O), and dinitrogen gas (N_2 - which is the most abundant gas in air). MPN analysis was therefore used to quantify these organisms.

Nitrate-reducing and denitrifying organisms were found associated with all sample types in the demonstration-scale CWTS (Figure 37). Roots and detritus had a high abundance of both nitrate and denitrifying organisms, with soil being similar to what was found during pilot-scale testing. These results indicate nitrate reducers have established in the CWTS during the commissioning period as expected. Nitrate-reducing microorganisms will continue to be monitored in 2017, alongside performance testing.

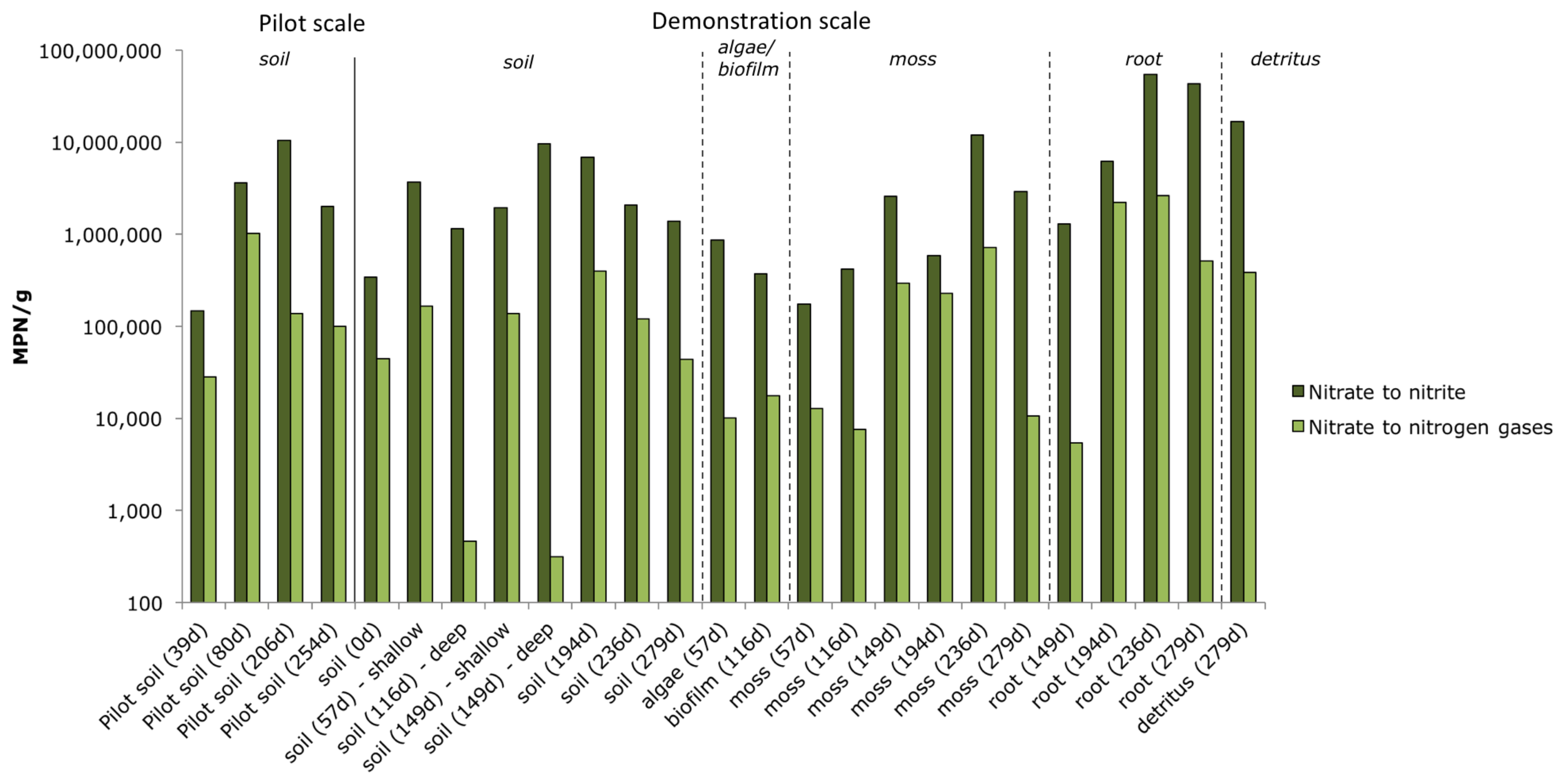


Figure 37 – Abundance of nitrate-reducing and denitrifying organisms in various CWTS sample types over time.
Nitrate-reducing = reduction of nitrate to nitrite; denitrifying = reduction of nitrate to nitrogen gases.
Shallow soil (0-5 cm); deep soil (10-20 cm); soil at 0d was that used for construction of wetland.

11.Summary of results

Table 13 summarizes results and findings from 2015 - 2016 commissioning of the demonstration-scale system at Minto.

Table 13 – Summary of Minto demonstration-scale 2015 - 2016 testing.

Objective	Purpose	Key Findings or Changes for Full-scale
Evaluate construction	Optimize construction and effectiveness of operation of full-scale systems	**Layout** -Outflow collection pond should have outflow at base (not top), with shutoff valve. -In 2016 sandbags were added at shores to prevent water short circuiting. Sandbags were also added to the outflow of series 1 to increase water depth.
		Soils -Use substrate with less total and leachable metals and metalloids (especially copper). -Higher sand content would improve hydrology, constructability (ability to level soils, ease of planting) and accessibility for sampling. -Organics should be mixed in bulk to soils prior to adding to cells.
Assess commissioning timelines	Allow for proper phasing of implementing full-scale systems for closure	**Water** -Commissioning-A period was complete at the end of July 2016 and the commissioning-B period (addition of organics to remediate the copper in substrates used) began July 29, 2016 and is ongoing. -Copper is being treated by the CWTS, and during the commissioning-B period the average influent concentration decreased by 37% compared to the average outflow concentration. -The wetland is achieving better treatment than suggested by inflow and outflow concentrations of the system, as soils are leaching aluminum and copper into the water. -Cadmium and zinc are also being treated in the CWTS, and during the commissioning-B period, the average outflow

Objective	Purpose	Key Findings or Changes for Full-scale
		concentrations were 64% and 69% lower than average influent concentrations respectively. - Molybdenum and selenium experienced notably greater treatment after during the commissioning-B period. The average outflow concentrations were 21% and 41% lower than average influent concentrations respectively. -The wetland is maturing as expected and is performing beyond anticipated based on the design. - Cadmium, copper, molybdenum, and selenium % removal and *k* rates are increasing over time. Zinc % removal is increasing over time. - HRT tracer study conducted in 2016 assessed hydrology and pore volume incorporation of the CWTS and determined HRT and removal rate coefficients for full-scale sizing. Rate coefficients should be re-evaluated after commissioning-B is completed. -Evapotranspiration study conducted to determine amount of evapotranspiration occurring in the CWTS in warmer months and to incorporate into load removal models. Due to rain the results were inconclusive and should be redone in 2017.
		Soils -Soil redox not consistently reaching targeted ranges by July 2016 therefore organics were added to stimulate desired reducing conditions, which marked the end of commissioning-A and the beginning of commissioning-B. -Cell 2B consistently reaching targeted ranges by the end of 2016. -In 2015 significant amounts of metals were leaching from soil substrate into water, putting additional treatment demands on system. In 2016 the amount of metals leaching from soil substrate into the water has decreased.
		Microbes -Sulphide-producing bacteria needed for copper and other metals removal have increased through the commissioning period as soil redox approached targeted ranges. Proportions are comparable to

Objective	Purpose	Key Findings or Changes for Full-scale
		those in pilot system at similar points in commissioning. After the addition of organics which marked the end of the commissioning-A period and the beginning of the commissioning-B period, sulphide-producing bacteria continued to increase, especially in the soil and roots in the B cells. -Abundance of selenium- and nitrate-reducing organisms are similar to those in pilot testing, indicating maturation as expected. -Selenium treatment performance increased through the commissioning period as mosses continued to grow, as they can sorb dissolved selenium and harbour highest abundance of selenate-reducing microorganisms to render the selenium insoluble. After the addition of organics which marked the end of the commissioning-A period, selenium-reducing bacteria were also associated with the added organic material once it started decomposing. Therefore the CWTS has established beneficial selenium reducing bacteria in several areas of the wetland (moss, detritus, roots, and soil).
Carex aquatilis transplantation effectiveness	Determine if plant propagation and/or replanting schedule will be needed for full-scale systems	->95% survival from transplanting. -Within first 2 months a further increase of >20%. -Full-scale system could be planted more densely to bring online faster, or less densely if time is less of an issue than sourcing plants (the plants are vigorous and will fill in the wetland in due time). - By the end of 2016 the plants had densely filled in the CWTS and transplanting was considered a success.
Moss colonization/distribution		-100% survival from transplanting. -Slower to spread, needs to be started more densely. -Staking helps maintain moss in ‘upstream’ parts of wetland, or could be transplanted multiple times through commissioning period. - Moss continued to mature in 2016 and does not appear to require additional transplanting.

12.Schedule and action items for 2017

Based on the performance results through 2015 and 2016, an action plan for CWTS optimization and testing for 2017 has been developed (Table 14). An updated multi-year schedule as per the proposed scope of work in the Minto Demonstration Scale Report Document 011_0315_01A (Contango, March 2015) is provided in Appendix C.

Table 14 – Minto 2017 CWTS demonstration-scale action items.

Who/When	Task	Contango Action Required	Additional Information
Minto Staff, prior to first site visit	Set flow rates at constant flow	Develop flow rate based on 2016 tracer study.	Do not change flow rate throughout year. Evaluate stability of wetland performance over one year, apply adjustments to models for full scale as necessary.
Contango site visit 7 (May/June 2017)	HRT Tracer study (salt)	Complete a second tracer study optimized from 2016 findings.	Coordinate an additional 1 m^3 tank at the CWTS site and a power source for the YSI.
	Aphid control (if needed)	Determine the appropriate method for aphid control.	
	General follow up	Complete seasonal sampling.	
Contango site visit 8 (July/August 2017)	Evapotranspiration study	Determine length of time and appropriate timeline to conduct the evapotranspiration study	Ensure the evapotranspiration study will not affect other planned activities at the site.
	General follow up	Complete seasonal sampling.	
Contango site visit 9 (September 2017)	General follow up	Complete seasonal sampling.	
Contango data monitoring throughout 2017 operations	Monitor metals leaching from soils	If metals continue to leach in 2017, flows could be stopped temporarily to promote this shift from oxidized to reduced forms. With the additional carbon sources of straw and wood chips now available for the bacteria to use to produce more sulphides for metals treatment	
	Monitor soil redox	Determine when it consistently reaches targeted range.	
December 2017	Report	2017 Update Report.	

13. 2017 Monitoring plan

A conceptual testing plan was developed for the demonstration-scale CWTS and has been refined and adapted based on performance and scientific findings. The demonstration-scale wetlands are expected to run until at least the end of 2018 in order to assess performance under a wider range of conditions. The conditions that are planned to be tested include both natural/environmental and selected influenced pressures, and can be imposed on the systems to mimic peak flow rates or droughts. In 2016 the systems completed the commissioning-A period and began the commissioning-B period, with plants becoming more established and abundant, microbial communities acclimating to the targeted conditions, and soil redox beginning to achieve targeted ranges. In 2017 the monitoring program will shift focus to testing of operations and performance. A multi-year plan is provided in Appendix C, and includes work performed to date as well as a schedule for 2017 and potential activities for 2018.

14. Closure

We trust the information herein satisfies your present requirements. Should you have any questions, please contact the persons listed below. We appreciate the opportunity to provide the services detailed in this report, and look forward to discussing any comments you may have.

Respectfully submitted,

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with contributions from: Jenny Liang, BSc

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Appendix A

Table 1 - Summary of analytical sampling types, frequencies and locations.

Water	
Dissolved and total metals	Weekly, outflow of each cell and feed
Ammonia	
Nitrate	
Nitrite	
Flow rate	Weekly, feed
pH, DO, ORP, Conductivity (in situ)	Weekly, all cells and feed
Anion Sum	Monthly, outflow of each cell and feed
Cation Sum	
Hardness ($CaCO_3$)	
Ion Balance	
Total Dissolved Solids (TDS)	
Chloride (Cl)	
Sulphate (SO_4)	
Nitrogen (Total)	
Alkalinity	
pH	
Conductivity	
Chemical Oxygen Demand (COD)	
Total Organic Carbon (TOC)	
Total Kjeldahl Nitrogen (TKN)	
Total Suspended Solids	
Dissolved Organic Carbon (DOC)	
Bicarbonate (HCO_3)	
Carbonate (CO_3)	
Hydroxide (OH)	
Soil	
Relative soil redox (in situ)	Monthly, all probes (6 per cell)
Analyses completed on soil sample	
SAR, pH, EC, %sat, Ca, F, Mg, Na, K, Cl, SO4	Seasonally (3x per year) from a depth of 0-10 cm.
Available NPK and sulphur	
Alkalinity	
Bicarbonate (HCO_3)	
Carbonate (CO_3)	
Total Organic Carbon (TOC)	
Metals Analysis (Total)	
Sulfur by LECO	
Metals Leach	
AVS+SEM	

Sequential Leaching (5 Acid Test)	
Metals SPLP	Spring Sampling (1x per year).
Analyses completed on special leach	
Bromide (Br)	Seasonally (3x per year)
Chloride (Cl)	
Sulphate (SO_4)	
Fluoride (F)	
Alkalinity	
Bicarbonate (HCO_3)	
Carbonate (CO_3)	
Hydroxide (OH)	
Dissolved Organic Carbon (DOC)	
Ammonia	
Nitrate	
Nitrite	
Total Dissolved Solids	
Anion Sum	
Cation Sum	
Cation/EC ratio	
Ion Balance	
Plant tissue samples	
Metals Analysis	*Carex aquatilis* and aquatic moss, each cell, year end
Microbial samples	
Growth-based most-probable number analysis (nitrate reduction, selenite and selenate reduction, total heterotrophs)	Seasonally (3x per year)
Genetic sequencing analysis for bacterial community composition and distribution	Seasonally (3x per year)

Appendix B – Additional graphs

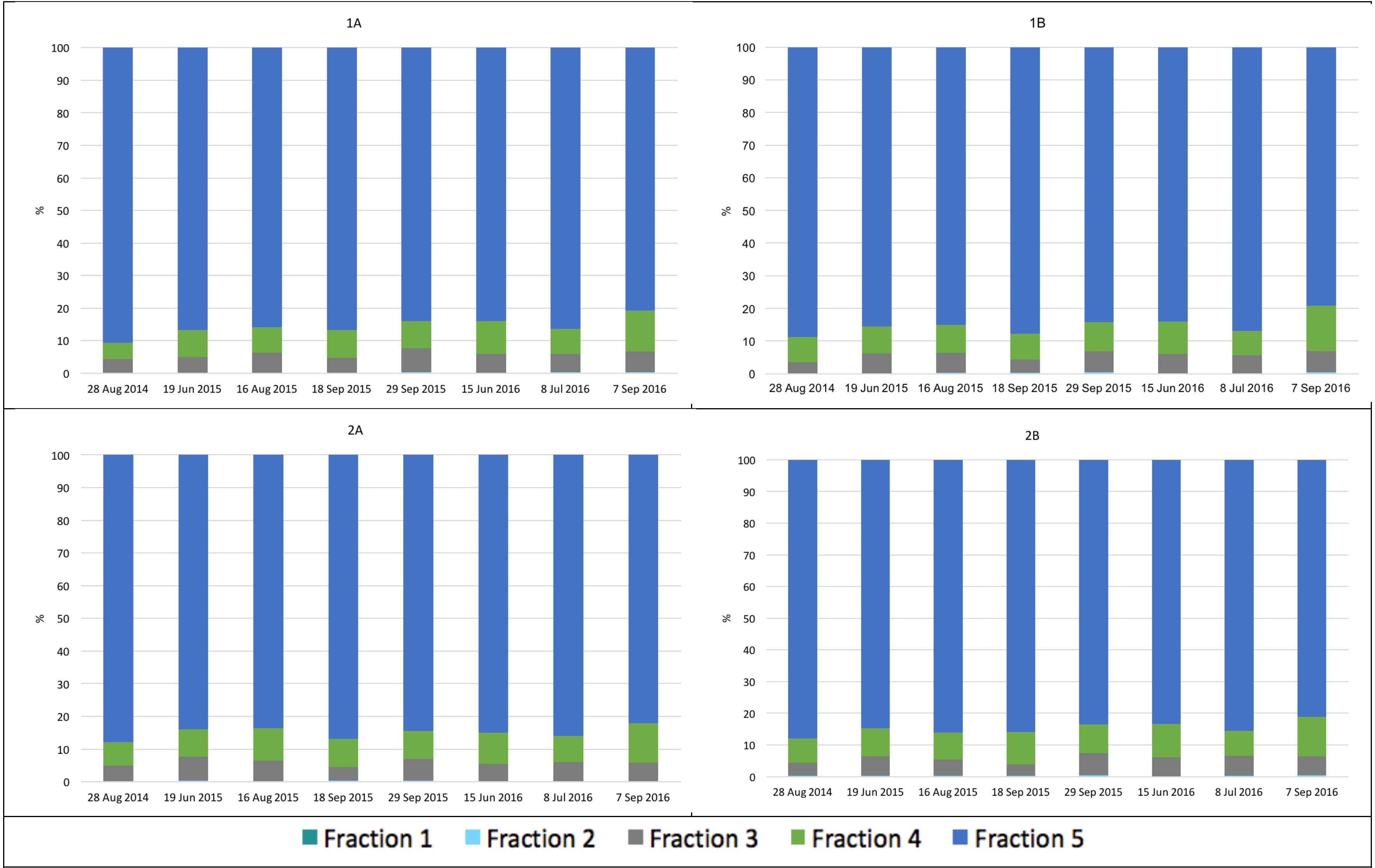

Figure B1 – Fraction distribution of aluminum expressed as percent over time (2015, 2016).

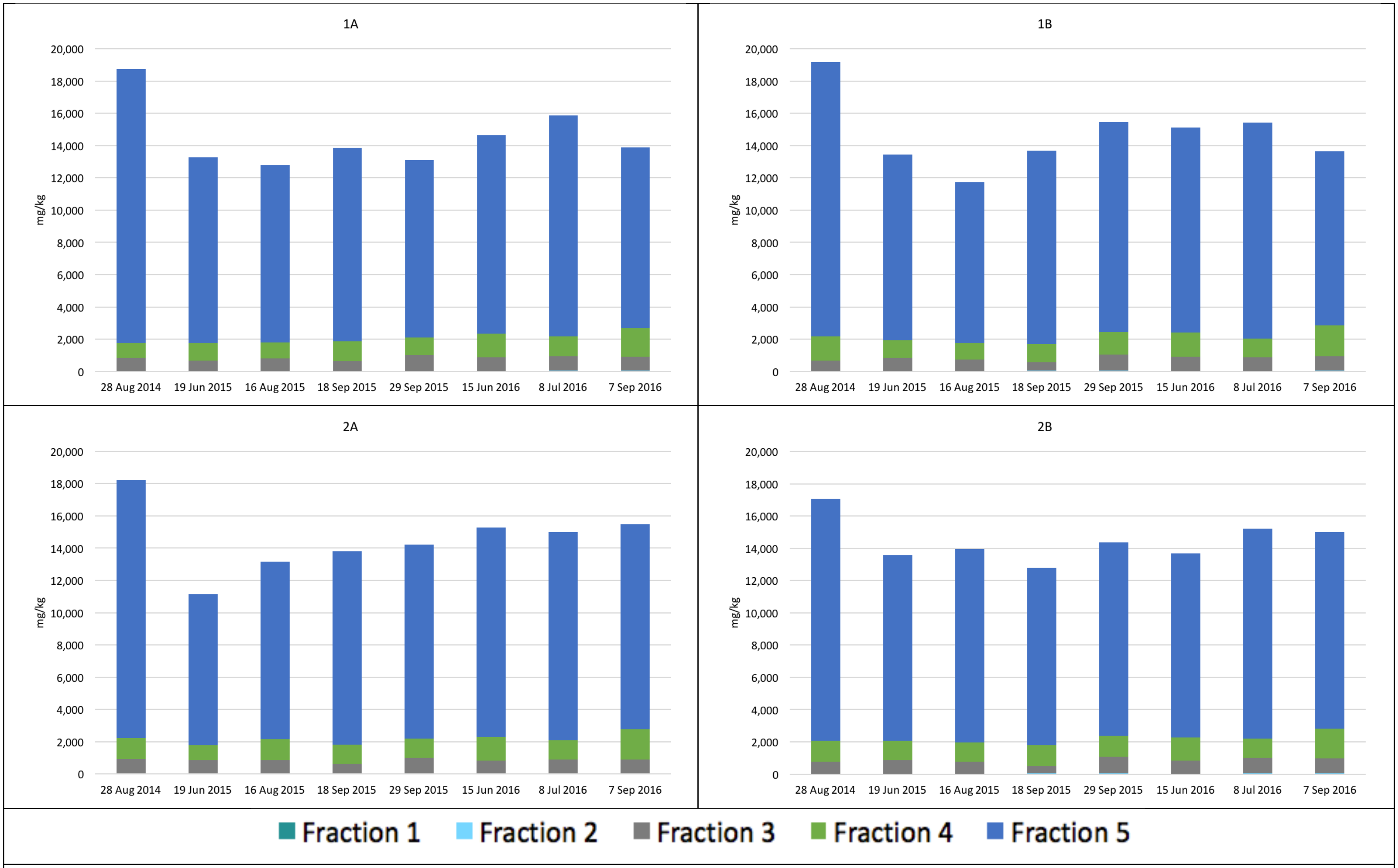

Figure B2 – Fraction distribution of aluminum expressed as mg/kg over time (2015, 2016).

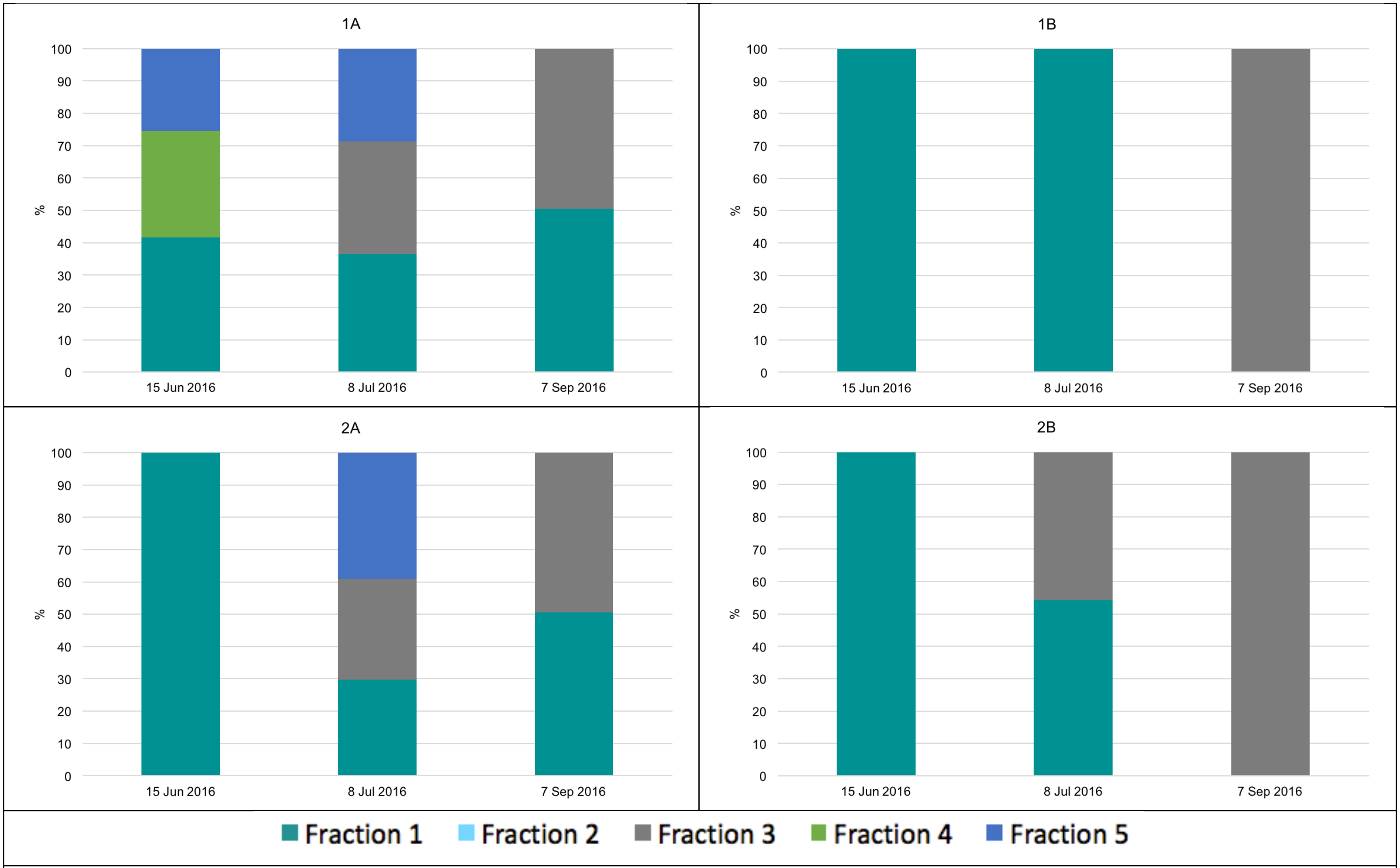

Figure B3 – Fraction distribution of cadmium expressed as percent over time (2016).
Data in 2014 and 2015 was below detection limits.

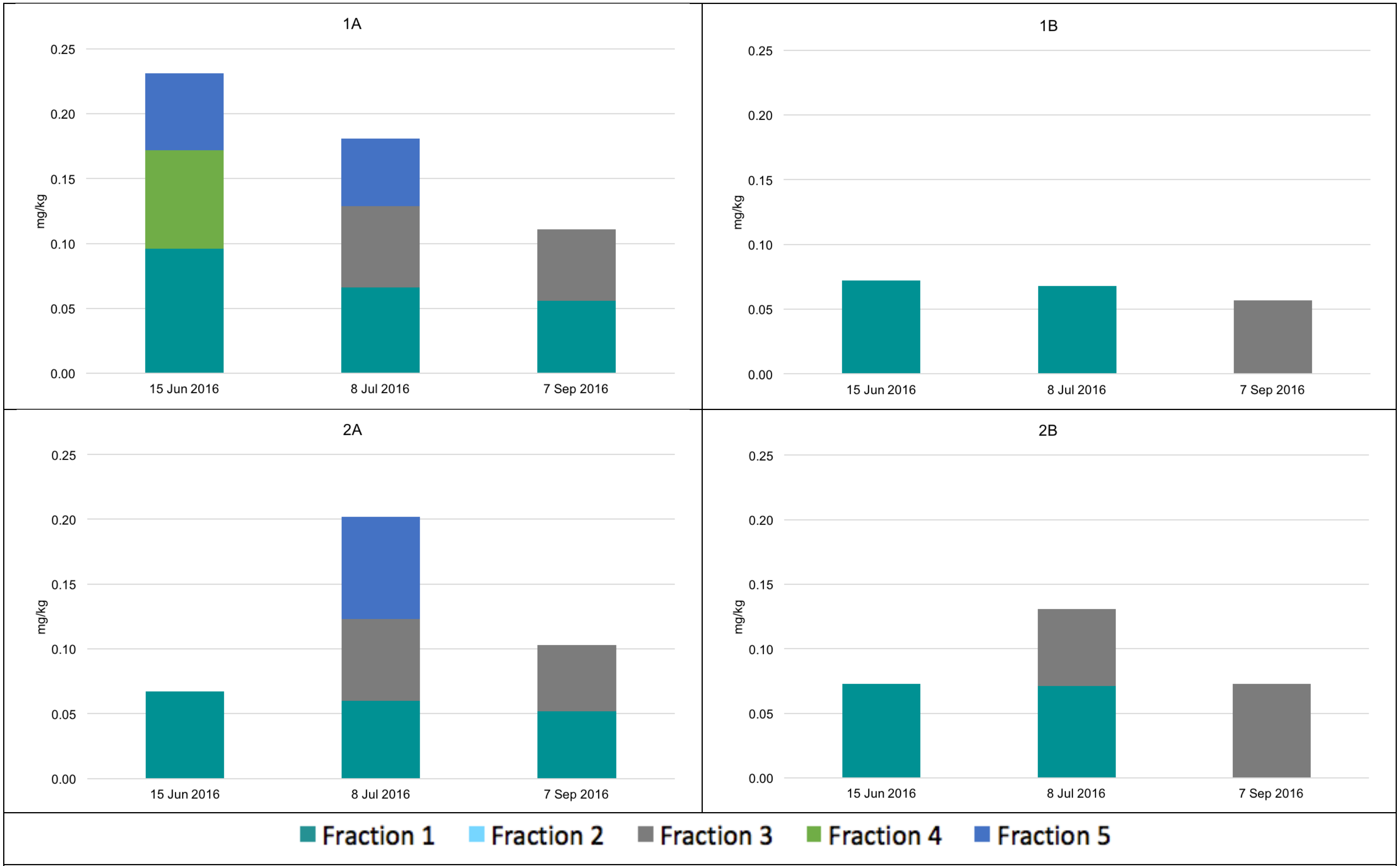

Figure B4 – Fraction distribution of cadmium expressed as mg/kg over time (2015, 2016).
Data in 2014 and 2015 was below detection limits.

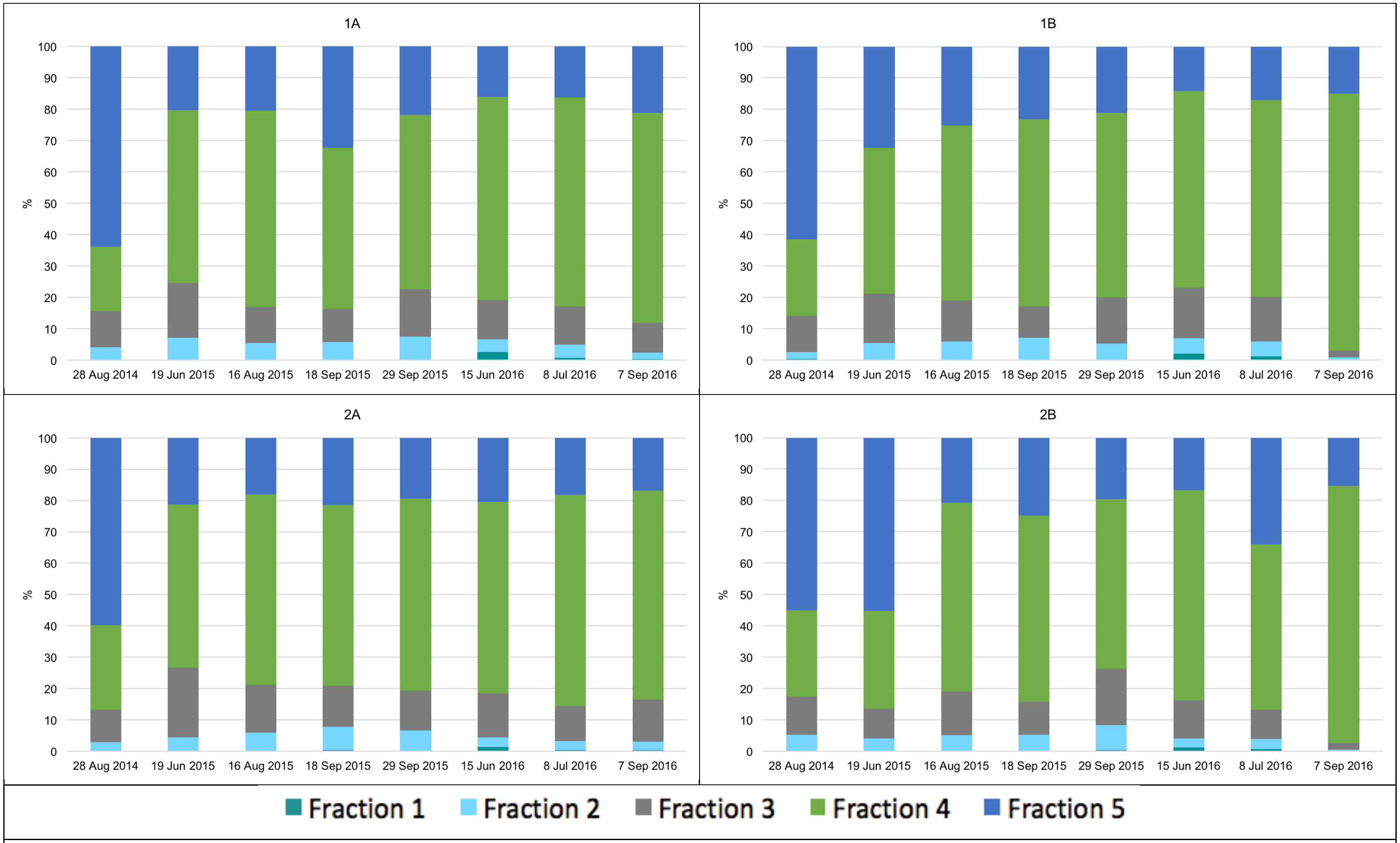

Figure B5 – Fraction distribution of copper expressed as percent over time (2015, 2016).

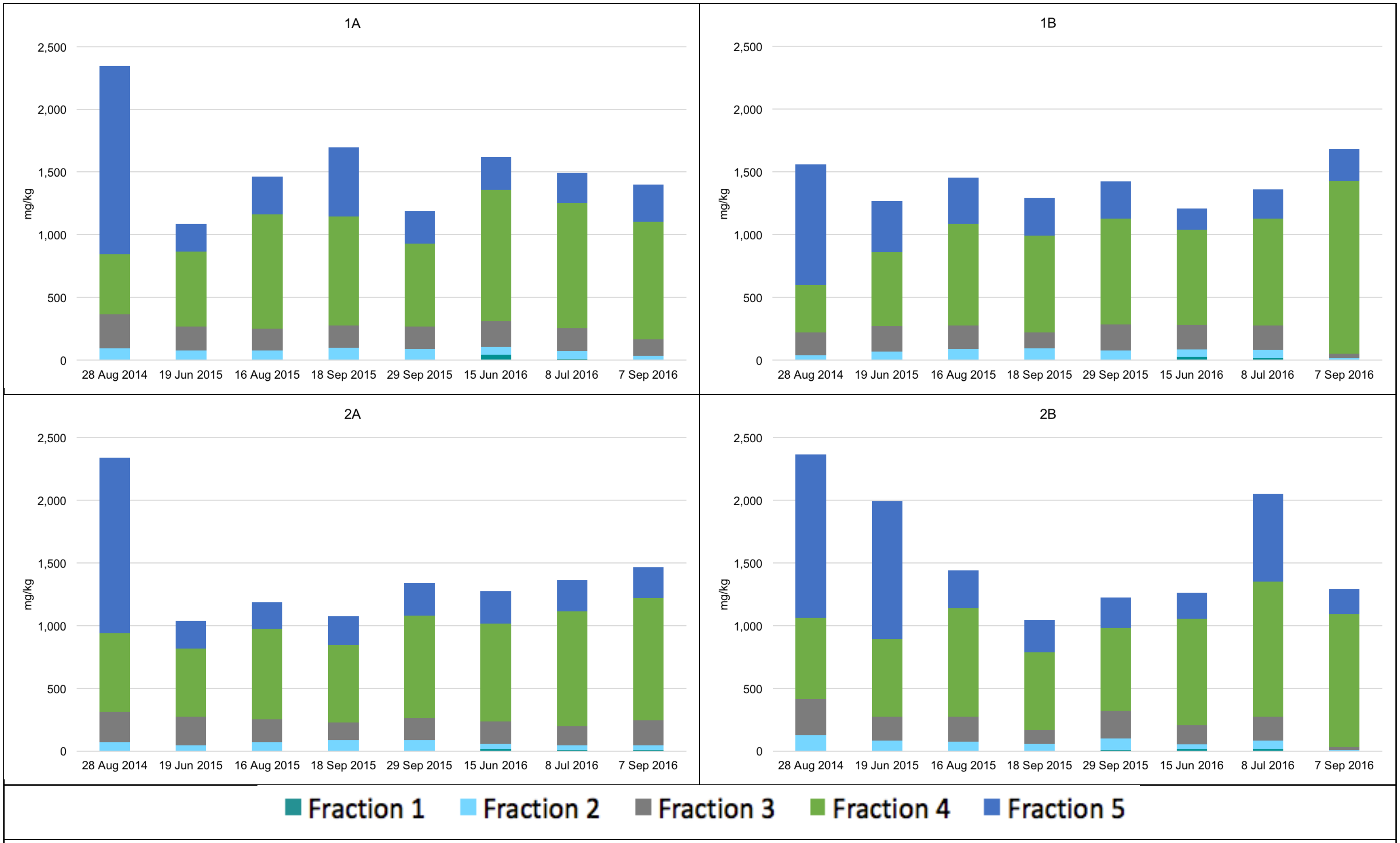

Figure B6 – Fraction distribution of copper expressed as mg/kg over time (2015, 2016).

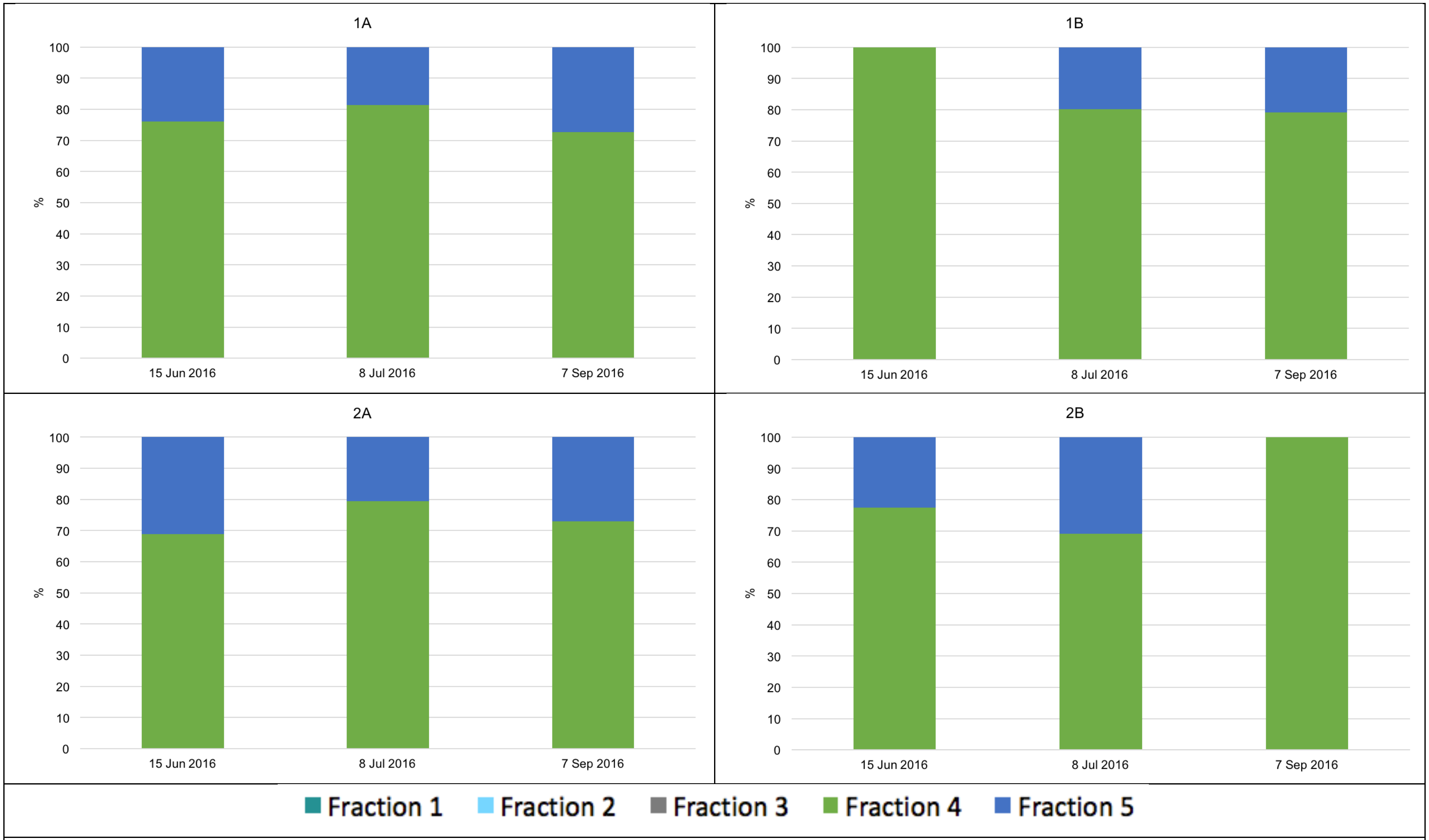

Figure B7 – Fraction distribution of selenium expressed as percent over time (2016).
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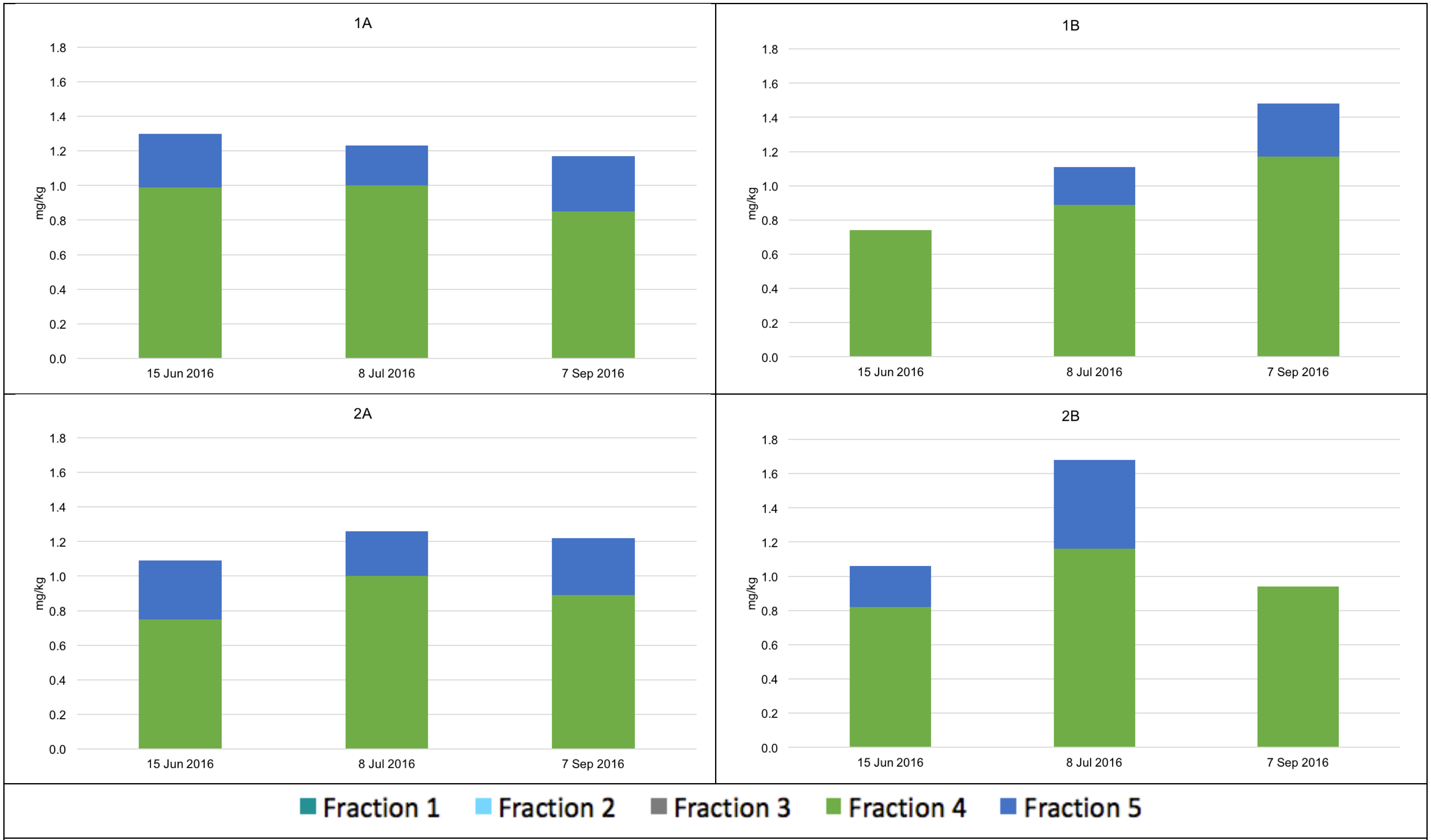


Figure B8 – Fraction distribution of selenium expressed as mg/kg over time (2015, 2016).
Data in 2014 and 2015 was below detection limits.

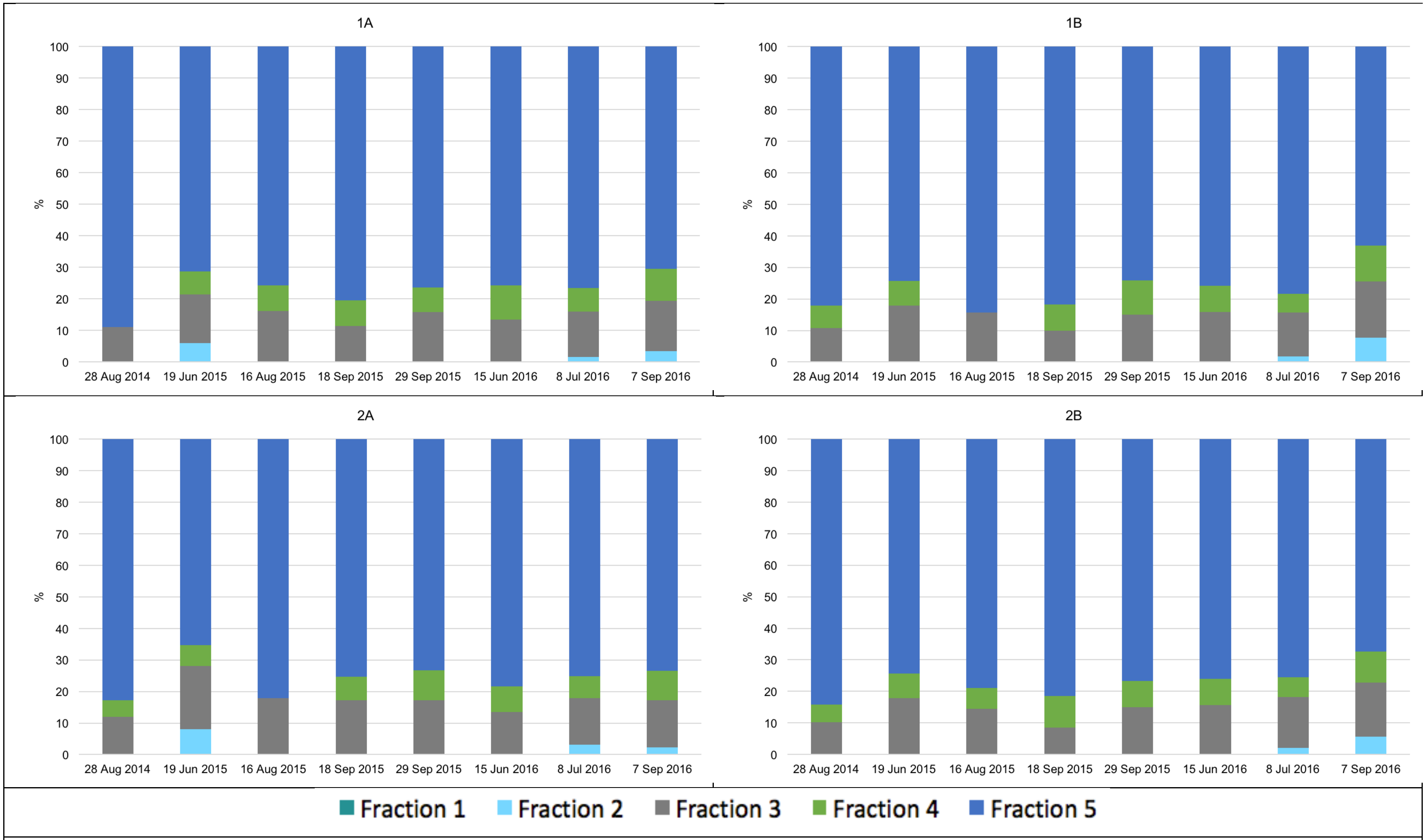


Figure B9 – Fraction distribution of zinc expressed as percent over time (2015, 2016).

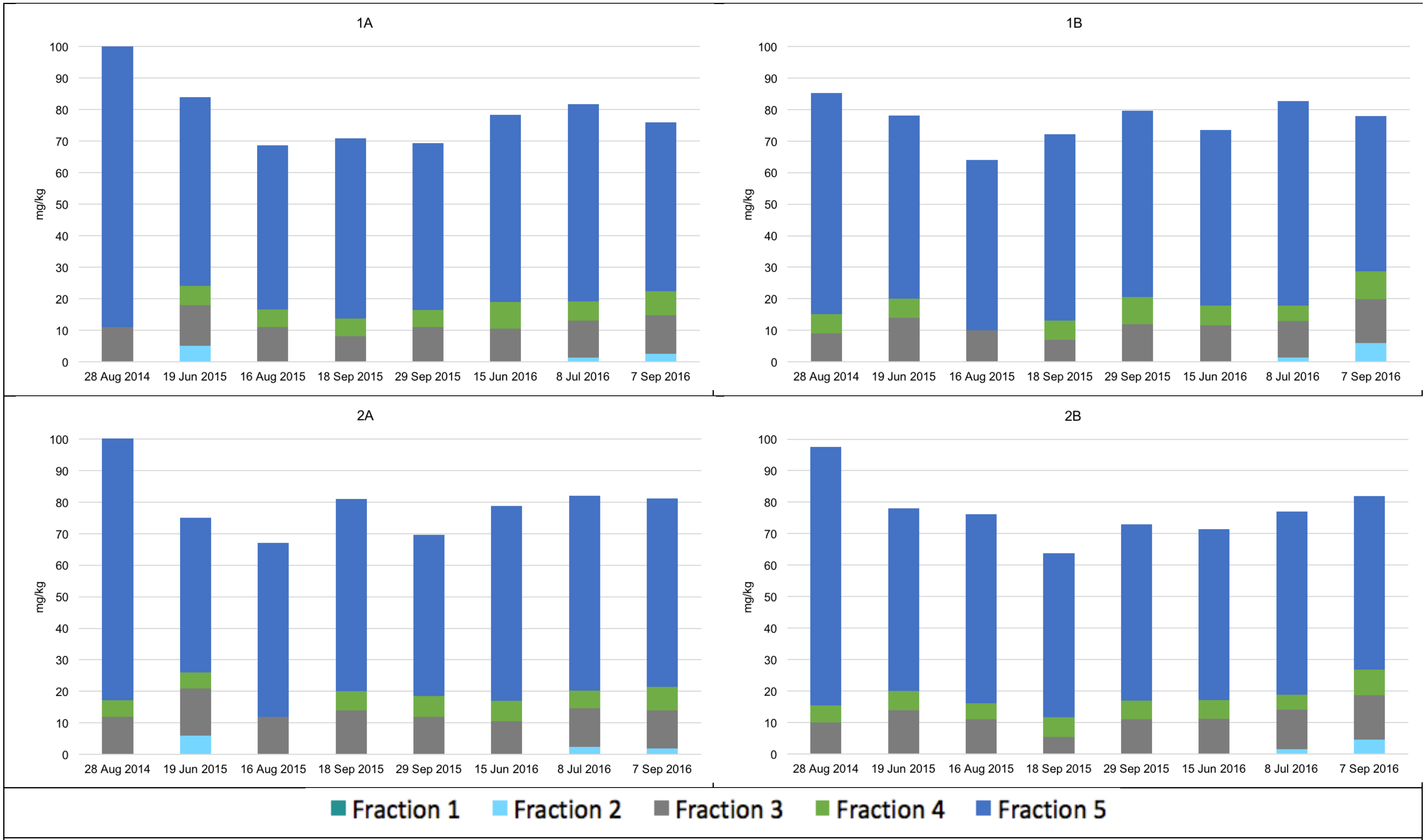


Figure B10 – Fraction distribution of zinc expressed as mg/kg over time (2015, 2016).

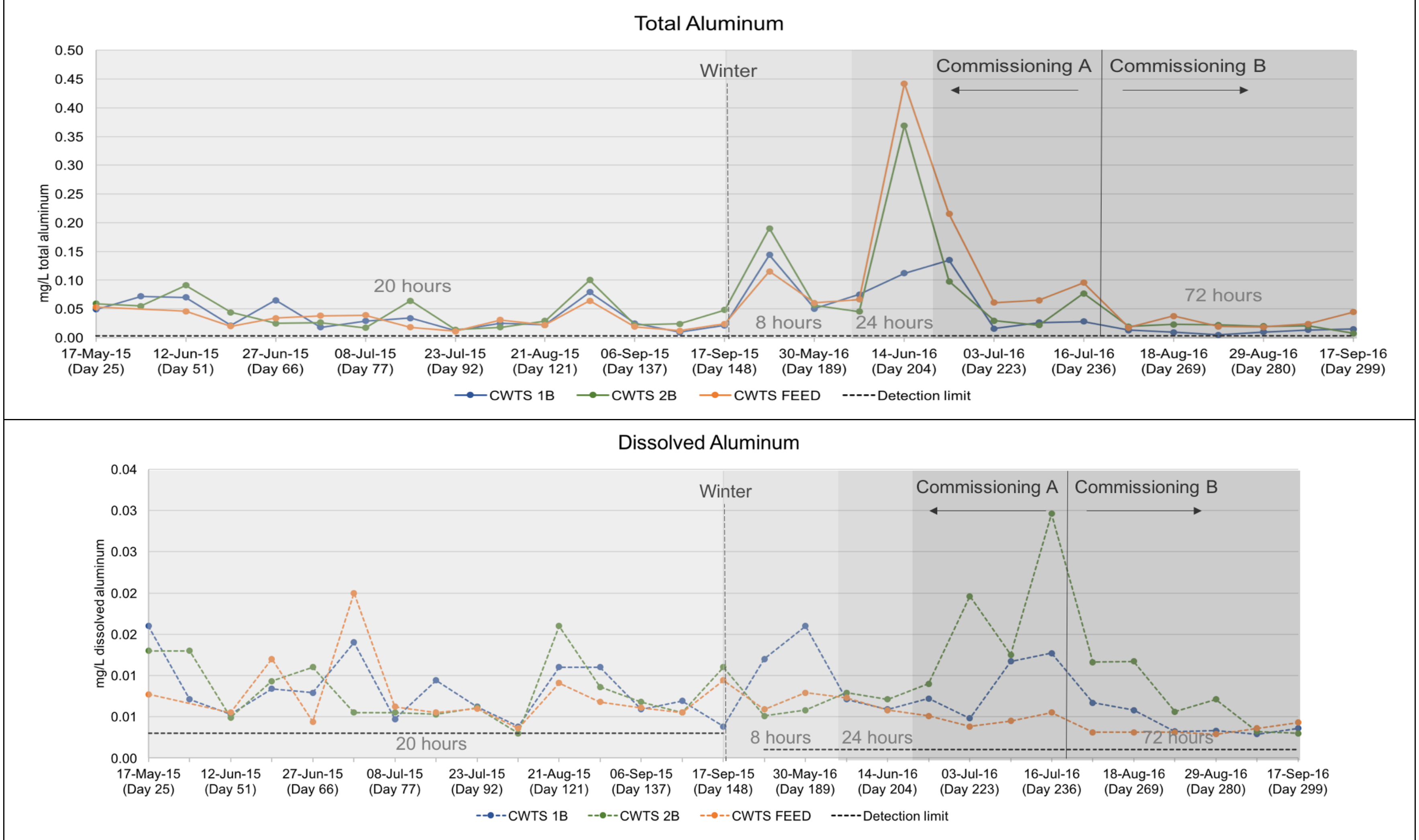


Figure B11 – Aluminum concentrations in the demonstration scale wetland from May 17, 2015 to Sept 7, 2016. The HRT is indicated by grey shading and the duration in hours. The Maxxam (2015 results) measurement uncertainty (MU) for aluminum is +/- 0.0030 mg/L. The ALS (2016 results) MU is +/- 0.0010 mg/L. Timepoints where the dissolved concentration is higher than the total concentration are within the limit of uncertainty.

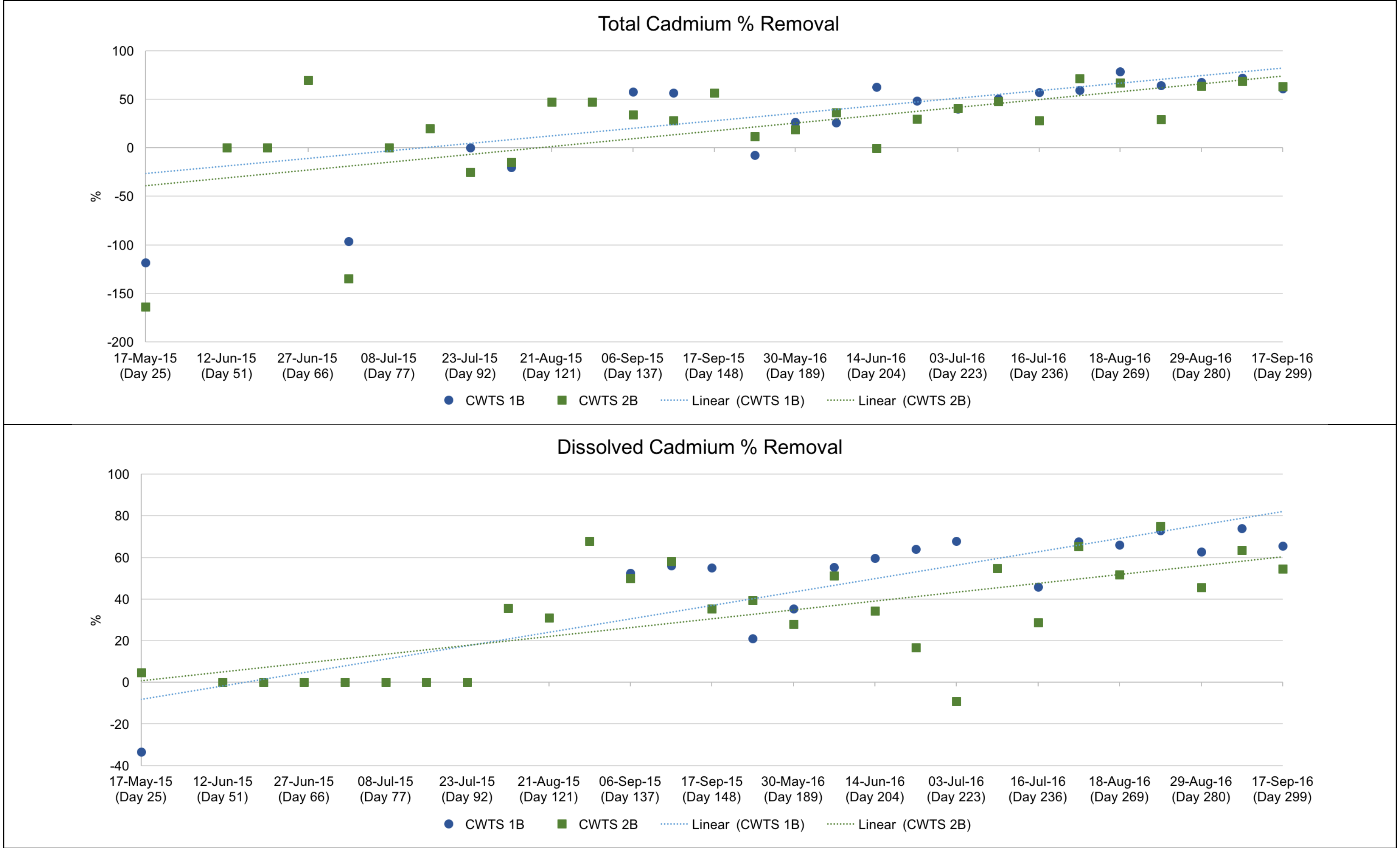
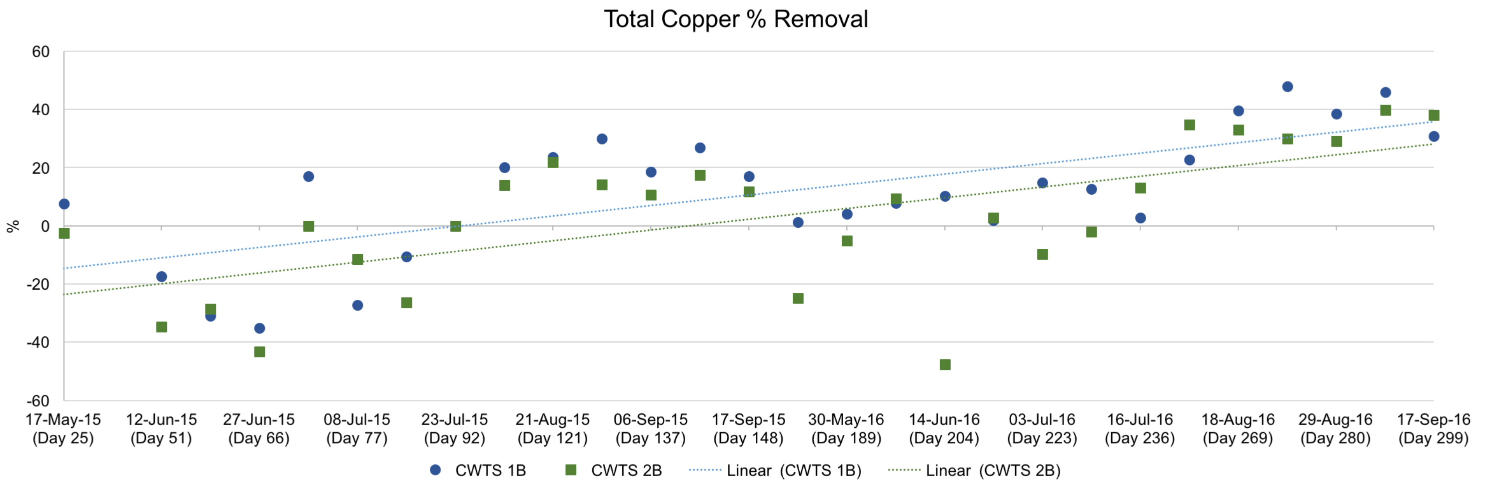


Figure B12 – Percent removal of cadmium in the demonstration scale wetland.
If the concentration was below the detection limit of the assay, the detection limit was used to calculate the percent removal. The Maxxam (2015 results) measurement uncertainty (MU) for cadmium is +/- 0.020 µg/L. The ALS (2016 results) MU is +/- 0.005 µg/L. The percent removal calculations for cadmium are therefore estimations within this range of error.



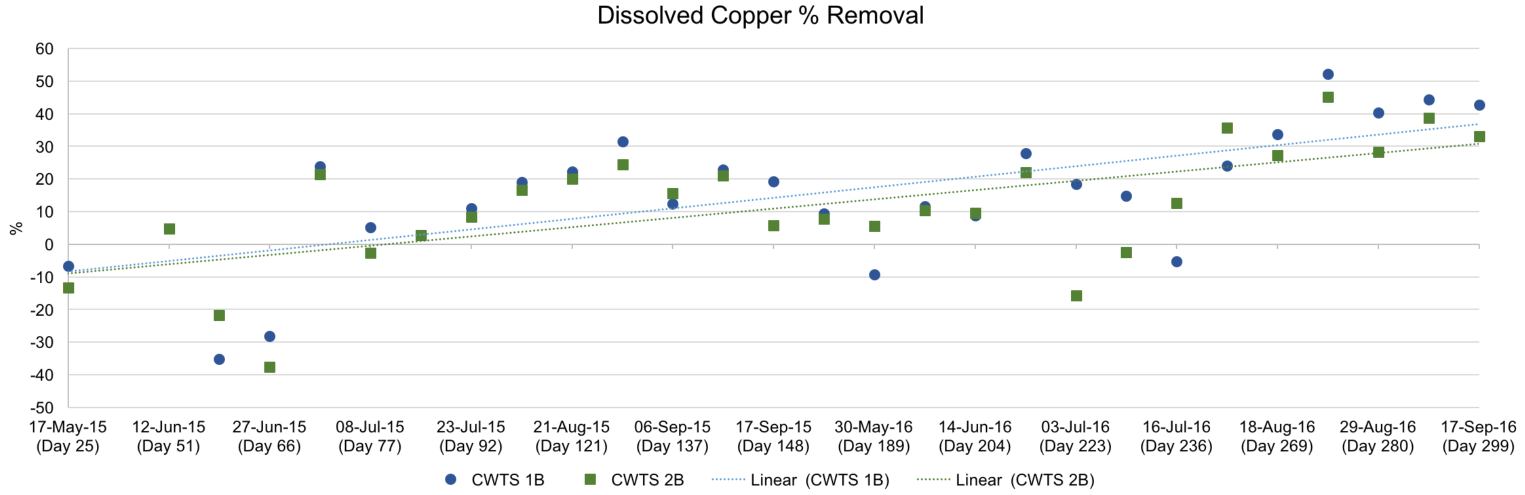


Figure B13 – Percent removal of copper in the demonstration scale wetland.
If the concentration was below the detection limit of the assay, the detection limit was used to calculate the percent removal. The Maxxam (2015 results) and The ALS (2016 results) measurement uncertainty (MU) for copper is +/- 0.0002 mg/L.

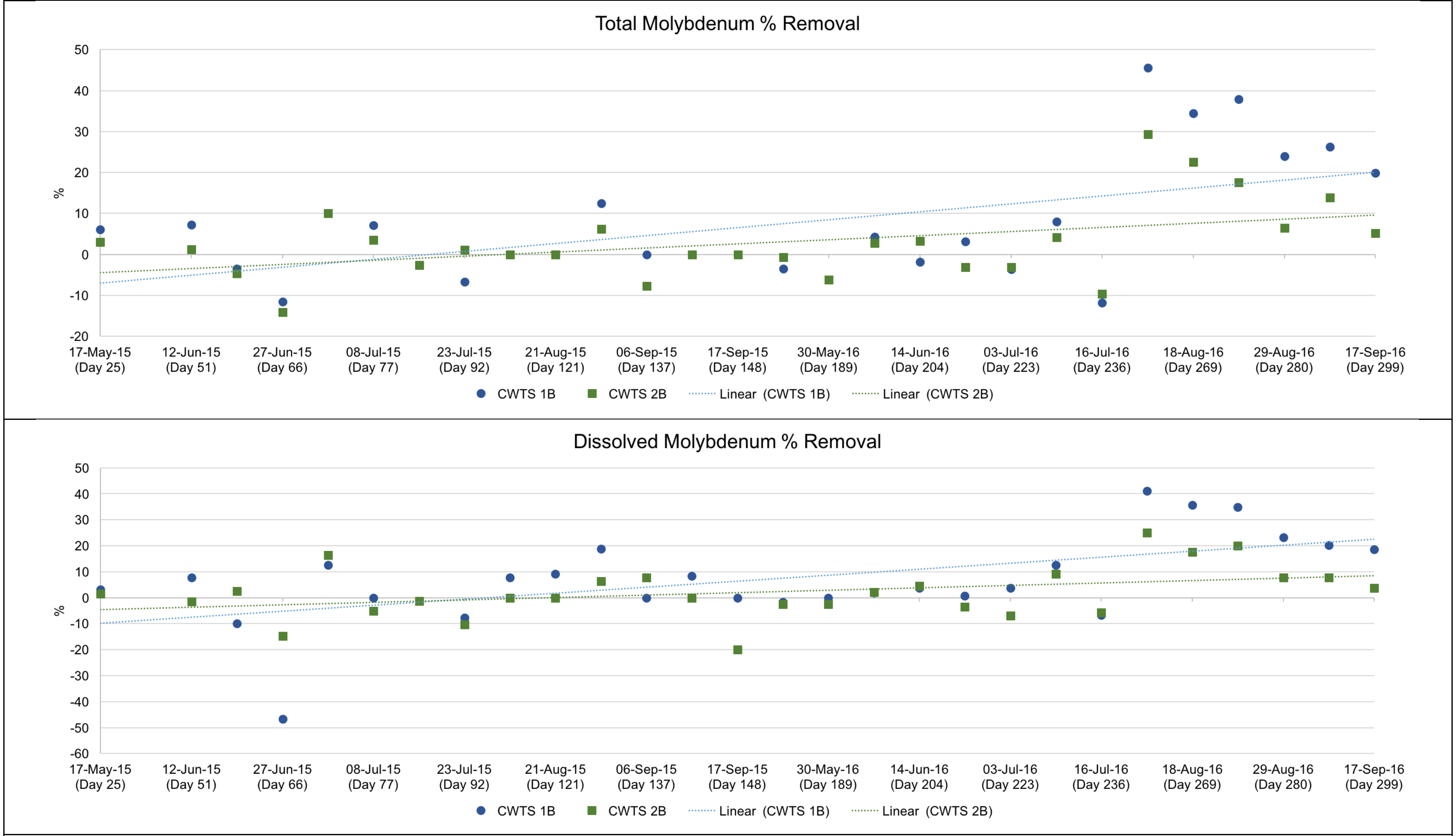


Figure B14 – Percent removal of molybdenum in the demonstration scale wetland.
If the concentration was below the detection limit of the assay, the detection limit was used to calculate the percent removal. The Maxxam (2015 results) measurement uncertainty (MU) for molybedenum is +/- 0.0002 mg/L. The ALS (2016 results) MU is +/- 0.000050 mg/L.

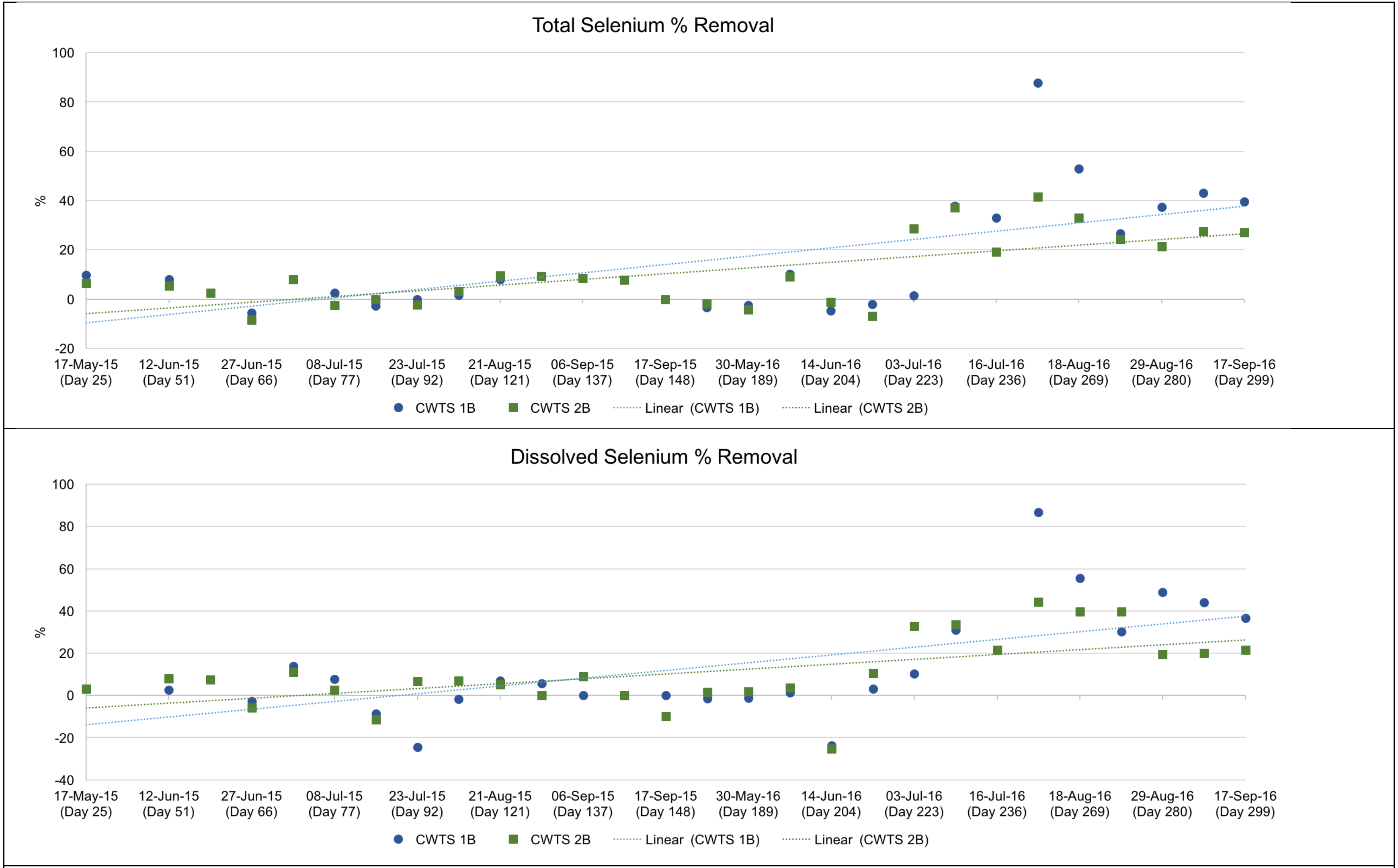
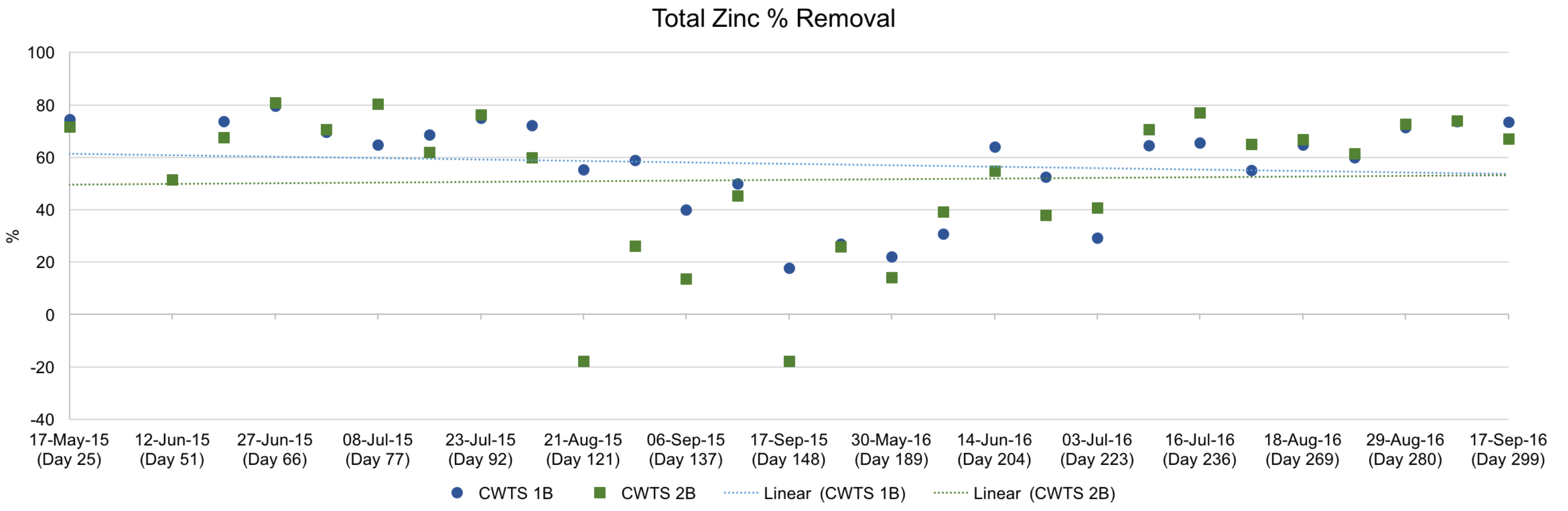


Figure B15 – Percent removal of selenium in the demonstration scale wetland.
If the concentration was below the detection limit of the assay, the detection limit was used to calculate the percent removal. The Maxxam (2015 results) measurement uncertainty (MU) for selenium is +/- 0.0002 mg/L. The ALS (2016 results) MU is +/- 0.000050 mg/L.



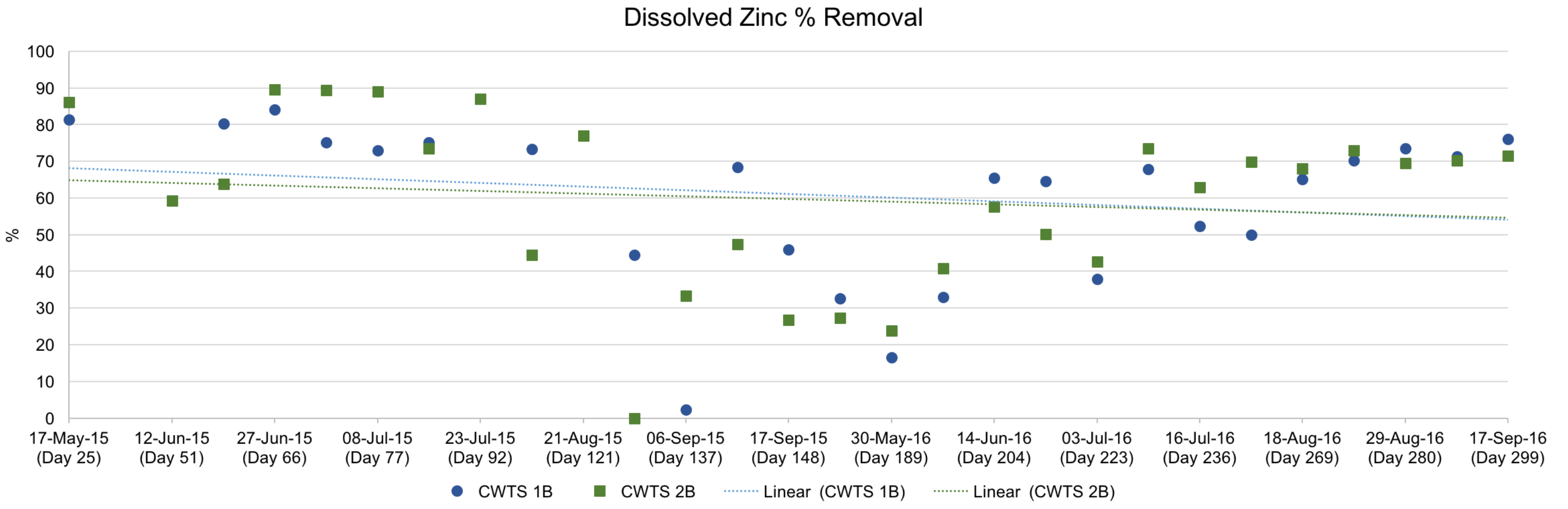


Figure B16 – Percent removal of zinc in the demonstration scale wetland.
If the concentration was below the detection limit of the assay, the detection limit was used to calculate the percent removal. The Maxxam (2015 results) measurement uncertainty (MU) for zinc is +/- 0.0030 mg/L. The ALS (2016 results) MU is +/- 0.0010 mg/L.

Appendix C

Table C1. Schedule of work

Item	Date	Activities	Actual
Construction	June 1-14 2014	Identify potential location for demonstration scale CWTS (Contango site visit – 1 scientist)	Completed
	June - July 2014	Engineering and geotechnical (Minto)	Completed
	July 2014	Construction (Minto)	Completed
	August 2014	Planting and bringing system online (Contango site visit – 1 scientist, 1 technologist), coordinate for local students to assist	Completed (no students available, brought 2 technologists)
Commissioning A	2014	Acclimation and maturation at constant flow rate, ~20 hr HRT	Completed
		September - Contango site visit/checkup (1 technologist, 1 scientist)	Did not occur because construction was last week of August
	2015	Continued commissioning. Operation at constant flow rate, ~20 hr HRT	Completed (at shorter HRT)
		Spring – Contango site visit/checkup (1 technologist, 1 scientist), includes micro sampling	Completed
		Summer - Increase depth from 10 cm to 20 cm (1 technologist), includes micro sampling	Completed (scientist)
		Fall – Contango site visit/checkup (1 technologist), includes micro sampling	Completed (scientist)
	2016	Minto to add sandbags prior to first site visit and begin W15 creek monitoring	Completed May/June 2016
		Spring – Contango site visit (1 scientist, 1 technologist), includes microbial sampling and tasks outlined in Table 5 of report. HRT tracer study completed, outlined in section 7 of report.	Completed June 2016
		Summer - Contango site visit/checkup (1 scientist, 1 technologist), includes microbial sampling and tasks outlined in Table 5 of report. Evapotranspiration study completed as outlined in section 9 of report. Organics were added to the CWTS as outlined in section 5.1 of report.	Completed July 2016
Commissioning B[1]		Fall - Contango site visit/checkup (1 technologist), includes microbial sampling and tasks outlined in Table 5 of report	Completed September 2016
	2017	Continue commissioning B. Operation at constant flow rate developed based on 2016 HRT tracer study.	Expected May 2017
		Spring – Contango site visit (1 scientist, 1 technologist), includes microbial	Expected May/June 2017

		sampling and tasks outlined in Appendix A of report. Proposed HRT tracer study. Sample for AVS to assess if the added organics are having the desired effect.	
		Summer - Contango site visit/checkup (1 scientist), includes microbial sampling and tasks outlined in Appendix A of report. Proposed evapotranspiration study.	Expected July/August 2017
		Fall – Contango site visit/checkup (1 scientist), includes microbial sampling and tasks outlined in Table 5 of report.	Expected September 2017
		Monitor soil redox. Determine when it consistently reaches targeted range.	Throughout 2017
Performance monitoring	*2018*	Fluctuate flow rates weekly, based on expected amount of water for full-scale wetland (scaled to size). Evaluate performance of wetland at different key periods.	*Putative activities, may not be necessary depending on performance and outflow water quality in other years.*
	2014-2018	Reporting will be performed annually, with verbal and/or emailed interim updates	On Schedule

[1] The commissioning-B period will continue in 2017 until the demonstration-scale CWTS performance is consistently achieving performance expectations.

Appendix A6
Minto Mine Constructed Wetland Treatment Research Program - Demonstration Scale 2017 Update

Forward looking. Lateral thinking.

Minto Mine Constructed Wetland Treatment Research Program – Demonstration-Scale 2017

Document # 011_1117_10B

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Date: November 2017

Executive Summary

The Minto Mine is an open pit and subsurface copper mine located 240 km northwest of Whitehorse in the Yukon Territory. As a result of mining activities, cadmium, copper, molybdenum, selenium, and zinc are slightly elevated beyond background concentrations and have been identified as constituents of concern in the Reclamation and Closure Plan for the Minto Mine. As part of the Reclamation and Closure Plan, a constructed wetland treatment system (CWTS) was designed by Contango with the objective of attaining suitable passive treatment of water quality at mine closure.

A phased approach is being followed to guide the site-specific design and implementation of a constructed wetland treatment system at closure. The phased approach for Minto Mine was initiated with a site assessment in 2013 that identified plants suitable for a CWTS as well as natural treatment processes that were already occurring on-site. Following the site assessment, pilot-scale testing was undertaken to confirm and provide proof-of-concept before constructing the on-site demonstration-scale wetland.

The demonstration-scale constructed wetland treatment system was constructed at Minto in 2014 and commissioned from 2015 through mid-2017 during which time the system matured and operational adjustments were made. Commissioning successfully established plant and microbial populations and achieved conditions conducive for treatment of constituents of concern. The demonstration-scale CWTS operational period ran for a month from mid-August to mid-September 2017. Various aspects of the system were measured in 2017 and are detailed in this report including operating conditions, water treatment performance, fate and distribution of treated metals, evapotranspiration, detritus decomposition rates, microbial community characterization (catalyzing treatment reactions), and pest control.

Throughout the operational period, the demonstration-scale CWTS successfully achieved an average decrease in concentrations of 0.0169 µg/L for cadmium (from 0.0261 µg/L to 0.0092 µg/L), 31.8 µg/L for copper (from 49.1 µg/L to 17.3 µg/L), 3.6 µg/L for molybdenum (from 6.3 µg/L to 2.7 µg/L), 3.5 µg/L for selenium (from 4.0 µg/L to 0.5 µg/L), and 47.3 µg/L for zinc (from 49.2 µg/L to 1.9 µg/L). Leaching of copper and other constituents from the mineralized soils used in the construction decreased by the end of 2017 with constituents showing a shift into stable reduced mineral forms in the soil (as the CWTS was designed to do for constituents from the water, but also has now done for the elements in the soil). Additional positive results were also documented; plant uptake of constituents remained minimal throughout operation and high abundance of beneficial sulphide-producing bacteria for treatment of Cu, Cd, Zn, as well as nitrate- and selenium-treating bacteria associated with plant roots.

The operational period of the demonstration CWTS confirmed that the predicted water quality for the Minto Mine at closure is amenable to treatment by these methods. Results from ongoing monitoring of the system in future years will be used to optimize performance and inform the designs for the full-scale constructed wetland treatment system.

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Abbreviations and definitions

Acid volatile sulphides (AVS) – Sulphide complexed with Fe (FeS) where the sulphide can preferentially exchange Fe for heavy metals (e.g., Ni, Zn, Cd, Pb, Cu, Hg) which are then more stably bound.

Amendment – A chemical or organic material added to encourage specific conditions (e.g., aerobic/anaerobic, pH, ORP) or as a source of something that is needed for passive treatment (e.g., nutrients, alkalinity, binding sites, etc).

Carbon source – A source of carbon (energy/electrons) for microbes (see **electron donors**). Examples include ethanol, methanol, acetate, sugar (glucose), molasses, wood chips, detritus (dead plant matter).

Carex aquatilis – A plant (emergent macrophyte) commonly known as water sedge.

Contango – Contango Strategies Ltd.

Constructed wetland treatment system (CWTS) – Wetlands that are designed and constructed to remove compounds from water, using natural processes to sequester them into the soils rendering them less bioavailable. They are different from wetlands that provide habitat for wildlife.

Constituent of Concern (COC) – Specific elements that have been identified for evaluation, including cadmium, copper, molybdenum, selenium, and zinc.

Denitrification – Where nitrate (NO_3^-) is reduced by microorganisms to form nitrite (NO_2^-), nitric oxide (NO), or nitrous oxide (N_2O), or nitrogen gas (N_2) (see **nitrate reduction**).

Dissolved oxygen (DO) – Diatomic oxygen (O_2) dissolved in water; oxygen can dissolve in water by diffusion from surrounding air, as a product of photosynthesis, or through forced aeration.

Electron donor(s) – A chemical compound that donates electrons to another compound (see **carbon source**). An electron donor is a reducing agent, which that by virtue of it donating electrons, is itself oxidized (see **oxidation** and **reduction**).

Explanatory parameters – Quantifiable parameters that indicate the type of water treatment reactions that are likely to take place (i.e., dissolved oxygen, pH, soil redox).

Evapotranspiration – The combined effects of open water evaporation and plant transpiration (Beebe *et al*, 2014).

Genetic analysis – Analysis to assess the presence, identity, and diversity of different microbes in a sample.

ICP-MS – Inductively coupled plasma mass spectrometry.

Macrophytes – An aquatic plant, large enough to be seen by eye. Can be emergent, submergent, or floating.

Microbes – Microscopic organisms that can be uni- or multi-cellular. This includes algae, bacteria, fungi, viruses, and yeast.

Most probable number (MPN) – A statistical value representing the viable population of microbes in a sample through use of dilution and multiple inoculations.

Oxidation – The loss of electrons, or increase in valence state, by a molecule, atom, or ion. Can be driven by microbes. Process is complementary to chemical reduction.

Oxidation-reduction potential (ORP) – A measure of the tendency of a chemical species to acquire or donate electrons, thus becoming reduced or oxidized, respectively, measured in millivolts.

Passive or semi-passive treatment system(s) (PTS) – General term used to refer to both passive and semi-passive treatment systems that use processes coupling transformations (e.g., chemical and biogeochemical reactions) with physical transfers (e.g., sorption, filtration) to remove constituents from water, often operationally passive with little long-term management required.

Redox – Oxidation-reduction potential (in sediment), a measure of the tendency of a chemical species acquire or donate electrons, thus becoming reduced or oxidized, measured in millivolts. This measurement is relative to the water ORP.

Reduction – The gain of electrons, or a decrease in valence state, by a molecule, atom, or ion. Can be catalyzed by microbes. Process is complementary to chemical oxidation.

Simultaneously extracted metals (SEM) – Amounts of heavy metals such as Ni, Zn, Cd, Pb, Cu, Hg in sediment, assessed in the context of AVS for excess sulphide. (also see **acid volatile sulphide**)

Sorption – The physical and/or chemical process by which one substance becomes attached to another substance.

Specific conductivity (SPC) – A measurement of electrical conductivity in water that is typically expressed in µs/cm, which has been adjusted for temperature (25°C).

Species (sp.) – One of the basic units of biological classification and a taxonomic rank. Rank in the classification of organisms below genus and above strain. Also can be used to refer to the oxidation state of a mineral (e.g., selenate and selenite are species of selenium).

SPLP – Synthetic precipitation leachate procedure.

Sulphide – An inorganic anion of sulphur that can form stable complexes with metals and make them insoluble in water (remove them from the water).

Sulphide producing bacteria (SPB) – Microbial reduction of sulphur compounds, such as sulphate, sulphite, thiosulphate, and sulphur, which produces sulphides and alkalinity. (see also **SRB**).

Sulphate reducing bacteria (SRB) – A form of sulphide producing bacteria that specifically uses sulphate for reduction (see **sulphide producing bacteria**).

Sulphide production – Microbial reduction of sulphur compounds, such as sulphate, sulphite, thiosulphate, and sulphur, which produces sulphides and alkalinity.

Thermodynamic minimum – The minimum concentration of a contaminant of concern that is consistently achievable.

Total dissolved solids (TDS) – A measure of the combined organic and inorganic salts dissolved in water.

Total organic carbon (TOC) – A measurement of the total organic carbons present in water.

Transfer – Processes that treat water by transferring a constituent to another location without changing its form. For example: absorption, adsorption, dilution, dispersion, filtration, precipitation (aqueous to solid), and volatilization.

Transform – Processes that change the chemical form or state of a constituent. For example: biodegradation, biotransformation, hydrolysis, ionization, oxidation, photolysis, and reduction.

1. Introduction

The Minto Mine, owned and operated by Capstone Mining Corp., is located 240 km northwest of Whitehorse on the west side of the Yukon River. The Minto property lies within the eastern part of the Dawson Range, with elevations from 700 to 1,000 m above mean sea level. The landscape has rounded mountains intersected by broad valleys and drainages that are part of the Yukon River watershed.

The Minto Mine has been in commercial operation since October 2007 and the deposits being mined are copper sulphide mineralized zones. Surface and groundwater water quality is a key consideration in the evaluation of potential effects of mining and mineral development projects and changes to water quality parameters have the potential to affect aquatic and human use of water resources. A Reclamation and Closure Plan (RCP) is required under both the Water License and the Quartz Mining License. The RCP is intended to address the long-term physical and chemical stability of the site and closure of the proposed features and disturbances associated with the mine. As a part of the RCP, a Constructed Wetland Treatment System (CWTS) is being designed, evaluated, and optimized for water treatment at closure through a phased program approved during the Minto Phase V/VI Expansion Project (Yukon Online Registry Project Number 2013-0100). Constituents of concern that are being evaluated through the CWTS program include cadmium, copper, molybdenum, selenium, and zinc.

1.1. Purpose and Objectives

The primary objective for operation of the demonstration-scale CWTS in 2017 was to complete commissioning and progress into operational performance. Once operational performance is achieved, the removal rate coefficients (RRC; *k*) can be assessed to evaluate and refine full-scale designs. To achieve the operational performance, it was recognized that the remaining copper in the soils used in construction needed to be converted into metal-sulphide form; therefore, this was addressed in the early months of 2017 and paired with evapotranspiration trials to make best use of this time.

In 2017, the monitoring program shifted focus from commissioning to testing of operational performance. Activities carried out in 2017 to achieve these objectives were:

- Monitor explanatory parameters and performance to determine when commissioning is complete and the operational period has begun;
- Assess removal of constituents from the water;
- Determine the hydraulic retention time (HRT) by tracer trial and associated correction factor to apply to the nominal (calculated) HRT;
- Evaluate CWTS performance, and determine achievable concentrations of contaminants of concern (thermodynamic minimums);
- Update site-specific removal rate coefficients (from commissioning period) with data from operational period;
- Determine amount of water loss due to evapotranspiration and effect on outflow concentrations;
- Monitor metals leaching from mineralized soils used in construction;

- Assess stability of constituents of concern in soils;
- Determine the rate and extent of detritus decomposition (*C. aquatilis* leaves) in the CWTS over time;
- Assess treatment mechanisms (including microbes); and
- Determine an appropriate method for insect pest control (aphids) in the CWTS.

1.2.Overall CWTS Project Approach

For a CWTS to be effective, it must be designed, piloted (tested), optimized, implemented, and maintained in a site-specific manner. A phased approach allows for improvements and optimization at each step. The phases used at the Minto Mine include:

1) site assessment and information gathering;
2) technology selection and conceptual design;
3) pilot-scale testing and optimization (controlled environment, off-site);
4) demonstration-scale confirmation and optimization (on-site); and
5) full-scale implementation.

Phases 1 to 3 are complete at Minto. This work is summarized in the Research Program, Pilot Plant and Demonstration reports completed by Contango (2014a and 2014b). Phase 4 of the project is underway, with the on-site demonstration CWTS constructed at the Minto Mine during fall 2014 (Contango, 2015). Commissioning of the CWTS occurred from 2015-2017 with operations beginning in late 2017. Performance results of the demonstration CWTS indicate that the CWTS is maturing as expected (Contango, 2015; 2016; 2017). This document reports on the 2017 on site demonstration-scale CWTS data, with focus on results from the operational period from August 18 – September 22, 2017.

2. Demonstration-Scale Constructed Wetland Treatment System Design

2.1.CWTS Layout and Dimensions

The demonstration-scale CWTS is located on the northeast side of the mine site, perched on the MVFE area as shown in Figure 1.

Construction of the demonstration-scale CWTS was completed in 2014 and includes two series in parallel with two cells in each series and a final catchment basin (Figure 1). Water flows from the feed tank through the A cells, through the B cells and into the final combined catchment basin. Water from the catchment basin of the demonstration-scale CWTS is not discharged off-site, rather it is collected in a sump at the toe of the Mill Valley Fill Extension (MVFE). Series 1 and series 2 flow independently of each other and are intended as replicates for analytical testing and operation confirmation. Additional details can be found in the Minto Demonstration-Scale Report (Contango, 2015) and Appendix A of this report.

Figure 1 – Picture of demonstration-scale CWTS at Minto Mine.
Demonstration-scale CWTS location in relation to its surroundings. To the far right is the mine camp while below is the tree line. This photo was taken on September 24, 2017.

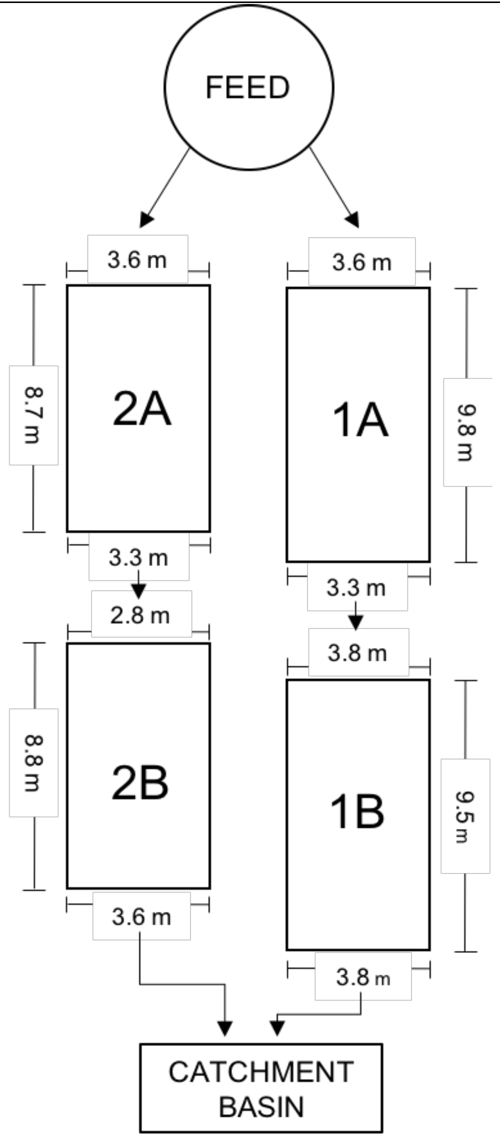


Figure 2 – Diagram of demonstration-scale CWTS.
Dimension measurements are indicated at soil surface. Water flows are indicated with black arrows. Water flows from the feed tank into the A cells, into the B cells then into the final catchment basin. Series 1 and series 2 flow independently of each other, and serve as replicates.

2.2.Soils

Soils used to construct the CWTS are described in Appendix A of this report and in the initial report that outlines construction (Contango, 2015). In brief, the recommended soil for the CWTS was sand, with 2-7% by volume organic material (e.g., woodchips, peat). The material used in the construction of the demonstration-scale CWTS was an organic peat, and analyses received after construction indicated an elevated concentration of leachable copper (Appendix A, Table A2). This leachable copper has affected the CWTS performance results. Therefore, this has been a focus of efforts through the commissioning period to transition these leachable copper minerals into stable sulphide minerals which will not leach from the CWTS.

2.3.Vegetation

The demonstration-scale CWTS was planted with *Carex aquatilis* (aquatic sedge) and aquatic mosses (bryophytes) from the W10 area of the Minto Site. The plant selection and borrow source were identified during the site assessment in 2014 (Contango, 2014a) and pilot-scale testing (Contango, 2014b).

2.4.Water Source

The water source for the demonstration-scale CWTS is seepage from the toe of the Mill Valley Fill Extension (MVFE) and was selected for the demonstration-scale CWTS as the seepage is similar to that expected upon closure in the MVFE area. Zinc concentrations were elevated in the water being used in the CWTS in 2016, and it was uncertain if this was due to a culvert used for water collection in the area or seasonal variation. However, zinc concentrations remained elevated in 2017, suggesting that the culvert is contributing to elevated zinc concentrations. Further details can be found in Appendix A and Contango's 2016 update report (Contango, 2017).

3. Commissioning and Operations

The period between the construction of the CWTS and achieving the expected treatment performance is referred to as the commissioning period. During this period, several criteria are monitored to determine when the commissioning period has been successfully completed. Criteria that were achieved that indicated the end of the commissioning period and the beginning of the operational period for the Minto Mine demonstration-scale CWTS include the following and are further discussed in the sections listed:

- Plant establishment and maturation such that the plants have grown in to densities visually similar to natural wetlands in the area, but in monoculture (Section 3.2),
- Establishment of reducing conditions within the CWTS (i.e., average soil redox was below -100 mV consistently in 2017; Section 5.1),
- No increase in aqueous copper concentrations through the CWTS (due to copper containing soils used in construction;Sections 5.2.1 and 5.6), and
- Microbial population establishment and maturation to levels similar or better to pilot-scale (Section 5.9).

Once the above criteria were met, the CWTS was deemed to be in the operational period. The same criteria, other than the copper leaching, could be used for the full-scale CWTS. The on-site demonstration-scale CWTS was commissioned from 2015 to 2017, comprising of 135 days in 2015, 150 days in 2016 and 82 days in 2017 (Table 1). The CWTS then proceeded to the operational period and operated for 35 days in 2017 (Table 1).

Table 1 – Days of operation of demonstration-scale CWTS.

Scale	Year	Period (days)	Date	
			Start	End
Commissioning-A[2]	**2014[1]**	23	Aug 27	Sept 19
	2015	135	May 16	Sept 29
	2016	87	May 2	Jul 28
Commissioning-B[3]	**2016**	63	Jul 29	Sept 30
	2017	82	May 27	Aug 17
Operational Period	**2017**	35	Aug 18	Sept 22

[1] The CWTS was constructed in 2014, but no water testing occurred during this first month of commissioning-A.
[2] The end of the commissioning-A period and the beginning of the commissioning-B period was marked by the addition of organics on July 28, 2016.
[3] The end of the commissioning-B period and the beginning of the operational period was marked by stabilization of flow rates and resolution of feed water delivery complications.

For the demonstration-scale CWTS the commissioning period was divided into two periods, commissioning-A, and commissioning-B. The end of the commissioning-A period and the beginning of the commissioning-B period was marked by the addition of organics on July 28, 2016. These organics (straw and wood chips) were added to further aid the copper in the soils to transition into sulphide mineral forms, and represents an amount of organic material similar to what would be produced by the CWTS once fully established with *Carex aquatilis*.

The end of the commissioning-B period was expected to be between July 16 and August 2, 2017. However, due to issues with feed-water pumps and flow meters, the end of the commissioning-B period was extended to August 17, 2017 and was marked by stabilization of flow rates and resolution of feed water delivery complications. Additionally, sandbags were added at the end of each cell on August 11, 2017 to increase the water depth and further promote reducing conditions. Therefore, the operational period began on August 18, 2017 and ran until September 22, 2017. Flow was turned off to prepare for winter freeze-up on September 30, 2017, and the last sampling date used was September 22, 2017. Discussions in this document are focused on the operational period and further details on commissioning in 2015 and 2016 can be found in Contango's past reports (2015 and 2016).

3.1.Flow Rates

The targeted flow rates were varied during commissioning of the demonstration-scale CWTS to target desirable conditions for establishment of the CWTS. Since the cells in series 2 are smaller than cells in series 1, a faster flow rate is used for series 2 to obtain an equal HRT to series 1.

In 2017, a long HRT was selected to aid in generating reducing conditions in the CWTS and, therefore, flow rates were set to as slow as they could operate. The nominal HRT was targeted to be 5 days. The operational ranges of the flow meters used in the CWTS were 0.3 to 3 gallons per minute (GPM). To obtain this long HRT, the targeted flow rates used during the commissioning and operational periods of the CWTS in 2017 were 0.37 and 0.31 GPM for series 1 and series 2, respectively. Due to pump and flow meter issues, the actual flow rates varied from the target flow rates throughout 2017 commissioning and operational periods. Table 2 summarizes known pump and flow meter issues that occurred in 2017. The average flow rate for the 2017 operational period was a calculated flow rate of 0.38 GPM and 0.29 GPM for series 1 and series 2, respectively. Additional information on flow rates and associated HRT calculations are provided in Appendix A.

3.2.Health and Establishment of CWTS Vegetation

3.2.1. Carex aquatilis

During the commissioning period, plants establish and mature, with density expected to increase over time. From planting in 2014 to the last site visit in 2017 *C. aquatilis* thrived in the CWTS creating a dense emergent macrophyte monoculture, supplemented with aquatic mosses (Figure 3). This suggests that *C. aquatilis* are very robust and reaffirms that they are a good candidate for use in the full-scale CWTS at Minto. In July 2017, an aphid infestation occurred in the CWTS which affected the *C. aquatilis*. The biomass above water appeared to partially die off, however the plants continued to send out new shoots suggesting the *C. aquatilis* were resilient to the infestation. Further discussion about the aphids and the control measures in 2017 is presented in Section 6.

3.2.2. Moss

Aquatic mosses have continued to mature and expand in size from 2014 through 2017. The mature mosses are beginning to show characteristics of the desired coupled transfer (sorption, filtration) and transformation (mineralization, reduction) processes. The top of the moss is growing and producing new green biomass that provides transfer sites, and the older, bottom of the moss is turning black and beginning to decompose which creates sulphide reducing zones that allow for transformation (Figure 4 and Figure 5).

Figure 3 – Maturation of the CWTS from construction through operations.
2015 pictures show cell 2A.

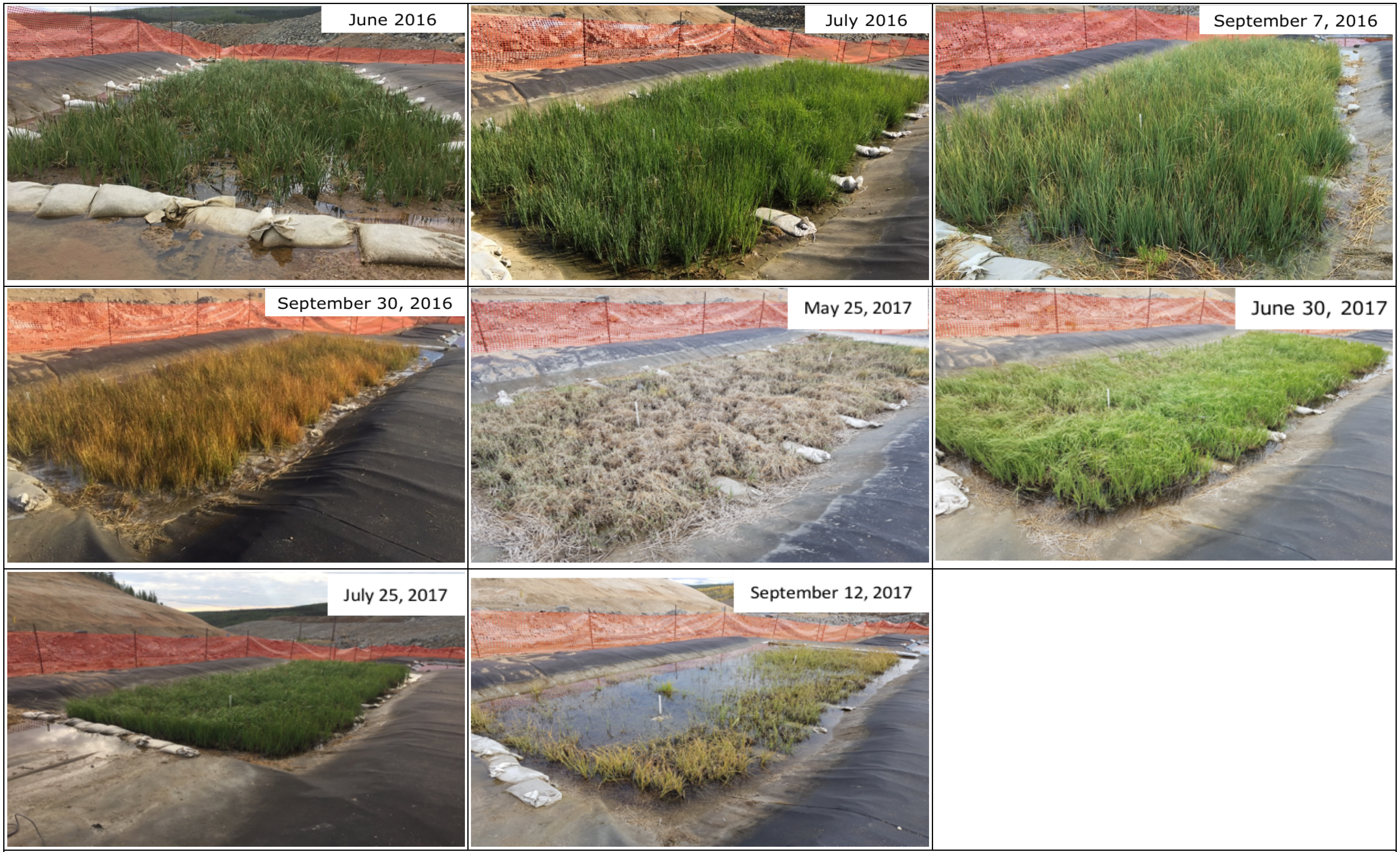


Figure 3 continued – Maturation of the CWTS from construction through operations.
2016 and 2017 pictures show cell 1B. September 12, 2017 shows increased yellowing and die off in cell 1B due to aphid infestation.

Figure 4 – Moss maturation in CWTS through 2016.

Figure 5 – Moss top and bottom view in June 2016 and September 2017.

4. Timeline and Sampling Schedule

Major events and operational adjustments or amendments for 2017 are listed in Table 2. Details for events up to 2017 can be found in the Minto Demonstration-scale 2016 Update Report (Contango, 2017). The actual dates as well as effective days of operation are provided, which adjusts for time that the CWTS was not receiving water when it was frozen. The effective days of operation allows for comparison to expected timelines from the pilot-scale testing, and for planning and scheduling to be done for full-scale construction and commissioning. The sampling schedule for 2017 was conceptually developed prior to beginning construction of the demonstration-scale CWTS (Appendix A). Actual dates of sampling were adjusted for timing of spring thaw and winter freeze-up, and the associated ability to have the pumps operating at the W62 sump to supply water to the demonstration-scale CWTS.

Table 2 – Events and sampling activities since construction.

Event	Key Activity	Flow Rate Setting m^3/day (gal/min)		Dates	Effective Days of Operation
		CWTS Series 1	CWTS Series 2		
CWTS constructed and planted	First sampling, water started.	*	*	August 27 – 31, 2014	0-4
Freeze up for winter	Feed water pumps turned off.	*	*	September 19, 2014	23
Winter 2014/2015					
Commissioning-A[2]				May 16 – September 29, 2015	136
Winter 2015/2016					
Commissioning-A[2]				May 2 – July 27, 2016	86
Commissioning-B[2]				July 28 – September 30, 2016	64
Winter 2016/2017					
Flow started	Flow started.	2.18 (0.40)	1.85 (0.34)	May 27, 2017	312
Evaporation Study	Flow stopped.	-	-	June 8, 2017	324
End of Evaporation Study	Flow re-started.	4.80 (0.88)	4.58 (0.84)	June 15, 2017	331
Flush CWTS	Flow increased.	5.07 (0.93)	4.20 (0.77)	June 15 – 19, 2017	331-335
Contango Site Visit #7 (Spring Sampling)	Microbiology, soils, and water tested.	2.07 (0.38)	1.42 (0.26)	June 20-22, 2017	336-338
	Detritus decomposition trial started.			June 21, 2017	337
Saline Tracer Study	Salt added to cells for tracer study.	1.74 (0.32)	0.55 (0.10)	June 21 – July 2, 2017	337-348
Flow interruptions	Flow rates increased causing feed tank to collapse, and flow stoppage.	*	*	July 16, 2017	362
Contango Site Visit #8 (Summer Sampling)	Microbiology and soils tested. Detritus bags collected.[3]	*	*	July 25 – 26, 2017	371-372
Flow interruptions	Pump issues. Repairs required and new totalizer installed on CWTS 1.	*	*	July 25 - August 16, 2017[1]	371-393
Sprayed for aphids	Insecticide applied 7 times to CWTS.	N/A	N/A	July 25 – September 13, 2017	371-421
Water level raised	Sand bags were added to the ends of each cell.	*	*	August 11, 2017	388
Beginning of operational period				August 18, 2017	395
Summer Water Sampling	Not completed during Contango Site Visit #8 due to flow interruptions.	2.40 (0.44)	1.64 (0.30)		
Fall Sampling	Completed by Minto. Microbiology, soils, water, and plants tested. Detritus bags collected.	2.02 (0.37)	1.42 (0.26)	September 11, 2017	419
Freeze up for winter	Flow stopped.	-	-	September 30, 2017	438

* This indicates no flow rate was given, flow rate was unmeasurable or variable; however, cells remained flooded throughout.

[1] Resolution of the flow interruptions marked the end of commissioning-B and the beginning of the operational period.

[2] Detailed information for Commissioning-A and Commissioning-B in 2015 and 2016 can be found in the Minto Demonstration-Scale 2016 Update Report (Contango, 2017).

[3] Due to flow interruptions during the Contango site visit, the summer seasonal water sampling occurred on August 18, 2017 when flows had re-started.

5. Performance

5.1.Monitoring Explanatory Parameters

The following are key findings regarding explanatory parameters, which are detailed further below:

- Dissolved oxygen (DO) decreased from an average of 8.4 mg/L during commissioning-B in 2016, to an average of 5.3 mg/L during operations in 2017. This elevated DO in the water column is likely the result of photosynthesis of algae and mosses. Despite this DO level in the water column being in oxidizing ranges, stable reducing conditions were achieved in CWTS soils within the targeted soil redox range (-100 to -250 mV).

Average water temperature of the demonstration-scale CWTS in 2017 were similar to those in 2015 (12.9°C) and 2016 (10.2°C). The average water temperature during the operational period in 2017 was 9.7°C, ranging from 5.3°C to 14.9°C. As expected, conductivity did not change from previous years and pH remained circumneutral.

DO concentrations in the CWTS cells were on average 5.3 mg/L, which is lower than commissioning-A and slightly higher than commissioning–B (Table 3). Reducing conditions are needed for nitrate and selenium treatment processes, and for creating metal sulphides that remove copper and cadmium from the water. Water oxidation-reduction potential (ORP) also decreased compared to 2016 by 73 mV, which is also indicative of reducing conditions in the CWTS.

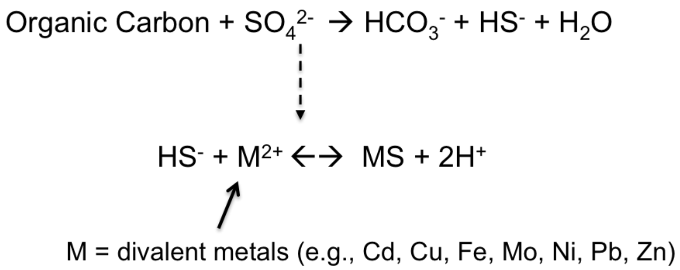
Table 3 – Average in situ measurements from the pilot scale and demonstration-scale CWTS.

Testing Period		DO (mg/L)	Conductivity (µS/cm)	pH	ORP (mV)	Soil redox (mV)
Demonstration-scale 2015		10.0	817.9	8.11	147.9	-52
Demonstration-scale 2016	Commissioning-A[1]	15.9	890.9	7.79	143.7	-85
	Commissioning-B[2]	8.4	1020	7.59	157.6	-89
Demonstration-scale 2017	Commissioning-B[3]	4.3	795.9	7.43	18.7	-162
	Operational period[4]	5.3	879.7	7.36	124.9	-152

[1] Data for commissioning-A period is from May 2-July 28, 2016.
[2] Data for commissioning-B period is from July 29-September 30, 2016.
[3] Data for commissioning-B period is from May 27-August 17, 2017.
[4] Data for operational period is from August 18-September 22, 2017.

A key explanatory parameter used to monitor maturation of the CWTS during the commissioning period is the soil redox potential, which is measured using platinum tip probes (in soil) and Calomel electrodes (in water). This measurement offers insight into the direction of electron flux between the sediment/soil/pore water and overlying water column (Faulkner et al., 1989; Huddleston & Rodgers, 2008), and can be used to confirm reducing conditions in the soil. Based on the information gathered in pilot-scale testing, the targeted soil redox for the demonstration-scale CWTS is between -100 and -250 mV. In these redox ranges, bacterial sulphide-production through reduction of sulphur compounds (e.g., sulphate) is expected. Sulphide production directly results in metals and metalloid treatment for constituents such as cadmium, copper, molybdenum, nickel, lead, and zinc by precipitation as metal sulphides (Figure 6).

This maturation period is necessary for sufficient quantities of microbes to populate the CWTS and become active in decomposing organic material. It is the electrons produced by the decomposition of organic material that is reported by the soil redox measurements. The decomposition of organic material then feeds the sulphate-reducing bacteria the type of energy they need to produce the sulphides that remove the copper, cadmium, molybdenum, and zinc from the water. The microbial activity of the CWTS is discussed further in Section 5.3.2.



$$\text{Organic Carbon} + SO_4^{2-} \rightarrow HCO_3^- + HS^- + H_2O$$

$$HS^- + M^{2+} \leftrightarrow MS + 2H^+$$

M = divalent metals (e.g., Cd, Cu, Fe, Mo, Ni, Pb, Zn)

Figure 6 – Example equation of sulphate reduction and resultant metals mineralization and treatment.
Equation is not balanced; demonstrates sulphate reduction with creation of alkalinity and sulphides, which can then form metal sulphide complexes.

As expected from the pilot-scale testing, the soil redox in all the demonstration-scale CWTS cells has decreased and stabilized over time, indicating maturation of the CWTS (Figure 7). At the end of 2016, the demonstration-scale CWTS had begun achieving soil redox values that are conducive to sulphide production due to the decomposition of the organics that were added on July 28, 2016 (Contango, 2017). By the end of 2017, soil redox values had decreased to within the targeted range, even without additional organics added to the CWTS. It is therefore evident that the commissioning period was successful and the CWTS has matured and become self-sufficient in producing organic matter to provide electrons to generate reducing conditions upon decomposition. Soil redox will continue to be monitored throughout operation in 2018.

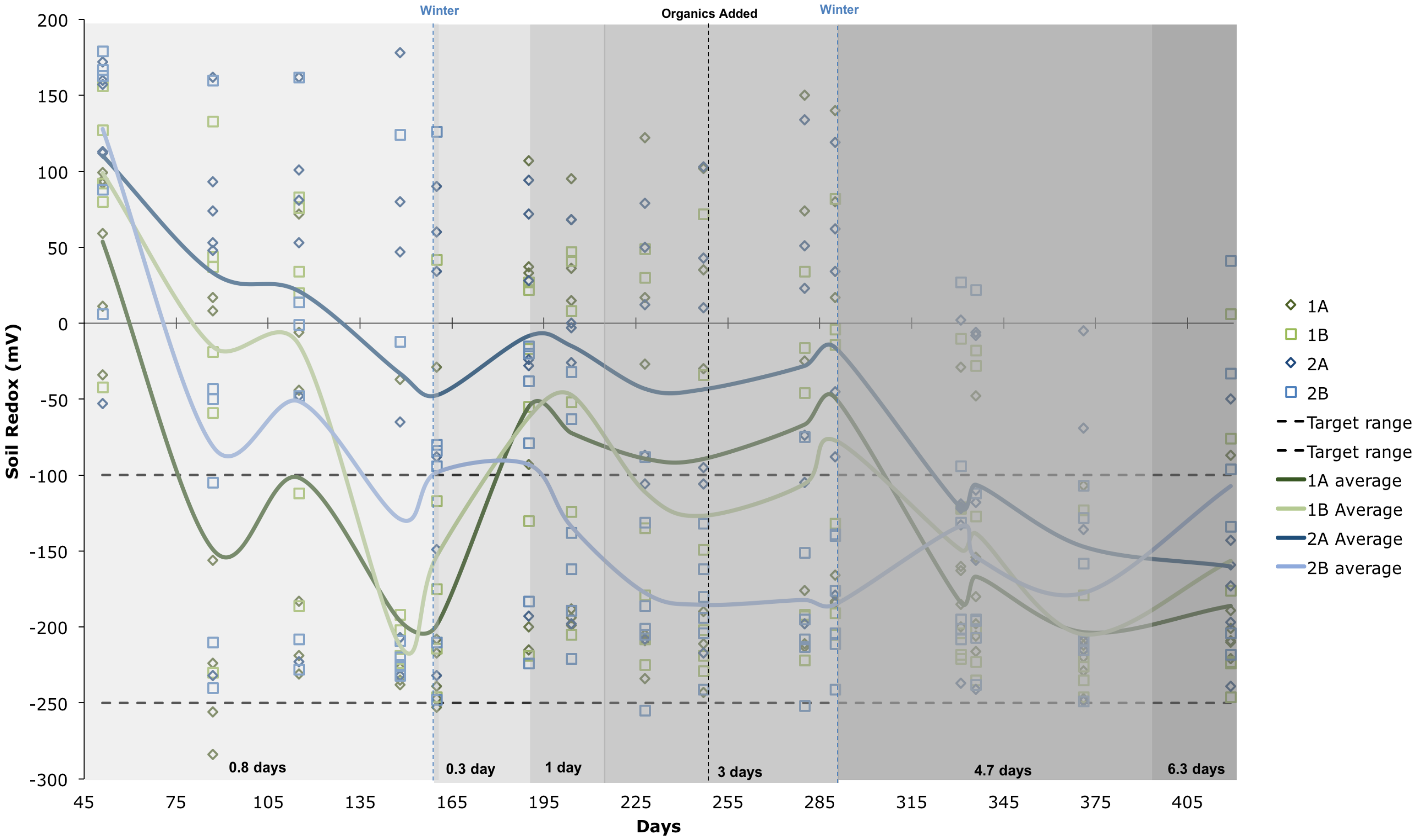


Figure 7 – Soil redox potential of each CWTS cell over time.
All demonstration-scale CWTS soil redox measurements are plotted. Targeted soil redox values based on pilot-scale testing are indicated with dotted lines. The blue dotted line indicates break in measurements for winter 2015 and 2016. Days and associated grey shading in 2015 and 2016 indicate the nominal HRT. Days and associated grey shading in 2017 indicate the actual HRT (average of series 1 and 2) using recorded water depths and flow rates during those time periods.

5.2.Water

The following are key findings regarding constituents in the water, which are detailed further below:

- Copper treatment in the CWTS was masked by leaching from the soils used in construction of the CWTS into the water, but this has mostly been remedied now by the wetland treating this copper and turning it into more stable sulphide forms in the soil.
- During the operational period the demonstration-scale CWTS successfully achieved an average decrease in concentrations of 0.0169 µg/L for cadmium (from 0.0261 µg/L to 0.0092 µg/L), 31.8 µg/L for copper (from 49.1 µg/L to 17.3 µg/L), 3.6 µg/L for molybdenum (from 6.3 µg/L to 2.7 µg/L), 3.5 µg/L for selenium (from 4.0 µg/L to 0.5 µg/L), and 47.3 µg/L for zinc (from 49.2 µg/L to 1.9 µg/L).
- Molybdenum and selenium treatment in the operational period is notable as the removal rates were negligible within the margins of error of the testing method in the commissioning-A period.

5.2.1. Metal Leaching from Soils into Overlaying Water

Although treatment improved through commissioning as the CWTS matured, copper and aluminum leaching from the soils into the overlaying water, masking the effects of treatment (Contango, 2017). Therefore, additional sampling was performed through the CWTS to identify these fluctuations. Details of the sampling methods can be found in Appendix A of this document and Figure A4 in Appendix A shows the sampling locations in series 2 of the demonstration-scale CWTS. Graphs showing concentrations of copper and selenium throughout the CWTS are presented below (Figure 8 and Figure 9, respectively) while graphs for the remaining constituents can be found in Appendix B (Figures B1 to B4).

Since the beginning of operations of the demonstration-scale CWTS, significant concentrations of copper have been leaching from the CWTS soils used in construction (Contango, 2016 and 2017; Section 5.6). Moreover, aluminum (which could not be accounted for by the influent water chemistry) was elevated in the CWTS. Because of metals leaching from the soils, the treatment occurring within the CWTS was far greater than what was being observed by simply measuring the inflow and outflow points (Contango, 2017). These soils first needed to be treated, before significant treatment could occur for the influent waters.

In early 2017 (June 20, 2017 sampling date), copper was still leaching from the soils into the water (Figure 8). However, at later sampling dates in 2017 copper was no longer leaching at a rate that the treatment wetland could not keep up with for treatment. Copper concentrations decreased by the end of the A cells and stabilized through B cells, indicating that treatment of copper is occurring and that copper leaching from the soils has subsided. Leaching of constituents from the soils is further described in Section 5.6.

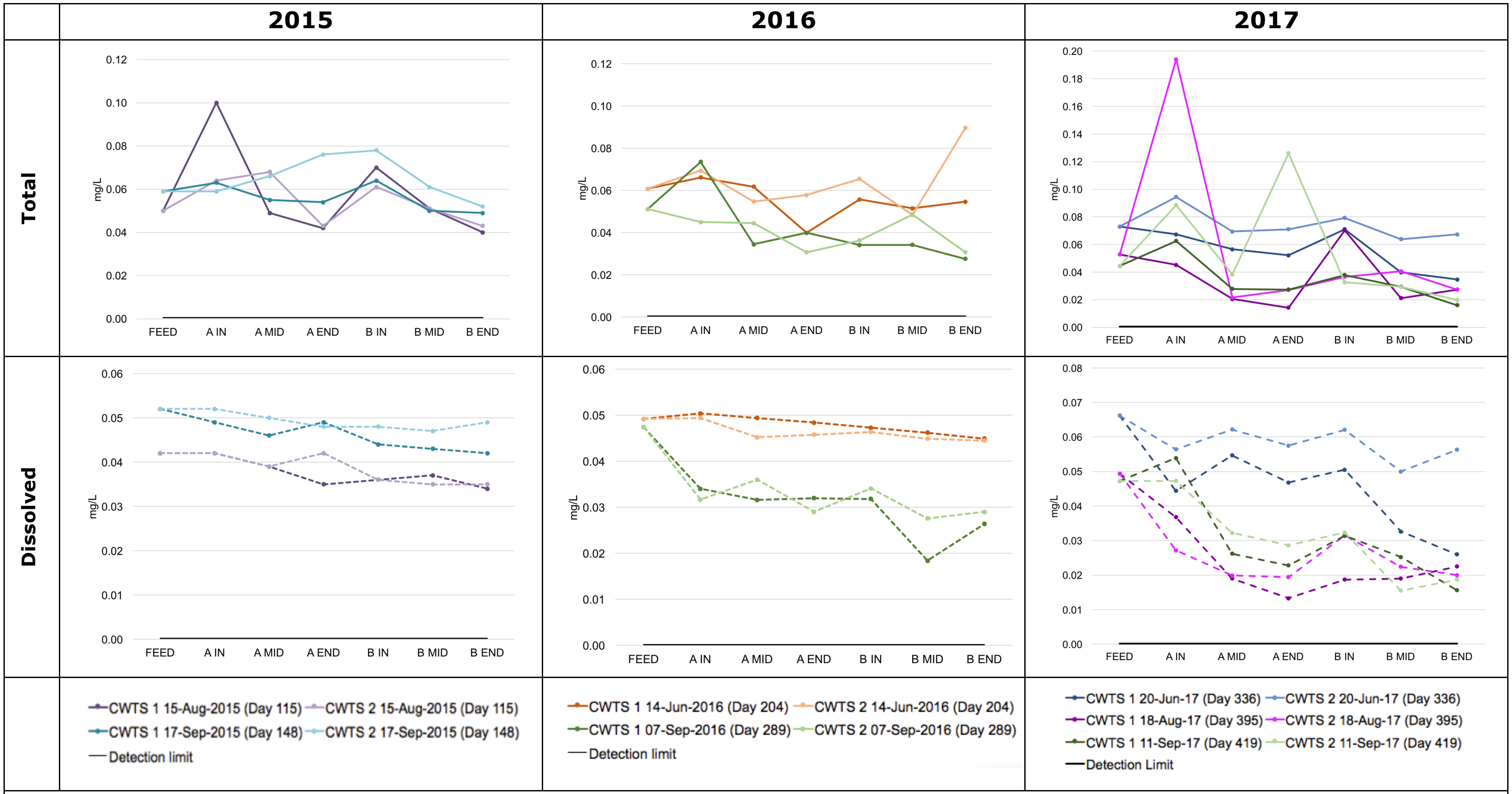


Figure 8 – Copper concentrations through the CWTS.
2015 (left), 2016 (middle), and 2017 (right) total (top) and dissolved (bottom) copper concentrations. Data shown for seven timepoints, where water was sampled at 7 locations through the flow path of the CWTS to assess for treatment fronts within the CWTS, or possible leaching of constituents from the soils into the CWTS. The Maxxam (2015 results) detection limit (DL; black line) for copper is 0.0002 mg/L. The ALS (2016 and 2017 results) DL for copper is 0.0005 mg/L. Spikes in copper concentrations were observed in early sampling points in the CWTS indicating leaching from the soils is occurring; however, later sampling points do not show any copper spikes and, therefore, leaching has subsided. The 2017 graphs are on different y-axes than previous graphs due to one data point from 18-Aug-17 for total copper and two data points from 20-Jun-17 for dissolved copper that are higher than previous axes.

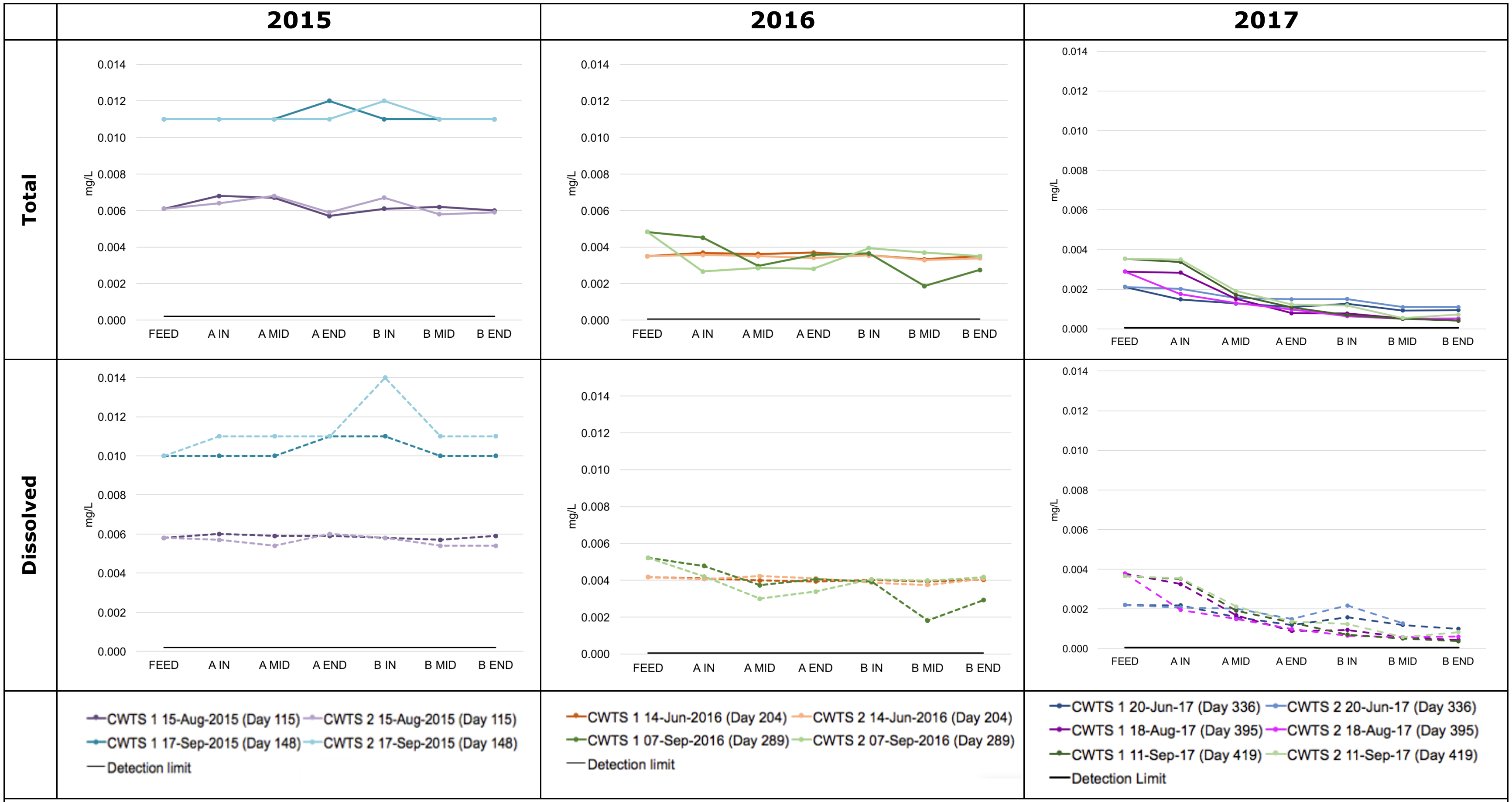


Figure 9 – Selenium concentrations through the CWTS.
2015 (left), 2016 (middle), and 2017 (right) total (top) and dissolved (bottom) copper concentrations. Data shown for seven timepoints, where water was sampled at 7 locations through the flow path of the CWTS to assess for treatment fronts within the CWTS, or possible leaching of constituents from the soils into the CWTS. Y-axes are set to be the same for total and dissolved. The Maxxam (2015 results) detection limit (DL; black line) for selenium is 0.0002 mg/L. The ALS (2016 and 2017 results) DL is 0.000050 mg/L. This graph indicates that leaching is not occurring as there are no spikes in selenium concentrations throughout the CWTS.

5.2.2. Performance during Commissioning-A

The commissioning-A period occurred from May 16 to September 29 in 2015 and May 2 to July 28 in 2016. Details regarding the results of the commissioning-A period can be found in Demonstration-Scale 2016 Update Report (Contango, 2017).

5.2.3. Performance during Commissioning-B

The beginning of commissioning-B was marked by the addition of organics to the CWTS and ran from July 29 to September 30 in 2016 and from May 27 to August 17 in 2017. These organics (straw and wood chips) were added to further aid the copper in the soils to transition into sulphide mineral forms, and represents an amount of organic material similar to what would be produced by the CWTS once fully established with *Carex*. Treatment of constituents was similar through 2016 and 2017 for commissioning-B. An evapotranspiration trial was also completed during commissioning-B to allow water to stagnate and provide time for copper in the soils to convert to sulphide mineral forms more readily.

5.2.4. Performance during Operations

Figures showing performance of the demonstration-scale CWTS in 2017 (commissioning-B and operational period) can be found in Appendix B (Figures B5 to B12). In the operational period from August 18 to September 22, 2017, dissolved cadmium, copper, selenium, and zinc treatment improved from the 2017 commissioning-B period. Dissolved metals concentrations were used for the discussion in this report instead of total metals concentrations, as total values were highly variable and not representative of the metals concentrations in the CWTS. The variability of the total metals concentrations is likely owing to particulate material containing metals being part of the grab sample collection method. During the operational period the CWTS achieved an average decrease of 0.0169 µg/L for cadmium (from 0.0261 µg/L to 0.0092 µg/L), 31.8 µg/L for copper (from 49.1 µg/L to 17.3 µg/L), 3.5 µg/L for selenium (from 4.0 µg/L to 0.5 µg/L), and 47.3 µg/L for zinc (from 49.2 µg/L to 1.9 µg/L; Table 4, Figure 10, Figure 11, Figure 12, and Figure 13, respectively). In contrast, molybdenum removal was fairly constant through 2017 (both commissioning-B and operations) with a decrease of 3.9 µg/L (5.7 µg/L to 1.8 µg/L) during commissioning-B and a decrease of 3.6 µg/L (from 6.3 µg/L to 2.7 µg/L) during operations (Table 4). The percent removal of molybdenum and selenium in 2017 is notable, as it has increased from 0% removal during commissioning-A in 2015 and 2016 (Contango, 2016 and 2017) (Table 4). Furthermore, nitrite and nitrate outflow concentrations also decreased from feed water concentrations throughout the demonstration-scale CWTS. Nitrite and nitrate are therefore being removed through treatment in the CWTS (Figure 15 and Figure 16). These results indicate that the commissioning periods were successful in establishing beneficial conditions for the removal of constituents in the CWTS and treatment of these constituents should continue through 2018.

Table 4 – Percent removal of dissolved constituents in the demonstration-scale CWTS.

COC (µg/L)		Commissioning period				Operational period
		2015[1]	**2016[2]**	**2016[3]**	**2017[4]**	**2017[5]**
Cd	In	0.0505	0.0240	0.0185	0.0163	0.0261
	Out	0.0248	0.0142	0.0066	0.0093	0.0092
	%	**49**	**40**	**64**	**41**	**66**
Cu	In	54.5	61.6	46.1	59.5	49.1
	Out	45.0	56.7	28.8	35.5	17.3
	%	**17**	**8**	**37**	**36**	**65**
Mo	In	11.0	7.6	7.3	5.7	6.3
	Out	11.3	7.6	5.7	1.8	2.7
	%	**0**	**0**	**21**	**62**	**57**
Se	In	11.0	3.7	5.7	2.5	4.0
	Out	11.3	3.4	3.3	0.9	0.5
	%	**0**	**8**	**41**	**61**	**87**
Zn	In	12.3	92.8	37.6	135.3	49.2
	Out	6.8	49.0	11.6	4.9	1.9
	%	**42**	**47**	**69**	**95**	**96**

[1] Values calculated from end of last two sampling event in 2015 before the addition of EDTA (September 9 and 17, 2015; during commissioning-A).

[2] Commissioning-A (May 2, 2016 to July 28, 2016).

[3] Commissioning-B (July 29, 2016 to September 30, 2016).

[4] Commissioning-B (May 27, 2017 to August 17, 2017).

[5] Operational period (August 18, 2017 to September 22, 2017).

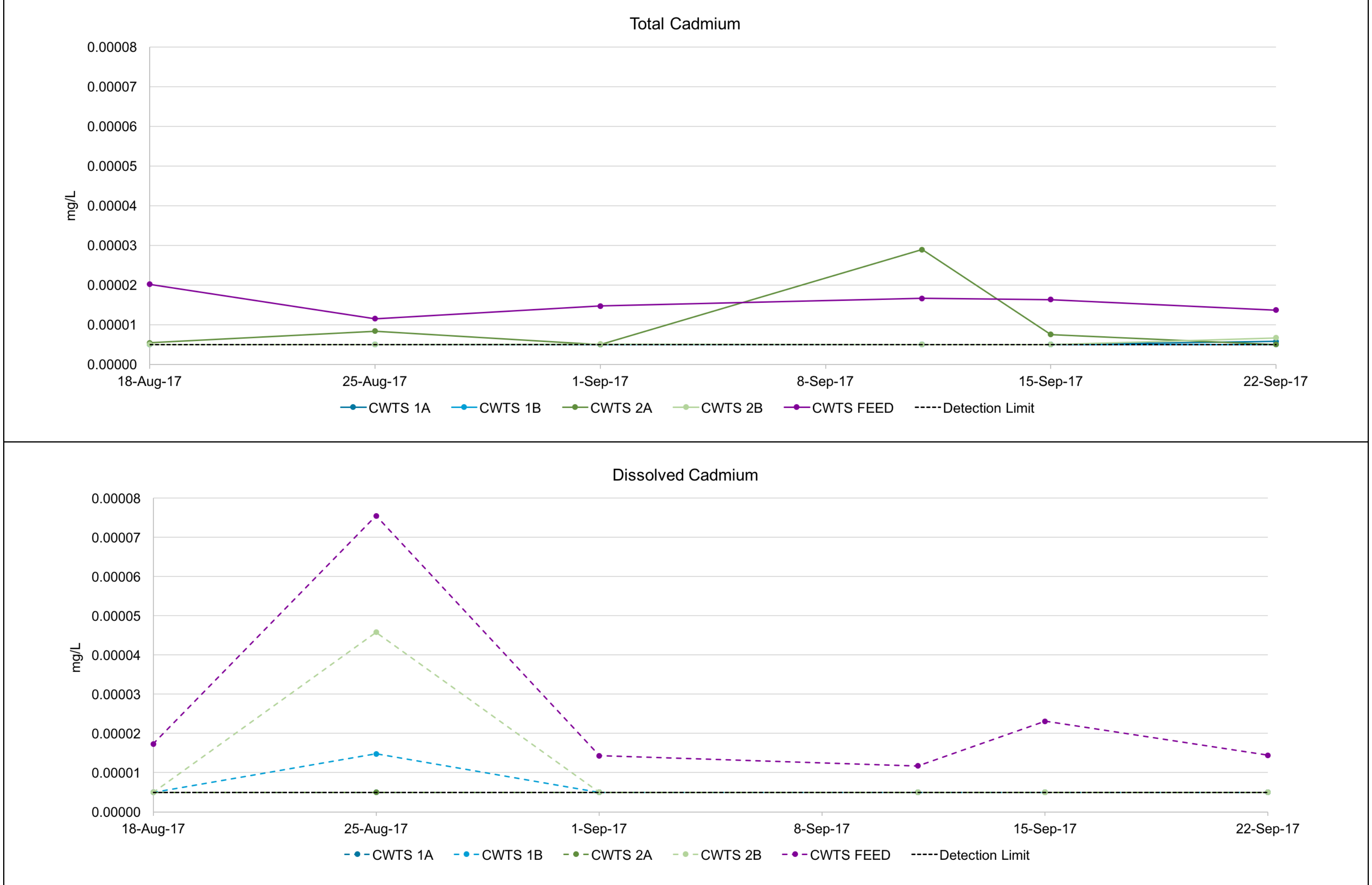


Figure 10 – Cadmium concentrations in operational period of the demonstration-scale CWTS.
The ALS detection limit for cadmium is 0.000005 mg/L.

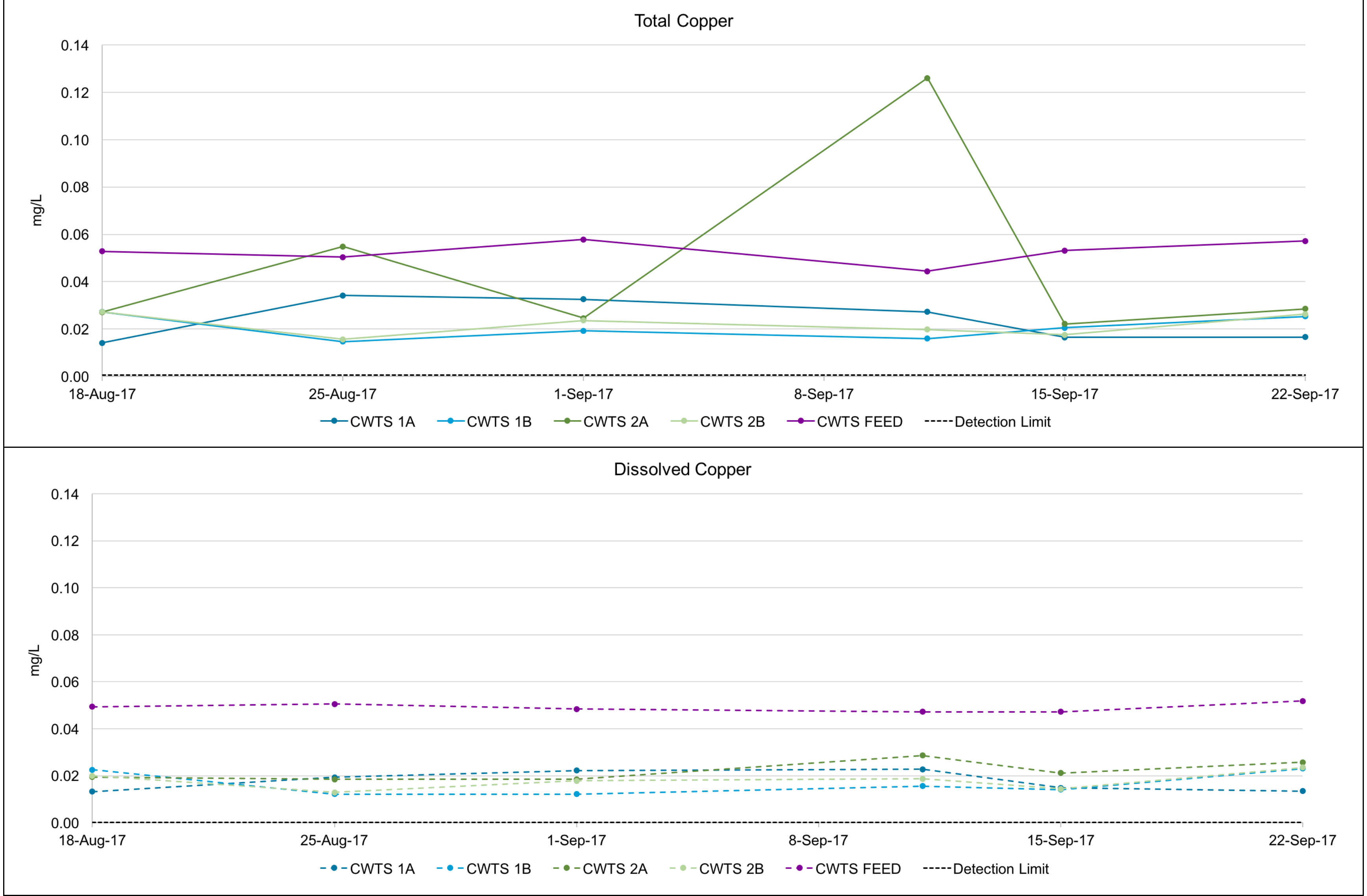


Figure 11 – Copper concentrations in operational period of the demonstration-scale CWTS.
The ALS detection limit for dissolved and total copper is 0.0002 mg/L and 0.0005 mg/L, respectively.

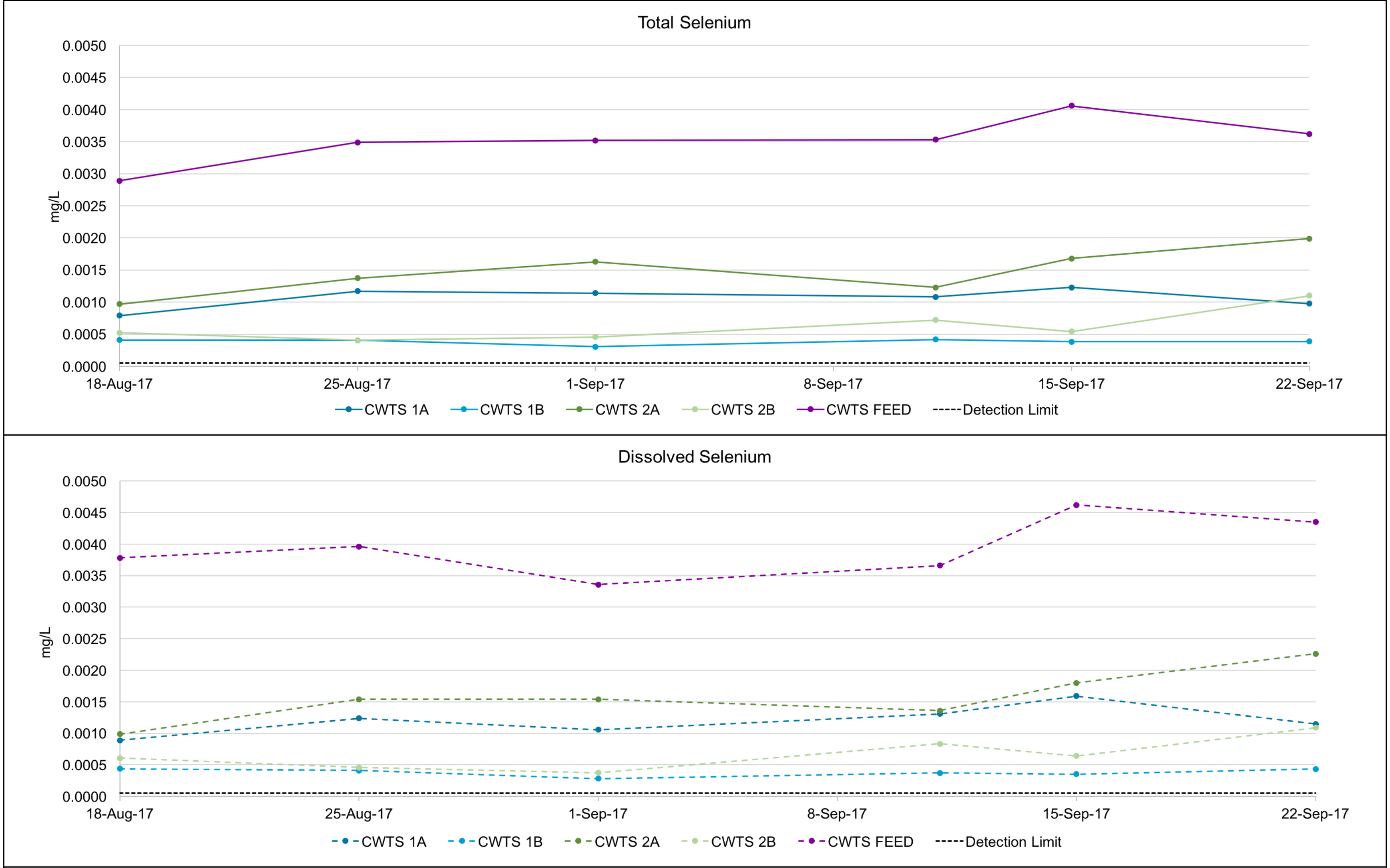


Figure 12 – Selenium concentrations in operational period of the demonstration-scale CWTS.
The ALS detection limit for selenium is 0.000050 mg/L.

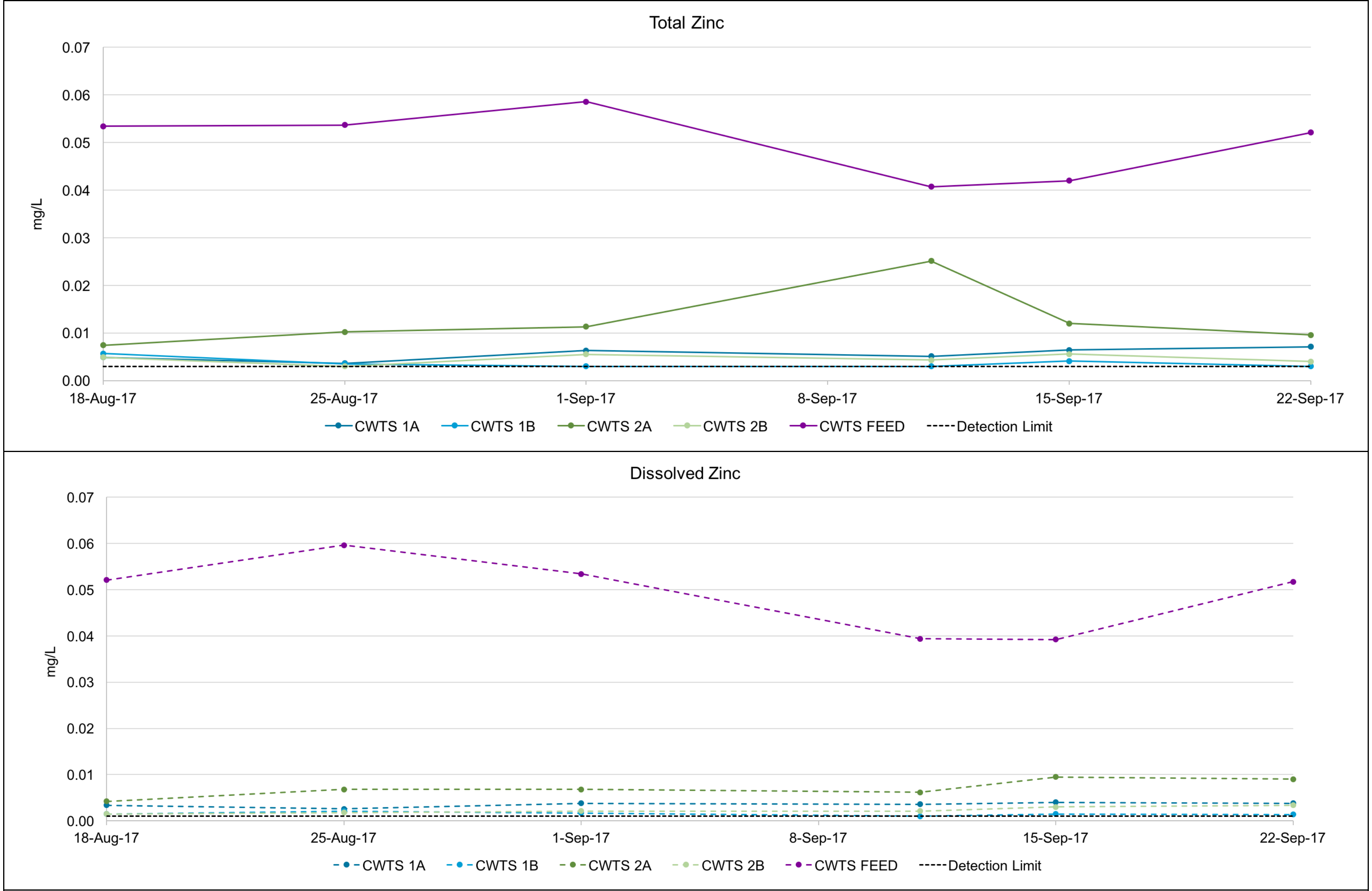


Figure 13 – Zinc concentrations in operational period of the demonstration-scale CWTS.
The ALS detection limit for dissolved and total zinc is 0.001 mg/L and 0.003 mg/L, respectively.

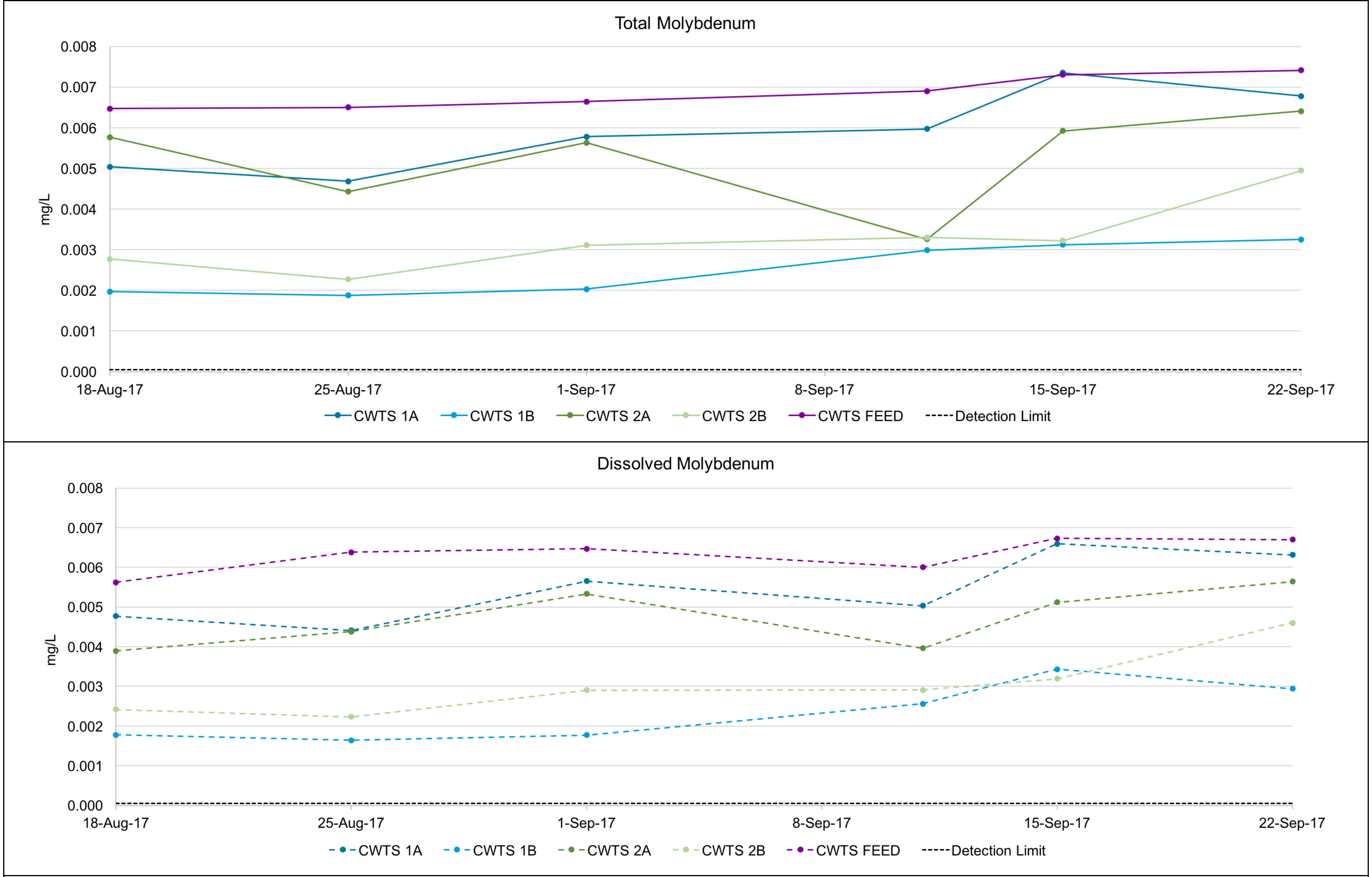


Figure 14 – Molybdenum concentrations in operational period of the demonstration-scale CWTS.
The ALS detection limit for molybdenum is 0.000050 mg/L.

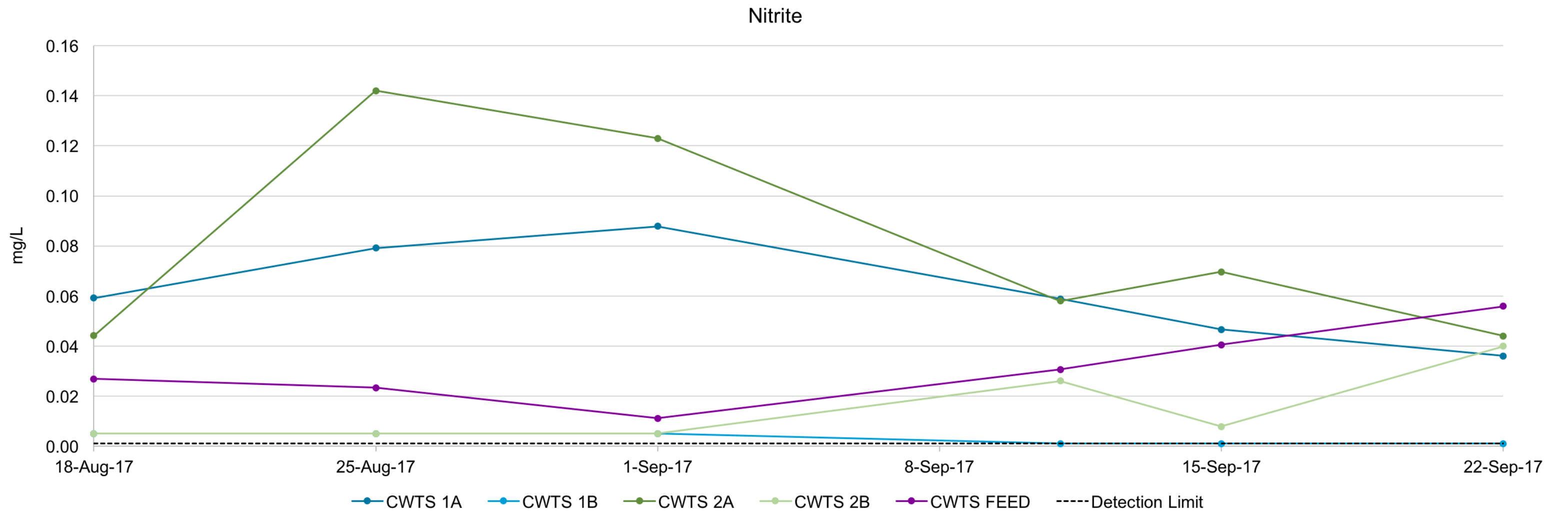


Figure 15 – Nitrite as N (NO_2) concentrations in operational period of the demonstration-scale CWTS.
The ALS detection limit for nitrite is 0.0050 mg/L.

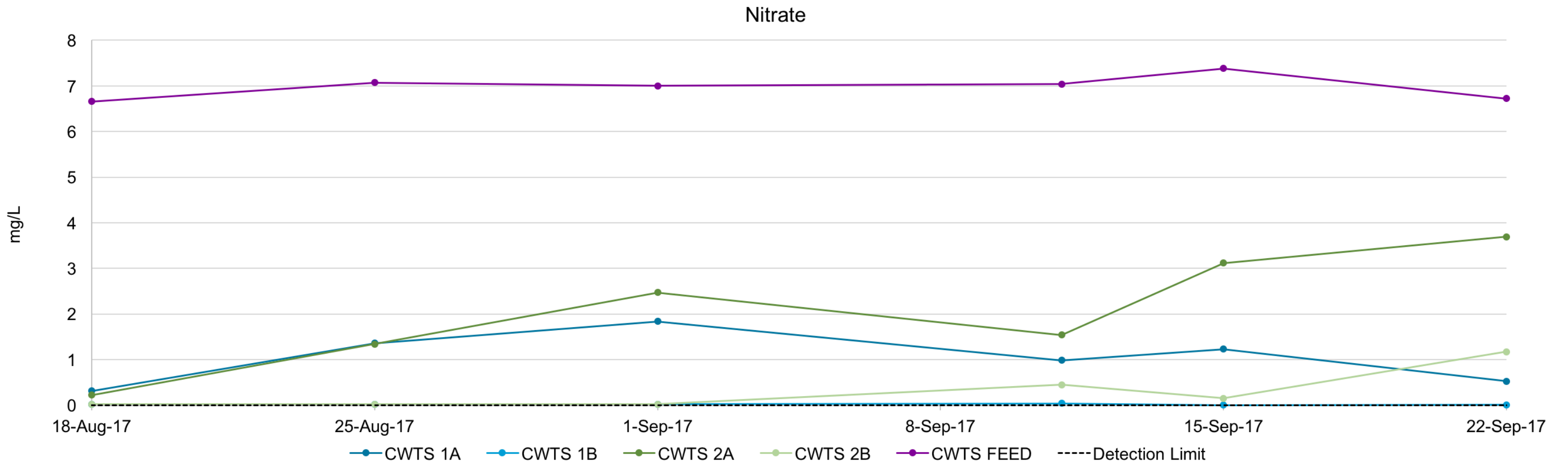


Figure 16 - Nitrate as N (NO_3) concentrations in operational period of the demonstration-scale CWTS.
The ALS detection limit for nitrate is 0.025 mg/L.

5.3.Hydraulic Retention Time

The following are key findings regarding the hydraulic retention time, which are detailed further below:

- The tracer study effectively demonstrated the HRT and flow symmetry through the CWTS.
- There was a single flow path in the CWTS (shown by a single peak in the tracer study)
- Water is incorporating in to the CWTS soils (shown by the long tail for depletion of the tracer).
- The nominal HRT is calculated from the area of the CWTS and the depth at the in situ measuring points. This nominal HRT does not account for depth variations, embankment slopes, vegetation (using space in the water), or substrate pore space involvement. It was found that once all of these factors are in play, the correction factor from nominal to actual is only 0.01 added to the depth of the CWTS, which is incorporated into the HRT calculation as expressed in Equation 3.

5.3.1. Tracer Study

A tracer study was conducted in cell 1A of the CWTS in 2016 (June 13-15, 2016) and in 2017 (June 21-July 2, 2017). Results from the 2016 tracer study can be found in the 2016 demonstration-scale CWTS report (Contango, 2017). The methods of the 2017 tracer study were refined from the 2016 tracer study methods and are further discussed in Appendix A. The nominal HRT is calculated from the area of the CWTS and the depth at the in situ measuring points. This nominal HRT does not account for depth variations, embankment slopes, vegetation (using space in the water), or substrate pore space involvement. The purpose of the tracer studies was to determine the actual hydraulic retention time (HRT) that occurs in the CWTS with a known inflow rate and depth measurement. Then, using this actual HRT form the tracer study, a correction factor can be developed for future CWTS HRT calculations.

Salt (NaCl) was used as the tracer in these tracer studies. By adding a salt solution at the inflow of the CWTS, and placing a YSI meter at the outflow of the CWTS, it could be determined how long it took for the salt to pass through the CWTS by monitoring the specific conductance (SPC) in situ (as salt raises the SPC). The actual HRT of the CWTS was determined by calculating the amount of time that passed between the addition of the salt tracer at the inflow of the CWTS and the peak in SPC at the outflow.

The nominal HRT at the time of the tracer study was calculated based on the flow rate at the time of the tracer study, the known area of cell 1A, and measured depth of cell 1A obtained from the depth sticks that were installed in the CWTS in June 2016 (Appendix A, Figure A5). The results from the 2017 HRT tracer study suggests that the actual HRT of cell 1A is 2.25 days while the nominal HRT of cell 1A is 2.05 days. Therefore, the actual HRT was approximately 10% slower than the nominal HRT. The actual HRT of 2.25 days obtained from the 2017 tracer study was used to solve Equation 1, implying 0.14 m of water involvement as the "depth", which was 0.01 m greater than the measured depth of 0.13 m of water. This results in a correction factor of 0.01 (Equation 2). Therefore, the correction factor can be applied to the operational HRT as shown in Equation 3 in order to more accurately estimate HRT of the CWTS.

This HRT correction factor has been incorporated into calculations for the operational HRT for the demonstration-scale CWTS in 2017. The correction factor was incorporated into the operational HRT calculations in Section 5.3.2 and used to determine the 2017 removal rate coefficients in Section 5.4.2.

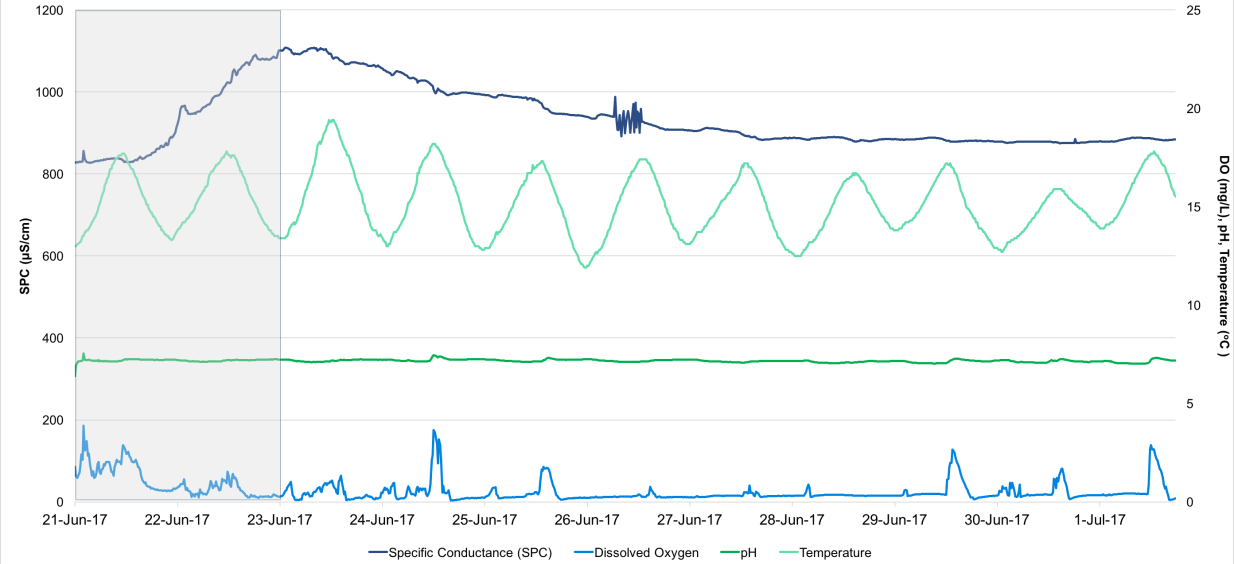


Figure 17 – Hydraulic retention time tracer study results.
Specific Conductance (SPC; µS/cm) on primary y-axis. Dissolved oxygen (mg/L), pH, and temperature (°C) on secondary y-axis. Grey shading indicates time from when CWTS was dosed to the peak of tracer breakthrough, which was used as the actual HRT. The fluctuation in temperature correspond to day (peaks) and night (lows). The dates on the x-axis are at 24 hr intervals, beginning from 7:52 am on June 21, 2017.

$$\text{Actual depth} = \frac{(Q \times \text{actual HRT})}{A}$$

Equation 1 – Equation for calculation of the actual CWTS depth including the correction factor.
Q is the flow rate; actual HRT is the HRT obtained from the tracer study (2.25 days); A is the area of cell 1A.

$$\text{Correction factor} = \text{Actual depth} - \text{measured depth}$$

Equation 2 – Equation for calculation of the correction factor.
The actual depth was calculated via Equation 1 (0.14 m); measured depth is the depth of cell 1A during the tracer study (0.13 m).

5.3.2. Operational Hydraulic Retention Time

The operational HRTs of the demonstration-scale CWTS for 2017 were calculated for each series using Equation 3. Equation 3 uses the volume of a CWTS series including a correction factor (calculated from the results of the tracer study in Equation 2; Section 5.3) and the flow rate from the operational period under consideration. For the operating period in 2017, the average HRT was calculated for August 17 – September 22, 2017 as the flows and depths were relatively stable during this time. The operational HRTs calculated were 5.85 days and 6.82 days for series 1 and series 2, respectively. The operational HRTs were then averaged and used in the calculation of removal rate coefficients in Section 5.4.2.

$$\text{Operational HRT} = \frac{A \times \text{actual depth}}{Q}$$

Equation 3 – Equation for calculation of hydraulic retention time.

Operational HRT is the confirmed hydraulic retention time; *A* is the area of the CWTS; actual depth was calculated using Equation 1 (0.14 m); *Q* is the flow rate.

5.4.Treatment Effectiveness

The following are key findings regarding treatment effectiveness of the CWTS, which are detailed further below:

- All targeted constituents are being treated by mineralization and sequestered to the soils (minimal plant uptake).
- The lowest concentrations consistently achievable for the treatment design (thermodynamic minimums) were reached by the end of the A cells for cadmium and copper.
- RRCs for cadmium and zinc in the 2017 demonstration-scale CWTS were artificially low because low flow rates did not provide the resolution needed to determine a RRC.
- Removal rate coefficients (RRCs, *k*) have been developed that can be used for full-scale sizing.
- Copper leaching from soils has decreased, but is still likely making the RRC artificially low in this CWTS; however, the RRC is expected to improve once copper leaching has subsided.

5.4.1. Thermodynamic Minimums

The thermodynamic minimum is the lowest concentration consistently achievable for a given treatment design and water chemistry. Once reached, making the CWTS bigger will not result in further decrease of outflow concentration (although outflow load may continue to decrease). Therefore, thermodynamic minimums are useful parameters to aid in developing appropriate RRCs, and determining appropriate sizing and outflow water quality objectives of a CWTS. The thermodynamic minimum was determined for each constituent in the demonstration-scale CWTS. The thermodynamic minimum was calculated by comparing the A cell and the B cell concentrations in a series to determine if the concentrations were significantly different or not. If a concentration had stabilized between the A and B cell in a series, the thermodynamic minimum was considered to have been met. To determine when concentrations had stabilized, statistical analyses were done (paired t-test, one-tailed, $\alpha=0.05$) to determine if the concentrations were significantly different or not. These analyses were then also visually compared to the concentrations of constituents at seven sampling locations throughout the CWTS from two time points, to further evaluate and confirm whether concentrations appeared to have leveled off (Figure 8 and Figure 9 for copper and selenium, respectively; Figures B1 to B4 in Appendix B for remaining constituents). However, there was not enough time points in the operational period for this data to be used in the statistical analyses to further refine the expected HRT for the thermodynamic minimums. This can be refined in 2018, by varying flow rates.

Based on the results of the t-test for the A cell and B cell concentrations, it was determined that the thermodynamic minimum was achieved for cadmium and copper by the end of the A cells in the demonstration-scale CWTS. The detection limit was reached for cadmium prior to the outflow of cell A, suggesting that faster flows would be needed to accurately determine the HRT at which the thermodynamic minimum was met (Figure 18). The thermodynamic minimum for molybdenum, nitrate, and selenium were not yet statistically achieved, suggesting that a larger CWTS would achieve lower concentrations of these constituents (Appendix B, Figures B13 to B17). The thermodynamic minimum for zinc was not statistically achieved, however, the majority of zinc load was removed within the beginning of cell A, with minimal load removal in the remainder of the CWTS (Figure 18). Furthermore, outflow concentrations of both cell A and B for zinc are at or near detection limit (Figure B17), so it is not necessarily beneficial to build a larger CWTS for zinc.

As shown by the graphs previously mentioned, concentrations in A cells and B cells were very similar for cadmium and copper. This shows that treatment is occurring in the A cells and has reached a thermodynamic minimum which does not decrease further for the B cells. However, these results for copper should be taken with consideration that there is still some residual copper in the soils from construction that is being treated, and therefore, there is more copper treatment ongoing that can be noted by just the water concentrations.

Interestingly, once cadmium, copper and nitrate are treated, zinc and molybdenum begin to have an increase in treatment. This phenomenon is referred to as a treatment front, which generally abides by reaction orders (i.e., nitrate treatment before sulphate, etc.; Murray-Gulde, 2008).

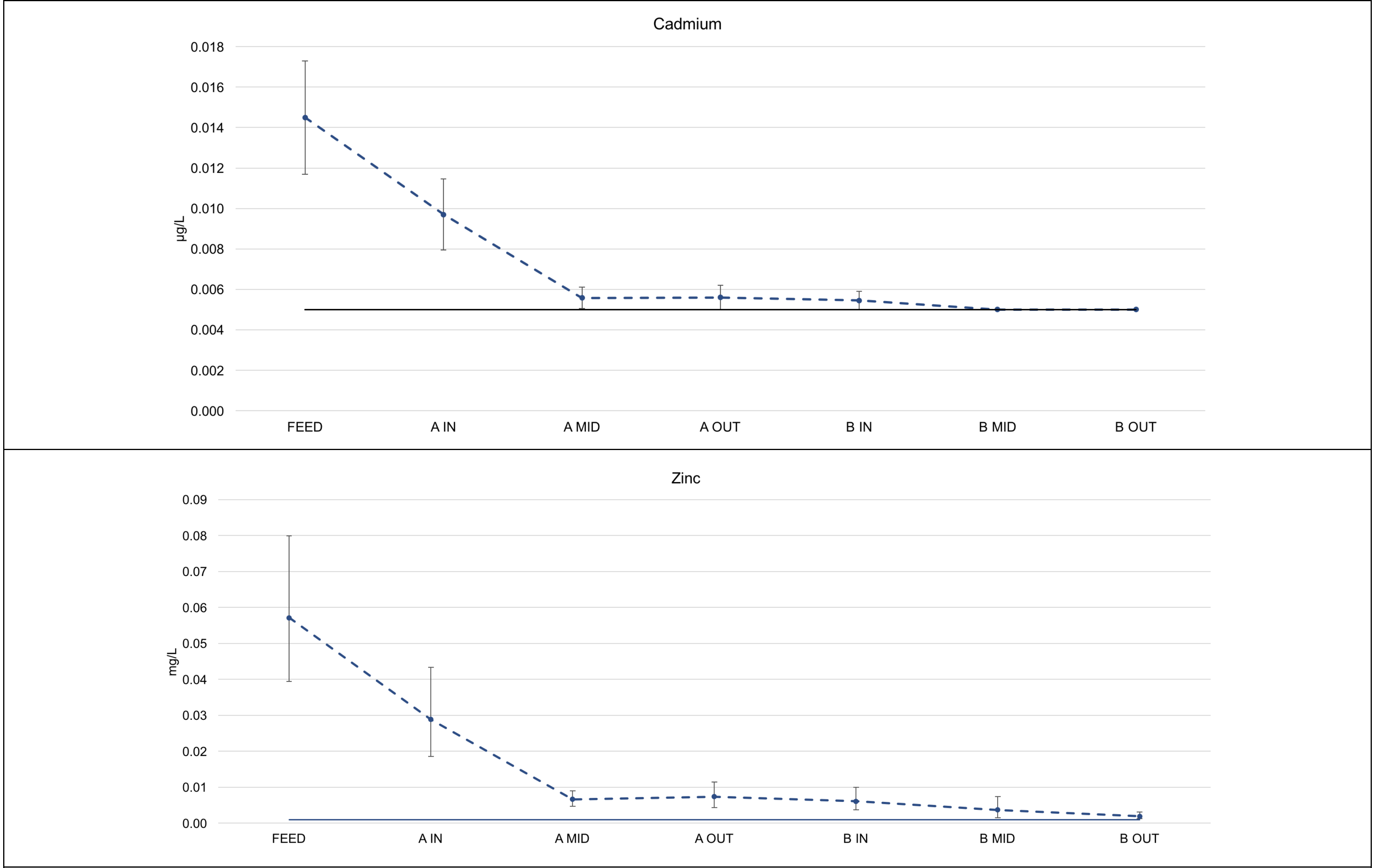


Figure 18 – Average dissolved cadmium and zinc concentrations through the CWTS during the operational period. Data shows the average of series 1 and series 2 for two sampling points during the operational period (August 18 and September 11, 2017). Error bars show minimum and maximum concentrations at each sampling point. The black horizontal line shows the detection limit of 0.005 µg/L for cadmium and 0.001 mg/L for zinc.

5.4.2. Removal Rate Coefficients

An important factor for CWTS design is the rate of treatment, also known as the removal rate coefficient (RRC; *k*). The RRC is based on the treatability of a specific compound and the hydraulic retention time of the CWTS, both of which are site-specific based on water chemistry, CWTS designs, and characteristics of the CWTS. A RRC was calculated and applied for cadmium, copper, molybdenum, selenium, zinc, and nitrate which can be used to refine future sizing and performance estimations of a full-scale CWTS (Table 5). In pilot-scale testing specific for the Minto CWTS, the RRC for selenium was a zero-order reaction kinetic, however, optimizations of the operation of the system through the demonstration-scale commissioning have enabled a first-order RRC to be maintained. Therefore, cadmium, copper, selenium, zinc, and nitrate are calculated as first-order kinetics, but molybdenum followed a zero-order kinetic. In other words, the reaction rate for molybdenum is a constant rate and does not depend on concentration, whereas the reaction rates for cadmium, copper, selenium, zinc, and nitrate are proportional to concentration (a half-life type of reaction).

In Equation 4 and Equation 5, *Cf* is the final concentration, *Ci* is the initial concentration, and *HRT* is the operational hydraulic retention time calculated in Equation 3 (Section 5.3.2) using the CWTS depth and correction factor calculated from the tracer study (Equation 1 and Equation 2; Section 5.3).

$$k = \frac{-\ln\left(\frac{Cf}{Ci}\right)}{HRT}$$

Equation 4 – Equation for calculation of first-order removal rate coefficient.
k is the removal rate coefficient; *Cf* is the final concentration; *Ci* is the initial concentration; *HRT* is the operational hydraulic retention time.

$$k = \frac{(Ci - Cf)}{HRT}$$

Equation 5 – Equation for calculation of zero-order removal rate coefficient.
k is the removal rate coefficient; *Cf* is the final concentration; *Ci* is the initial concentration; *HRT* is the operational hydraulic retention time.

RRCs were calculated for each constituent (dissolved and total) and series 1 and series 2 were averaged for the operational period in 2017 and compared to RRCs calculated to the commissioning period of 2016, and pilot-scale RRCs (Table 6). In 2016, all RRCs were calculated using outflow concentrations from the B cells while in 2017, cadmium and copper RRCs were calculated using outflow concentrations and HRTs from the A cells as they had reached their thermodynamic minimum at the end of cells 1A and 2A (Section 5.4.1). The RRCs for the remaining constituents did not reach their thermodynamic minimum in the A cells and, therefore, outflow concentrations and HRTs from the B cells were used. RRCs for cadmium and zinc in the 2017 demonstration-scale CWTS were artificially low because low flow rates did not provide the resolution needed to determine a RRC. Additionally, RRCs for copper in demonstration-scale CWTS are also artificially low due to copper leaching from soils used in construction of the system. Therefore, the RRCs for copper are expected to improve once leaching has subsided. In general, RRCs improved from those calculated in 2016 (Table 5; Contango, 2017).

Applying the removal rate coefficients (*k*) from Table 5 to Equation 3 above, parameters can be rearranged to solve for those of interest, such as the volume needed, that in turn determines the area of CWTS required which is dependent upon the design. Analytical results from August 17 – September 22, 2017 were chosen to calculate *k* because this is the operational period after commissioning-B was completed and flow rates were stable and at targeted values. The treatment rate coefficients applied here are intended to be conservative estimates for conceptual sizing purposes, and will need to be refined through further demonstration-scale (on site) testing.

Table 5 – Removal rate coefficients (k) for constituents of concern.

COC	Pilot[1] k*day^{-1}	2016 Demonstration[2] (Commissioning) k*day^{-1}		2017 Demonstration[3] (Operational) k*day^{-1}		Recommended[4] k*day^{-1}
	Total	**Dissolved**	**Total**	**Dissolved**	**Total**	**Dissolved**
First order removal rate coefficients						
Cd	1.142	0.172	0.174	>0.521[5]	>0.226[5]	1.142
Cu[6]	1.171	0.0778[6]	0.0740[6]	>0.3100[6]	>0.1356[6]	1.171
Mo	0.1010	0.0416	0.0468	N/A	N/A	N/A
Se	N/A	N/A	N/A	0.3186	0.3069	0.3186
Zn	1.144	0.195	0.183	0.512[5]	0.394[5]	1.144
Nitrate	0.559	0.0914	N/A	0.591	N/A	0.591
Zero order removal rate coefficients						
Mo	N/A	N/A	N/A	0.0006	0.0006	0.0006
Se	0.00181	0.000357	0.000316	N/A	N/A	N/A

[1] Values calculated from data in Contango, 2014b (pilot-scale report) for *Carex aquatilis* + moss with low nitrogen scenario.

[2] Analytical results from August 10 – September 17, 2016 were used.

[3] Analytical results from August 18 – September 22, 2017 were used.

[4] Cadmium, copper, and zinc recommended RRCs are developed from total concentrations in pilot-scale testing and are conservative proxies for dissolved concentrations.

[5] RRCs for cadmium and zinc in the 2017 demonstration-scale CWTS were artificially low because low flow rates did not provide the resolution needed to determine a RRC, so the lowest potential k value based on available data is reported here.

[6] RRC's for copper in demonstration-scale CWTS are artificially lowered due to copper leaching from soils used in construction of the system and are therefore expected to improve once leaching has subsided.

N/A = an RRC is not available. All RRCs are for first-order reaction kinetics except for selenium in the 2016 demonstration-scale CWTS and molybdenum in the 2017 demonstration-scale CWTS, which are zero-order reaction rate kinetics. All RRCs in 2016 and 2017 used outflow concentrations for the B cells in the CWTS.

5.5.Evapotranspiration in the Demonstration-Scale CWTS

The following are key findings regarding the evapotranspiration studies, which are detailed further below:

- The evapotranspiration studies revealed a significant loss of water, which will impact calculations of loads to the receiving environment (making them lower than previously estimated).
- In May and June, an average water loss of 5.3 L/day/m^2 was observed, which is equivalent to 18-20% of water (~700 L/day lost in the demonstration CWTS).
- During the evapotranspiration trials, copper leached into the water as it was transformed from an oxide mineral to a sulphide mineral (because of the copper in the soils used for construction). This is not representative of what would occur during periods with no flow in a full-scale CWTS, where soils with minimal leachable copper are used and copper is deposited in sulphide form (fraction 4) by the biogeochemical activity of the CWTS (Section 5.6).

Total evapotranspiration from a CWTS is measured as the combined effects of open water evaporation and plant transpiration (Beebe et al., 2014). The purpose of calculating the evapotranspiration of a CWTS is to understand the amount of water lost per day over the surface area of a wetland, which in turn concentrates constituents, and should be considered in the context of the decrease in outflow concentration (or not) and outflow load reduction. It should also be noted that evapotranspiration will vary depending on temperature, humidity, and wind on-site and, therefore, will fluctuate over time. This should be considered when interpreting evapotranspiration rates, however, for conceptual calculation purposes, a set rate is applied here.

The off-site evapotranspiration study conducted in 2016 suggested that approximately 15.5 L/day/m^2 could be lost due to evapotranspiration (Contango, 2017). The results of the 2017 on-site evapotranspiration studies were intended to provide more accurate estimates at the CWTS than the off-site study and had an average water loss of 5.3 L/day/m^2 (Table 6). These results are consistent with pilot-scale results from another CWTS planted with *Carex* where 5.1 L/day/m^2 were lost through evapotranspiration. Although the off-site study can be informative, the on-site study is more representative of what would occur during operation of the full-scale CWTS in the spring. The difference in the two rates is expected to be due to temperature difference of the trial. The on-site during the evapotranspiration study were on average 9.6°C in May and 13.7°C in June while temperatures in the off-site study were on average 22°C during the day (12 hr) and 16°C during the night (12 hr) which is less representative of site conditions. Temperatures in July and August at Minto were only slightly higher than June temperatures and were on average 15.8°C and 13.9°C, respectively. Therefore, we would expect marginally higher rates of evapotranspiration in these months.

Table 7 shows the amount of water lost to evapotranspiration during the operational period (August 18 – September 22, 2017) in each cell of the demonstration-scale CWTS. The amount of water lost in the CWTS during each flow rate period tested is calculated using Equation 6.

$$Water\ loss\ (\%) = \frac{ET}{Q} \times 100$$

Equation 6 – Equation for the calculation of the water loss due to evapotranspiration.

Q is the flow rate (L/day); *ET* is the evapotranspiration rate (L/day).

Table 6– Water loss through evapotranspiration in the CWTS.

Study	Cell	Water loss[1] (L/day)	Water loss[2] (L/day/m^2)
Trial 1: May 16 – 24, 2017	1A	575.0	8.3
	1B	143.7	2.1
	2A	509.0	8.8
	2B	152.7	2.6
		L/day/m^2 Average	**5.4**
Trial 2: June 8 – 11, 2017	1A	580.8	8.3
	1B	116.2	1.7
	2A	775.7	13.3
	2B	339.4	5.8
		L/day/m^2 Average	**7.3**
Trial 3: June 11 – 15, 2017	1A	292.7	4.2
	1B	27.9[3]	0.4
	2A	273.4	4.7
	2B	203.6	3.5
		L/day/m^2 Average	**3.2**
		L/day/m^2 Overall Average	**5.3**

[1] Water loss (L/day) = (initial depth (m) – final depth (m)) * area of CWTS (m^2) * 1000 L/m^3/days.

[2] Water loss (L/day/m^2) = Water loss (L/day) / area of CWTS (m^2).

Total days of study in trials 1, 2, and 3 were 8, 3, and 5 days, respectively. The area of series 1 is 69.7 m^2 and the area of series 2 is 58.2 m^2.

[3] Depths in this cell had minimal change throughout trial 3.

Table 7 shows how this water loss likely affected the load leaving the wetland. The average ambient temperature on-site for this time period was 9.9°C, and so the evapotranspiration rates from the trials are expected to be relevant to the operational period. The information in Table 7 is calculated based on Equation 7 and Equation 8.

Evapotranspiration has a significant effect on the calculation of constituent load to the receiving environment. Therefore, future models for assimilative capacity in the downstream receiving environment should take into account not only the predicted outflow concentrations from the CWTS using removal rate coefficients (Section 5.4.2), but also adjust the load accounting for evapotranspiration.

Concentrations of copper (and other metals) were measured in the water during the evapotranspiration studies to determine if any leaching occurred during periods of no flow because the soils used in construction contained oxidized copper minerals. In the 2017 study, this is noted by an average decrease of 63.3 µg/L copper after flow was restarted and treatment of copper resumed. This is not representative of what would occur during periods with no flow in a full-scale CWTS, where soils with minimal leachable copper are used and copper is deposited in sulphide form (fraction 4) by the biogeochemical activity of the CWTS (Section 5.6). In a full-scale CWTS, lower flows and stagnation will result in greater treatment of constituents into sulphide mineral forms.

The demonstration-scale evapotranspiration studies were conducted to inform evapotranspiration rate estimates for full-scale CWTS design. However, these results are fortuitous because the study was conducted during the commissioning-B period, rather than the operational period when the CWTS was running optimally. Additionally, since the studies were conducted in the spring, they do not capture the seasonality of evapotranspiration rates and are therefore conservative numbers. Thus, it is recommended that another evapotranspiration study be conducted on-site in 2018.

$$Load_{in} = C_i \times V$$

Equation 7 – Equation for the calculation of load of a constituent into a CWTS over a period of time.

$Load_{in}$ is the mass of a constituent that enters a CWTS over a period of time; C_i is the inflow concentration of the constituent; V is the volume of water that enters a CWTS over a period of time.

$$Load_{out(ET)} = Water\ Out_{ET} \times C_f$$

Equation 8 – Equation for the calculation of the load out of a constituent over a period of time, adjusted for evapotranspiration.

$Load_{out(ET)}$ is load out of a constituent over a period of time, adjusted for evapotranspiration; $Water\ Out_{ET}$ is the outflow water volume over a period of time, adjusted for evapotranspiration; C_f is the outflow concentration of the constituent.

Table 7 – Average constituent load in, load out, load out adjusted for evapotranspiration and load removed adjusted for evapotranspiration in the demonstration-scale CWTS.

COC	Form	Load in (mg/ day)	Load out[1] (mg/day)	Load out Adjusted for evapotranspiration[2] (mg/day)	Load removed adjusted for evapotranspiration (mg/day)	Load removed[3] (%)
Cd	D	0.0476	0.0162	0.0131	0.0345	71
	T	0.0283	0.0094	0.0076	0.0207	73
Cu	D	89.7	31.4	25.4	64.3	72
	T	96.2	38.4	31.1	65.1	67
Mo	D	11.5	4.8	3.9	7.6	65
	T	12.6	5.2	4.2	8.3	66
Se	D	7.2	0.9	0.7	6.5	89
	T	6.4	0.9	0.7	5.7	88
Zn	D	90.0	3.4	2.8	87.2	97
	T	91.6	7.5	6.0	85.5	93

[1] Inflow volume was used for the calculation of load out using outflow concentrations without adjusting for evapotranspiration (Appendix A, Equation A2).

[2] Outflow volume adjusted for evapotranspiration was used for the calculation of load out adjusted for evapotranspiration.

[3] Load Removed (%) = (Load out adjusted for evapotranspiration)/(Load in) * 100

Water loss for each flow period is an average of all time points and is calculated using Equation 7. Average water loss in series 1 and 2 is 377.9 L/day/m2 (18%) and 315.4 L/day/m2 (20%), respectively. D = dissolved, T = total. Results in the table are from the operational period only (August 18 – September 22, 2017) and are therefore not representative of what would occur year-round. Ambient temperature on-site for this period was on average 9.9°C.

5.6.Soils

The following are key findings regarding constituents in the soil, which are detailed further below:

- In 2017, leachable copper concentrations in soils decreased in the top 0-10cm while total copper concentrations increased.
- Most constituents, including copper, have shifted primarily into stable reduced and residual minerals fractions in the soil.
- Acid volatile sulphides (AVS) were non-detectable in the CWTS in 2016. In 2017 small amounts of AVS were detected in cells 1A and 2A which indicates that residual sulphides are starting to become available for metal treatment and that copper in the soils are becoming rendered inert through sulphide mineralization.

Although unintentional, the high initial leachable copper concentrations in the CWTS soils (Appendix A, Table A2) allowed for additional testing to be carried out on these CWTSs. Because the soil substrates used for construction of the CWTS were from overburden sources, the copper was in oxidized form rather than in a mineral form that would typically be found in a reducing CWTS (i.e., soils with negative redox). Therefore, there was some initial leaching of copper from the soils into the water.

To assess the effect of the elevated metals in the soils used in construction on CWTS functionality, four soil analytical test methods were used and are described in Appendix A. Analytical methods tested for total metals, leachable metals, and metal speciation. Results of these test methods during the operational period are discussed in the following sections. Table 8 shows the definitions of extractable fractions from the sequential extraction procedure for the speciation of metals (Tessier et al., 1979).

Table 8 - Summary of extractable fractions from sequential extraction procedure for the speciation of metals[1].

Fraction	Description	When COCs Become Unstable and Release to the Water Column
1	Exchangeable fraction for adsorbed minerals	Readily released (i.e., soluble and exchangeable)
2	Mineral fraction bound to carbonates or solubilized at pH 5	Decreased pH
3	Oxidized mineral fraction bound to Fe-Mn oxides	Reducing conditions
4	Reduced mineral fraction and sulphides	Oxidizing conditions
5	Residual mineral fraction (primary and secondary minerals)	Not expected to be released in solution over time under conditions normally encountered in nature

[1] Method based on Tessier et al., 1979.

Analysis of leachable metals in 2017 used the same leach method as in 2016 and results can be found in Appendix B, Table B2. When compared to early 2016 results, leachable copper concentrations in 2017 soils decreased throughout the CWTS (Figure 19) while total copper concentrations increased overall as copper shifted from its leachable to mineral form (Figure 20). In general, soils in the demonstration-scale CWTS appear to be reaching a steady-state with concentrations of leachable copper changing little throughout 2017. We expect leachable copper decrease further in 2018.

Sequential extraction procedure for the speciation of particulate trace metals was conducted for all constituents of concern and results and figures can be found in Appendix B (Tessier et al., 1979). The analysis shows that despite elevated initial leachable copper concentrations, the soils have become more stable (less leachable) over time in the CWTS setting as the soils have aged, shifting from oxidized to reduced, mineral forms (Figure 21; Figures B18 and B19). This beneficial aging of soils to a less soluble mineralized form of sulphide is expected for this type of treatment CWTS design. It should also be noted that copper leached from the original substrate into the water put additional treatment demands on the CWTSs.

For the CWTS to treat the copper from the soils, additional organic carbon is needed beyond that necessary for the waters alone. Organic carbon is contributed to the CWTS through decomposition of plant material as the CWTS matures. Organic carbon is used as food by the microbes, which in turn produce sulphides which drive metals treatment through mineralization that is helped by biogeochemical processes. Presently, as there is excess copper in the soils in oxidized forms transitioning to reduced forms, these will bind to and consume the sulphides produced, transforming them to the sulphide-bound fraction 4 (Table 7). This in turn impacts the ability to treat water, as it uses the available sulphides that would otherwise treat metals in the water. When the mineral fractions of the soils have completed their transformation into sulphide-bound minerals, the soils will no longer be “sulphide hungry”, allowing for the soil-produced sulphides to be utilized for metals treatment in the water. This progress can be tracked in results from the sequential extraction tests, the appearance of acid volatile sulphides (AVS) in the soils (iron sulphates, which will only occur after the copper is transformed), and the change of sulphate concentrations in the water.

Additional reserve treatment capacity can be stored in a CWTS through creation of a reserve of AVS (newly formed amorphous iron sulphides). AVS are referred to as such because of the testing method, which is also done alongside simultaneously extracted metals (AVS:SEM; at Minto, cadmium, copper, and zinc were tested for) to determine the ratio of iron sulphides to free metals. An excess of AVS suggests the metals would be non-bioavailable and not likely to leach. In the case of Minto, where the soils used in construction had excess copper, the appearance of measurable AVS would also indicate that the copper in the soils is nearing an endpoint of transformation to sulphide forms.

AVS was tested for in 2016 prior to adding the straw and wood chips and was non-detectable (hence, the decision to add the straw and wood chips). The appearance of small amounts of measurable AVS over time (cell 1A in June and cell 2A in September, 2017) indicates that the amount of sulphide produced in the soils is beginning to exceed the total amount of copper placed with the original soils and the CWTS should eventually start performing the way it should have if substrates with high leachable copper had not been used. However, the AVS:SEM ratio is indicating there is significant copper in the soils still consuming the sulphides, and treatment performance is expected to improve as that continues to be remedied over time. An AVS:SEM ratio greater than one indicates excess copper in the soils has been reduced to sulphide form and is no longer consuming excess sulphides, allowing for AVS to form. Once the AVS:SEM ratio of all cells is consistently greater than one, we do not expect any further copper leaching to occur, and copper treatment within the CWTS should improve until this time.

Zinc (Figures B20 and B21) mineral forms have become stable over time, with most of these constituents found in the reduced or mineral form (fraction 4 and 5) by the end of 2017. Cadmium concentrations are at or near detection limits for all fractions (Figures B22 and B23). Molybdenum was mostly found in the most stable residual mineral fraction 5, which contained around 40% of the total molybdenum in the samples (Figures B24 and B25). Selenium was at or near the detection limit for all fractions and at the end of 2017, and was barely detectable for the stable fractions 4 and 5 (Figures B26 and B27).

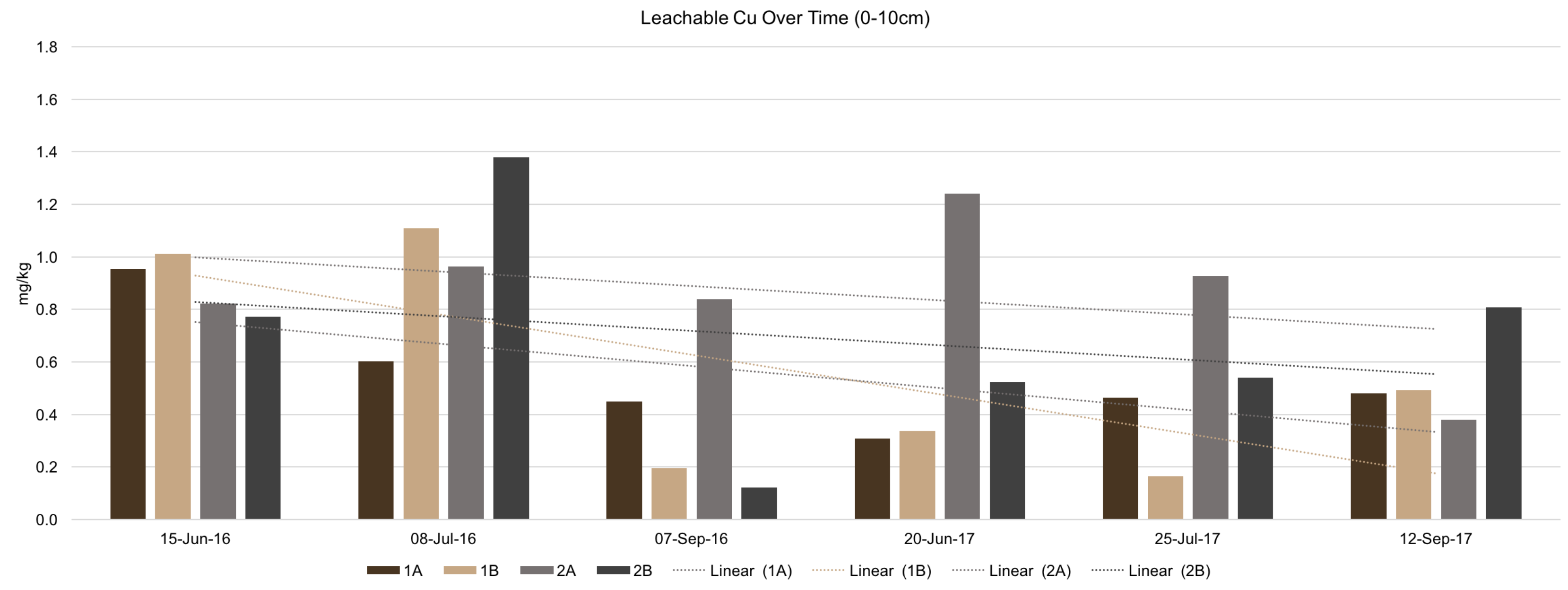


Figure 19 – Leachable copper concentrations in soils over time in the demonstration-scale CWTS.
Figure shows concentrations in shallow soil (0-10 cm). Trendlines (dotted lines) show a general decrease in leachable copper over time.

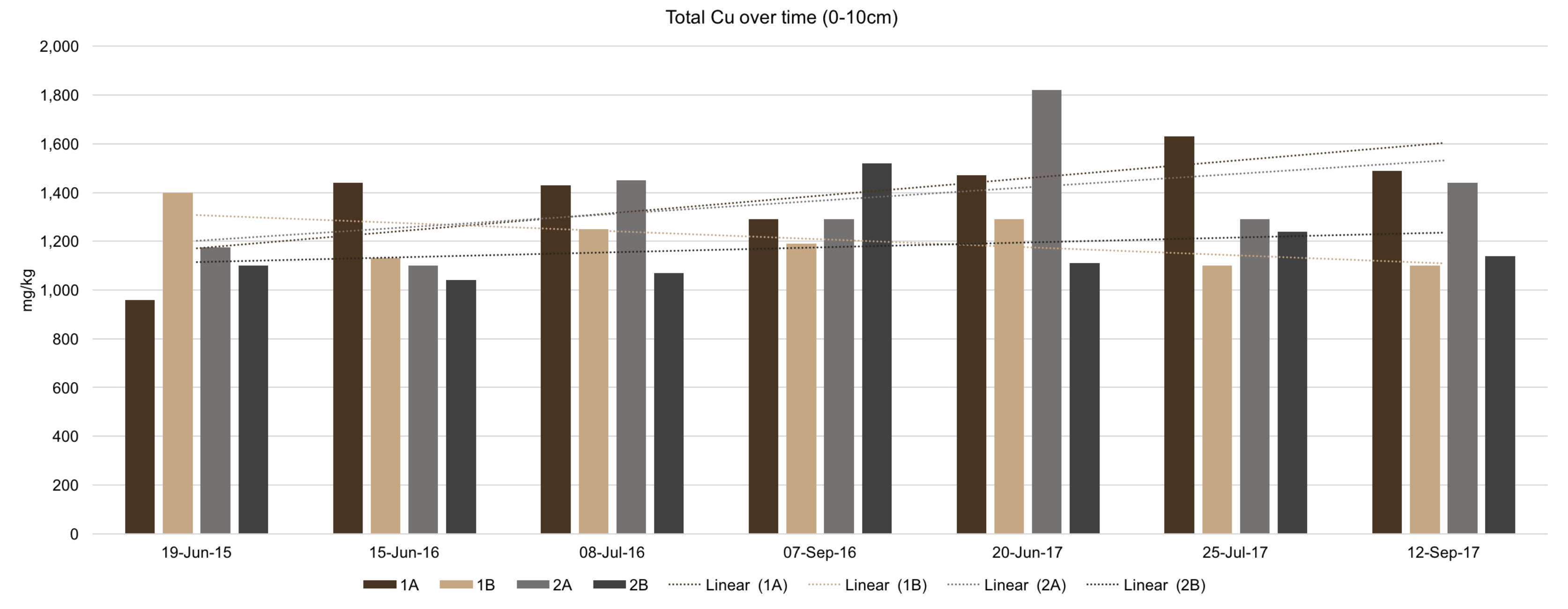


Figure 20 – Total copper concentrations in soils over time in the demonstration-scale CWTS.
Figure shows concentrations in shallow soil (0-10 cm). Trendlines (dotted lines) show a general increase in total copper over time.

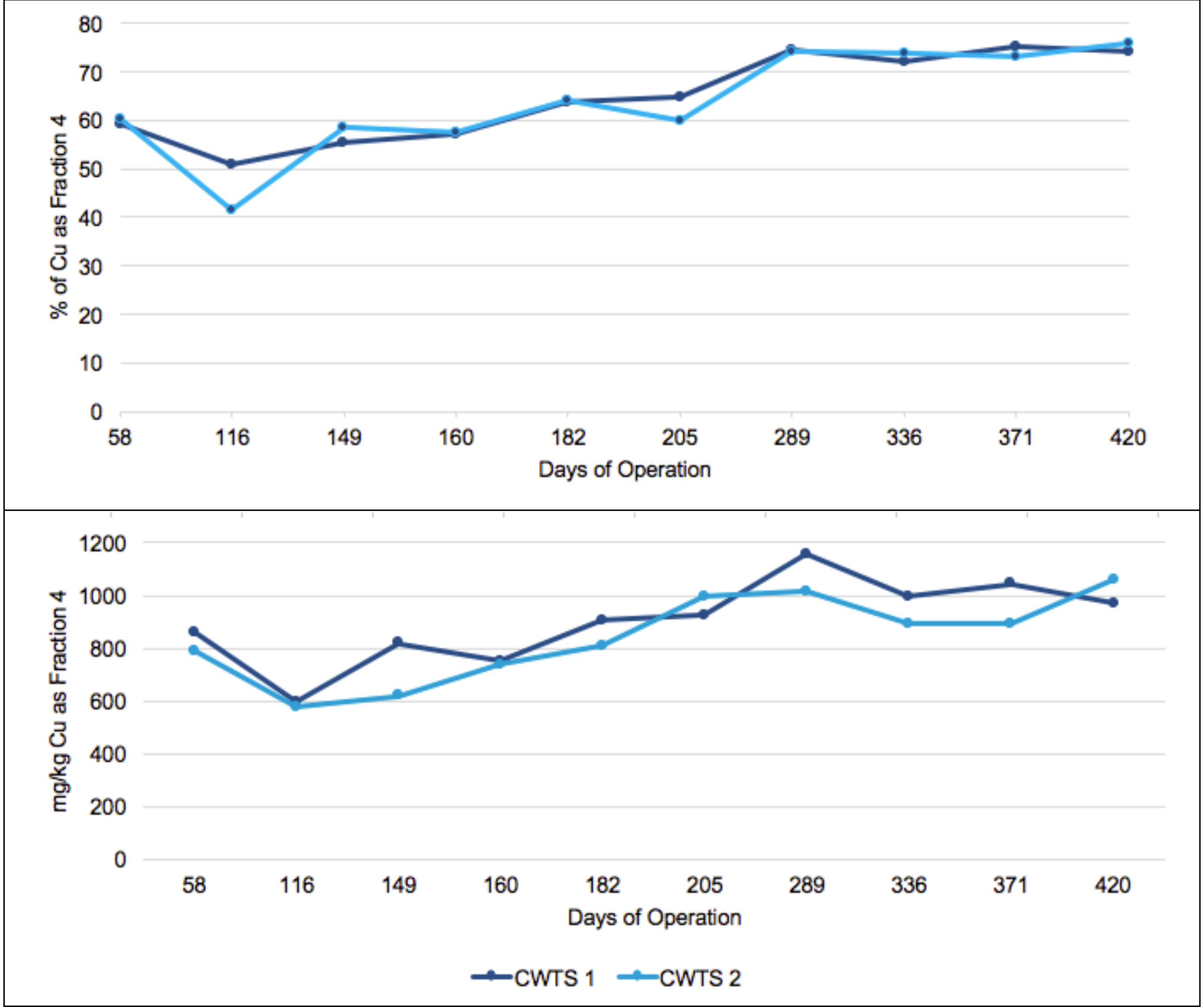


Figure 21 – Copper as sequential leach fraction 4 over time.
Copper in the form of the targeted Fraction 4 (sulphide mineral form and bound to organics), increased in the CWTS over time as the soils matured. Additional information can be found in Appendix B.

5.7.Metals Uptake

The following are key findings regarding metals uptake, which are detailed further below:

- Overall, uptake of metals in *C. aquatilis* was low and generally lower in 2017 than in 2016 demonstration-scale CWTS results.
- Targeted treatment mechanisms are becoming more robust, rendering elements non-bioavailable.

Concentrations of the constituents of concern in *C. aquatilis* and moss from the demonstration-scale CWTS in 2017 were compared to those from 2016. *C. aquatilis* and moss in the demonstration-scale CWTS had greater copper concentrations than the pilot CWTSs, likely reflecting the bioavailable copper that was in the soils used for construction. Concentrations of copper in the *C. aquatilis* at the end of 2017 were similar or lower than 2016 concentrations (Figure 22). The moss had higher copper concentrations in the A cells than in 2016, but lower concentrations in B cells, indicating more treatment earlier in the CWTS as it matures (Figure 22). Over time, constituents sorbed to mosses will form reduced minerals, rendering them less bioavailable.

Cadmium concentrations in *C. aquatilis* and moss were similar in 2017 and 2016, except for higher concentrations in cell 1B where concentrations were higher for *C. aquatilis*, (Figure 23). Similar selenium concentrations were observed in both plant types in 2017 as in 2016, (Figure 24; Contango, 2016 and 2017). Concentrations of molybdenum in moss generally decreased from 2016 to 2017, while concentrations of molybdenum in *C. aquatilis* decreased significantly and now remain around the detection limit (Figure 25). In 2017, overall concentrations of zinc decreased in *C. aquatilis* and moss from 2016, except for cell 1B in *C. aquatilis* and cell 2A in moss where concentrations of zinc remained the same (Figure 26).

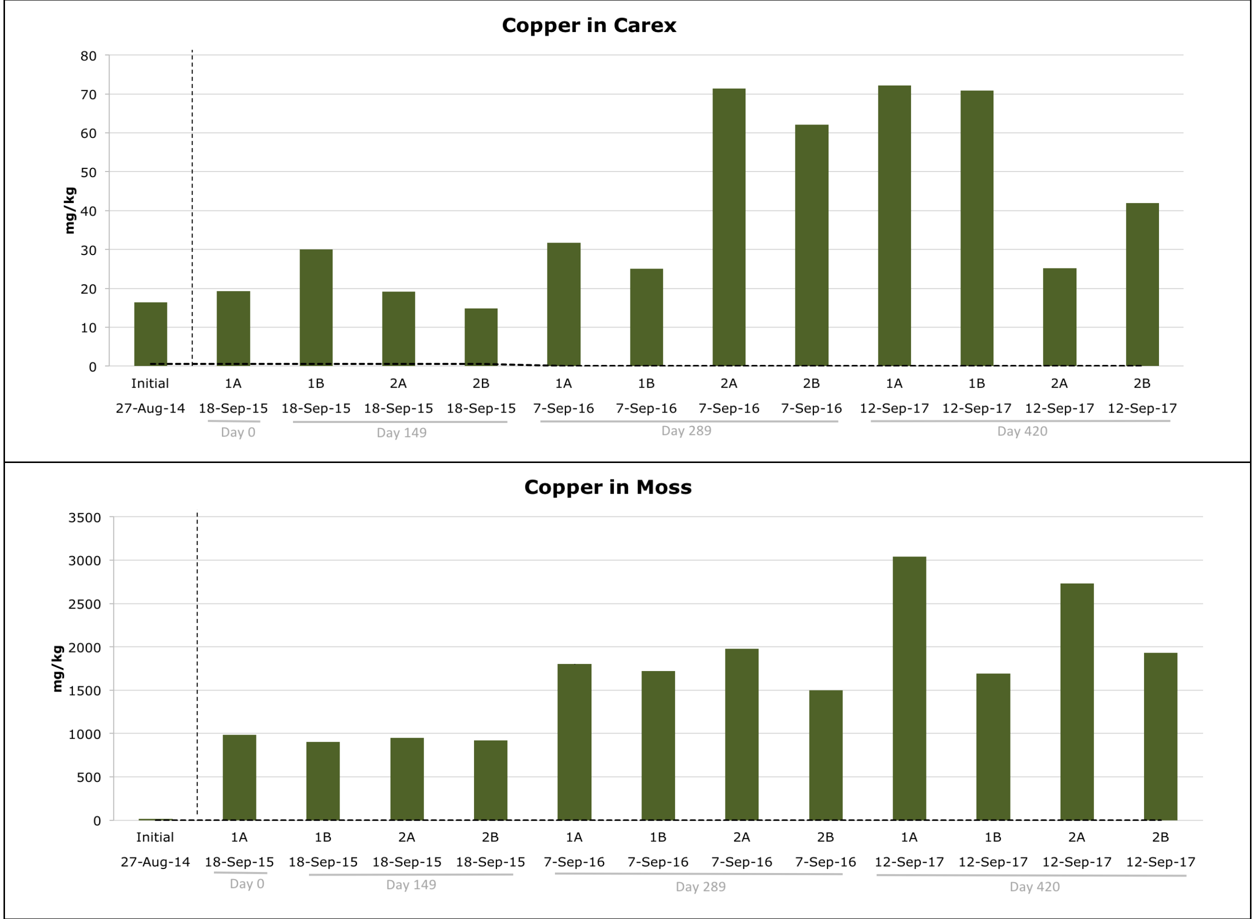


Figure 22 – Copper concentrations in plants.
The 2014 detection limit (DL; horizontal dotted line) for copper is 0.5 mg/kg, the 2015 DL is 0.1 mg/kg, and the 2016 and 2017 DL is 0.05 mg/kg. The initial data set is the average of three *Carex* replicates at construction.

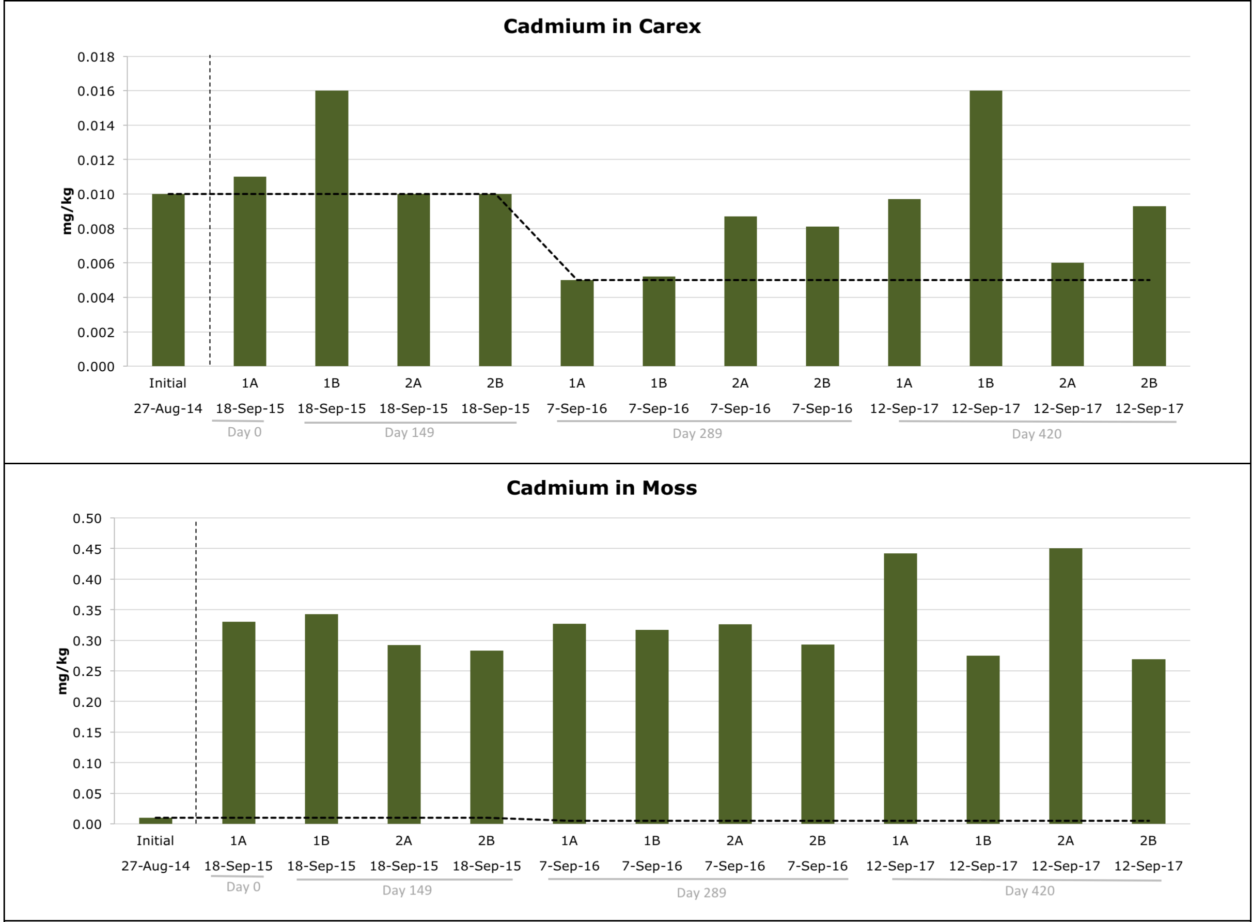


Figure 23 – Cadmium concentrations in plants.
The 2014 and 2015 detection limit (DL; horizontal dotted line) for cadmium is 0.10 mg/kg. The initial data set is the average of three *Carex* replicates at construction.

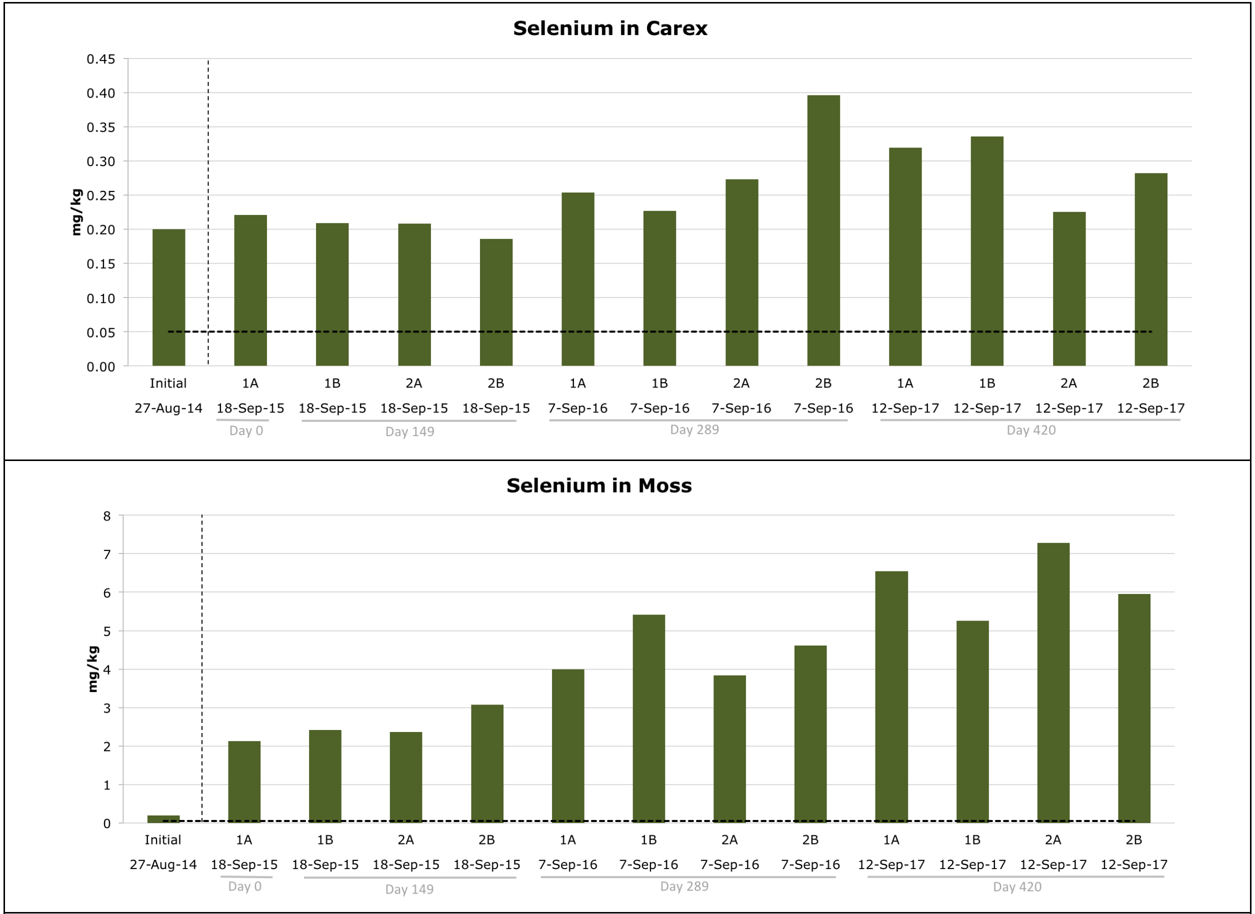
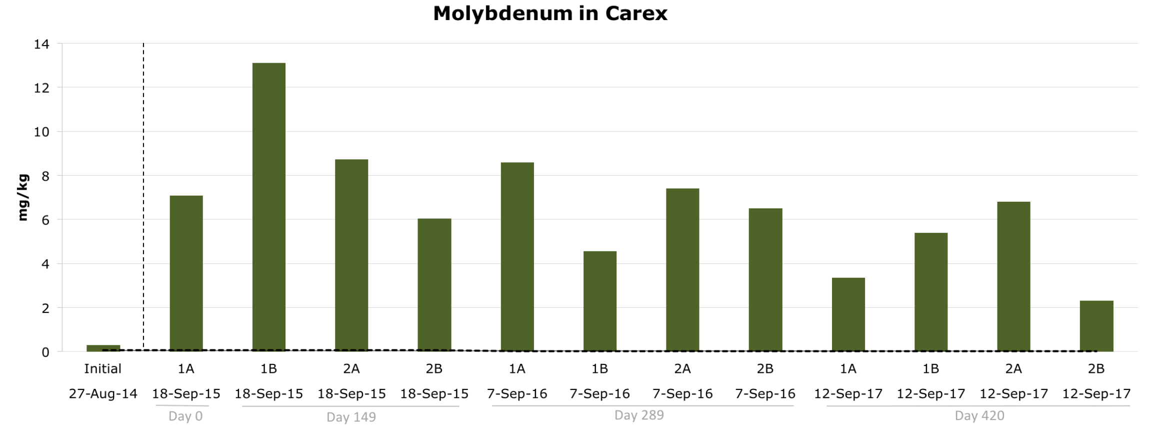


Figure 24 – Selenium concentrations in plants.
The method detection limit (DL; horizontal dotted line) for selenium is 0.2 mg/kg. The initial data set is the average of three *Carex* replicates at construction.



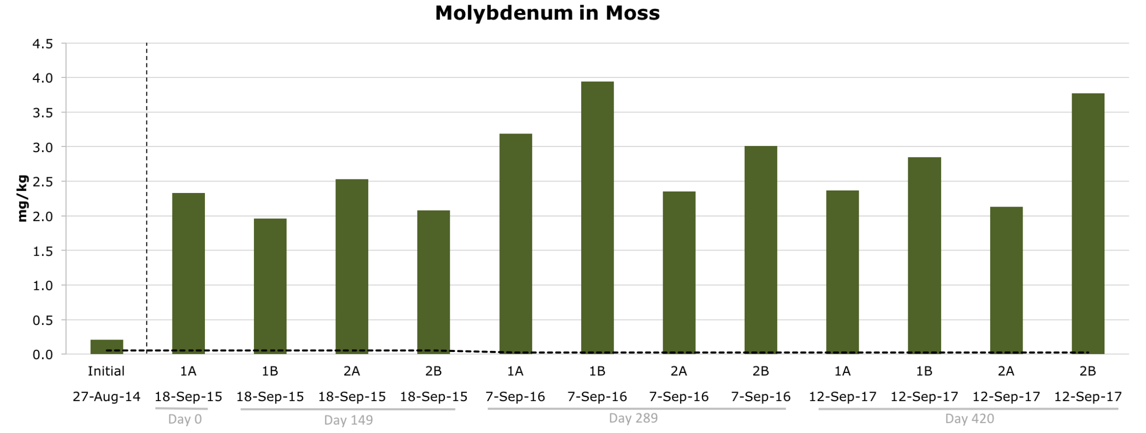


Figure 25 – Molybdenum concentrations in plants.
The 2014 and 2015 detection limit (DL; horizontal dotted line) for molybdenum is 0.05 mg/kg, the 2016 and 2017 DL is 0.020 mg/kg. The initial data set is the average of three *Carex* replicates at construction.

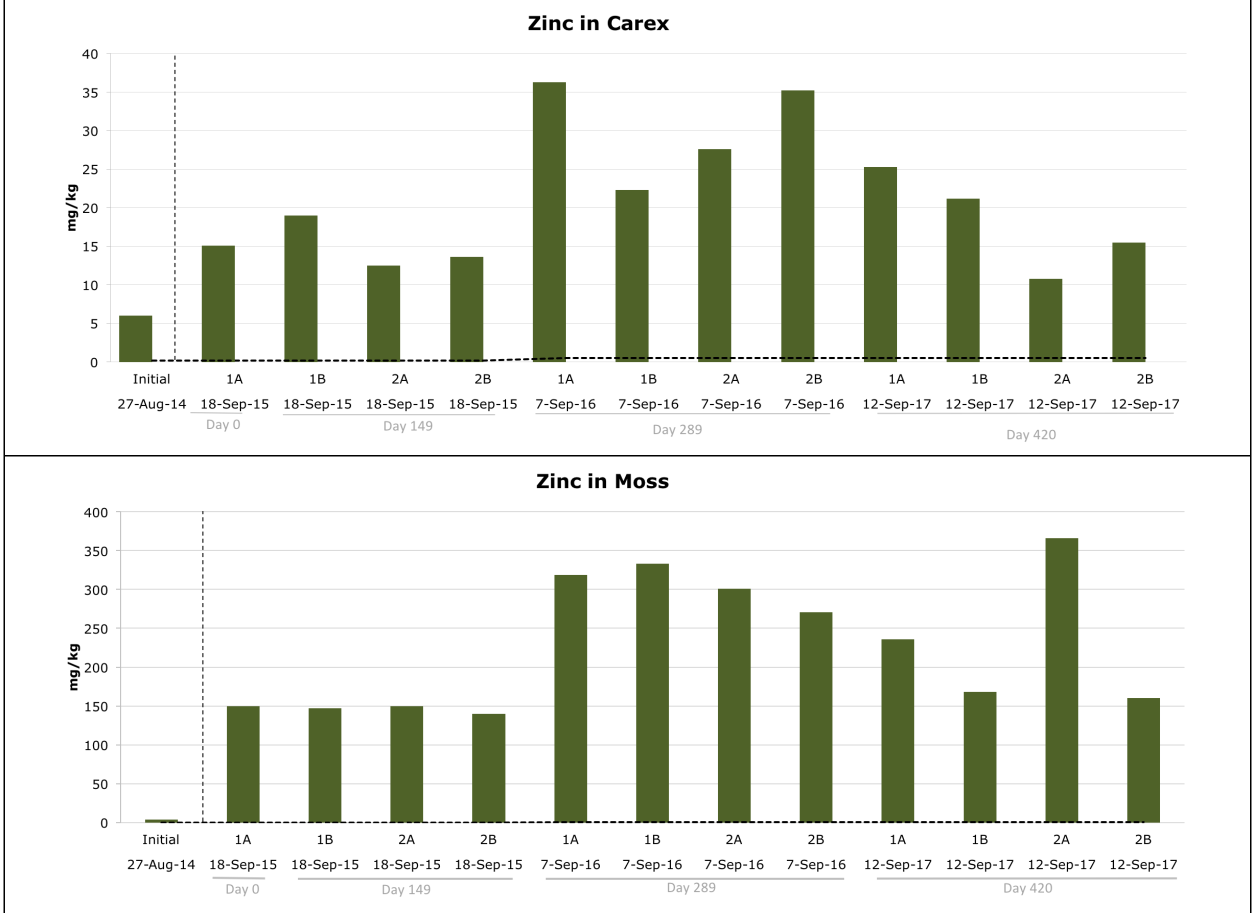


Figure 26 – Zinc concentrations in plants.
The 2014 detection limit (DL; horizontal dotted line) for zinc is 2.0 mg/kg, the 2015 DL is 0.002 mg/kg, and the 2016 and 2017 DL is 0.5 mg/kg. The initial data set is the average of three *Carex* replicates at construction.

5.8.Detritus Study

The following are key findings regarding the detritus study, which are detailed further below:

- The detritus study suggested that algae growth on the assay devices had reached a steady state (growth vs decomposition) by ~23 days of the study.
- After 83 days submerged in the CWTS, *C. aquatilis* decomposed on average 64%.

A detritus study was conducted in 2017 to assess decomposition rates of *C. aquatilis* in the CWTS over time as well as to determine the steady state of carbon contribution from algae growth on CWTS materials (Chimney and Pietro, 2006; Hammerly et al., 1989). Additional details describing the methods can be found in Appendix A. The study began on June 21, 2017 when six bags filled with 5g of oven dried *C. aquatilis* were submerged into each CWTS cell to determine the decomposition rate of *C. aquatilis* (Figure 27). Variability between samples are indicated by error bars (minimum and maximum values) in Figure 28. Six additional bags filled with 3.8 g of polyester filter fiber material were submerged into each cell of the CWTS to determine the algae growth rate. On July 25, 2017 and September 11, 2017 (after 34 and 83 days of submersion in the CWTS, respectively) one bag filled with *C. aquatilis* and one bag with the polyester fiber were sacrificed from each CWTS cell and the dried weights compared to initial sample weights (Table 9). This resulted in four replicates for each treatment and sampling date.

The weight of the polyester fiber bags increased by an average 23% after 34 days, and by 21% after 83 days, suggesting that the algae growth had reached a steady state prior to 34 days. After being submerged for 34 days in the CWTS, *C. aquatilis* decomposed on average 56% from the initial weight (decreasing from 5 g to 2.2 g), and continued to decompose to an average of 64% (decreasing from 5 g to 1.8 g) after submersion for 83 days in the CWTS (Table 9). There was little variability between cells. These detritus decomposition rates have been adjusted for by subtracting the weights of algal growth of the corresponding polyester fiber filled bag (Appendix A).

Four bags of each material remain in each cell for future sampling. The detritus study will continue in 2018 to enable monitoring and calculation of decomposition and accretion rates.

Figure 27 – Detritus study bags.
Left are mesh bags filled with sedges and polyester fiber fill stuffing. Left are mesh bags with *C. aquatilis* and control polyester prior to addition to the CWTS, middle are bags submerged in a CWTS cell and attached to depth stick, and right is a mesh bag with decomposed sedges and polyester fiber fill stuffing.

Table 9 – Results of the *C. aquatilis* detritus study.

	Initial weight of *C. aquatilis* (g)	Dry weight after 34 days (g) [2]	Decrease in weight after 34 days (%)	Dry weight after 82 days (g) [2]	Decrease in weight after 83 days (%)
1A	5.0[1]	2.1	57%	1.7	65%
1B		2.1	59%	1.7	67%
2A		2.3	54%	2.0	61%
2B		2.4	52%	1.9	63%
Average		**2.2**	**56%**	**1.8**	**64%**

[1] Initial weight prior to bags being placed in CWTS.
[2] Weights of *C. aquatilis* corrected by subtracting the increase in weight from the polyester fiber fil to account for algae growth.

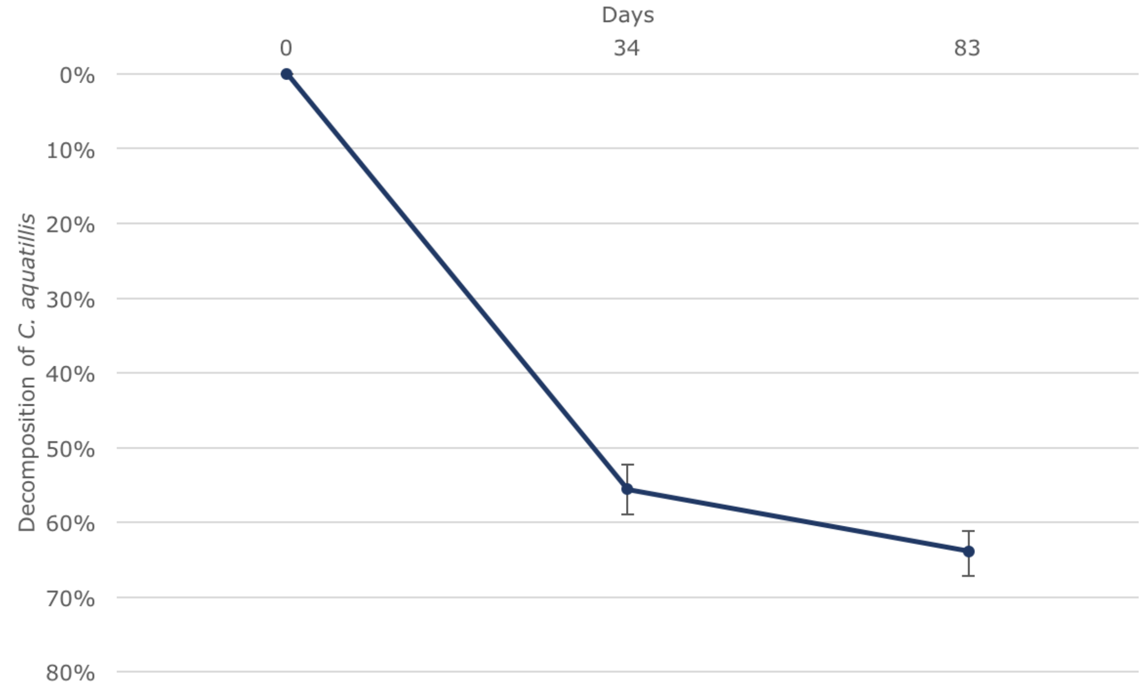


Figure 28 – *C. aquatilis* decomposition over time.
Decomposition was measured by the decrease in weight over time of the *C. aquatilis* samples compared to the initial weight. The decomposition rate was corrected for algae growth by subtracting the increase in weight of the polyester filter foam from the dry weight of the *C. aquatilis* samples over time. Error bars indicate the variation in results for each time point.

5.9. Beneficial Microbes

The following are key findings regarding beneficial microbe establishment in the CWTS, which are detailed further below:

- Establishment of sulphide-producing bacteria (SPB) increased throughout 2017 and was highest after commissioning was completed.
- SPB were found in highest abundance in root and soil samples.
- The average number of different types of sulphide-producing bacteria increased over time in all sample types tested (root, soil, detritus, and moss).
- Selenium-reducing and nitrate-reducing bacteria increased over time with the highest abundances found in *C. aquatilis* roots.

Microbes are the driving force of many treatment pathways that are targeted in CWTSs. The beneficial microbes in these CWTSs catalyze biogeochemical processes that remove specific constituents of concern from the water column. Careful design of CWTSs can create the environmental conditions needed to enhance the abundance and metabolic activity of these beneficial microbes. Accordingly, complimentary methods of genetic and growth-based testing were used to characterize the microbial populations associated with a range of microbial habitats in the demonstration-scale CWTS (e.g., soils, sediment, biofilms, aquatic mosses, and plant roots).

In the context of the Minto Mine CWTS, beneficial microbes include those that are involved in the reduction of selenium (i.e., selenate and selenite), nitrate, and sulphur compounds. Reduced sulphur can in turn treat copper, cadmium, molybdenum, and zinc through geochemical interactions. Information on each of these mechanisms and the associated microbial populations in the demonstration-scale CWTS is outlined in the following sections.

5.9.1. Sulphide-producing Bacteria

Treatment of metals and metalloids can be achieved by targeting the lithic biogeochemical sequestration of divalent metals through sulfide (i.e., S^{2-}, HS^{-}) precipitation as mineralized species (e.g., chalcocite [CuS], covellite [Cu_2S]). These sulfide-bound species are relatively insoluble (CuS; $K_{sp}=10^{-16}$; Stumm and Morgan 1996), and are transferred from the water column into the CWTS soil as non-bioavailable fractions (Murray-Gulde et al., 2003; Huddleston et al., 2008). Moreover, similar reactions occur with cadmium and zinc, rendering them non-bioavailable. As such, sulphide production is a key biogeochemical mechanism for water treatment at Minto Mine. Sulphides can be created by beneficial microorganisms through the reduction of sulphur-containing compounds, such as sulphate, sulphite, thiosulphate, and elemental sulphur.

Based on the information gathered in pilot-scale testing, the targeted soil redox for the demonstration-scale CWTS is between -100 and -250 mV to facilitate these reactions. This is in agreement with literature that indicates anaerobic conditions with relatively low ORP (-250 to -100 mV) are necessary to promote anaerobic metabolism in bacteria which oxidizes organic matter and produces electrons, which in turn reduces sulfate to hydrogen sulfide (H_2S) and other sulfide species (i.e., bisulfide ion (HS^-), sulfide ion [S^{2-}]; Mitsch and Gosselink 2007). In these redox ranges, bacterial sulphide-production through reduction of sulphur compounds is expected, alongside increases in the proportion (percentage) and abundance of these microbes.

As expected, diversity (Table 10), proportion, and inferred abundance of sulphide-producing bacteria (SPB) increased as the soil redox decreased in the demonstration-scale CWTS with the highest proportions observed in 2017 compared to 2016, as the CWTS has matured (Figure 29, Figure 30, Figures B28 and B29 in Appendix B; Contango, 2017). Proportions of SPB increased in all sample types (soil, roots, moss, and detritus) over time through 2017 (Table 10). As observed in 2016, the *C. aquatilis* roots were again found to harbour the highest proportions and abundances of beneficial SPB, followed by the soil, detritus, and moss. Furthermore, the highest proportions were observed in the operational period for both soil and root samples. Root, detritus, and soil samples harboured the highest average number of different SPB types, followed by moss (Table 10). However, the average number of different types of SPB increased over time in every sample type tested.

The microbial analysis of various sample types in the CWTS has therefore confirmed that the commissioning period proceeded as expected and was successful in establishing beneficial SPB populations alongside reducing conditions. Monitoring of soil redox as well as microbial populations will continue to be monitored for stability or further improvement in 2018.

Table 10 – Average number of different types of sulphide-producing bacteria in 2014/2015, 2016, and 2017.

Sample Type	2014 & 2015	2016	2017
detritus	NT	6	9
moss	3	4	8
root	6	8	9
soil	4	8	9

NT – not tested. The number of different types is based on counting the number of operational taxonomic units (clustered at 97% identity) that are classified as known sulphide-producing bacteria.

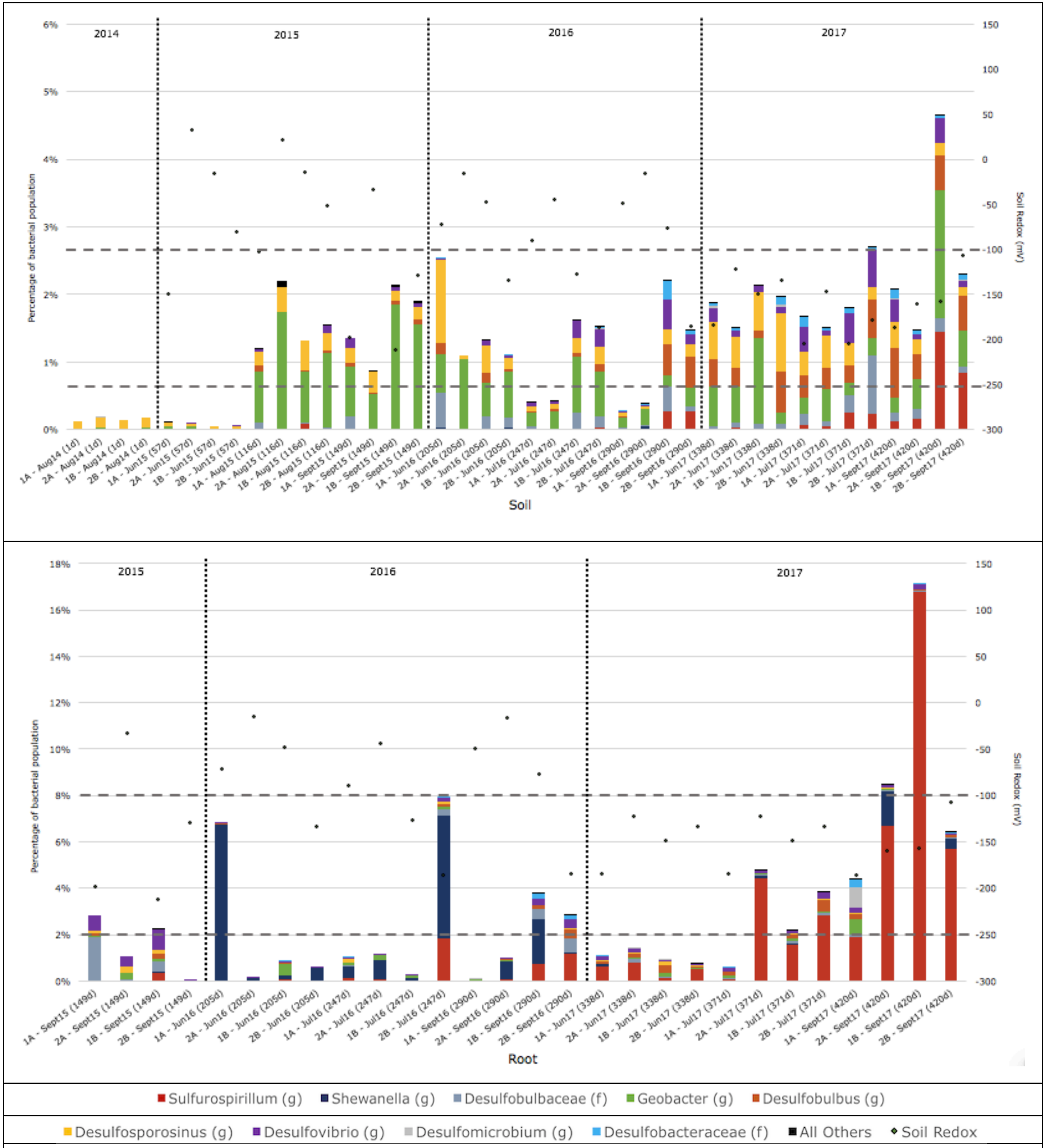


Figure 29 – Percentage and identity of sulphide-producing bacteria in soil (top) and roots (bottom) demonstration-scale CWTS.

The horizontal dashed lines indicate the targeted soil redox range. Organism classifications and data analysis methods have been updated from Contango (March 2016). The y-axis provides the percentage of the bacterial community (relative abundance) that corresponds to sulphide-producing bacteria through the reduction of sulphate, sulphite, thiosulphate, and sulphur. Percentage is based on identification via genetic sequencing. Organisms are either classified to the genus (g) or family level (f). The root y-axis is different from the soil y-axis as the % SPBs is much higher in one sample of root (1B – Sept17 (420d)).

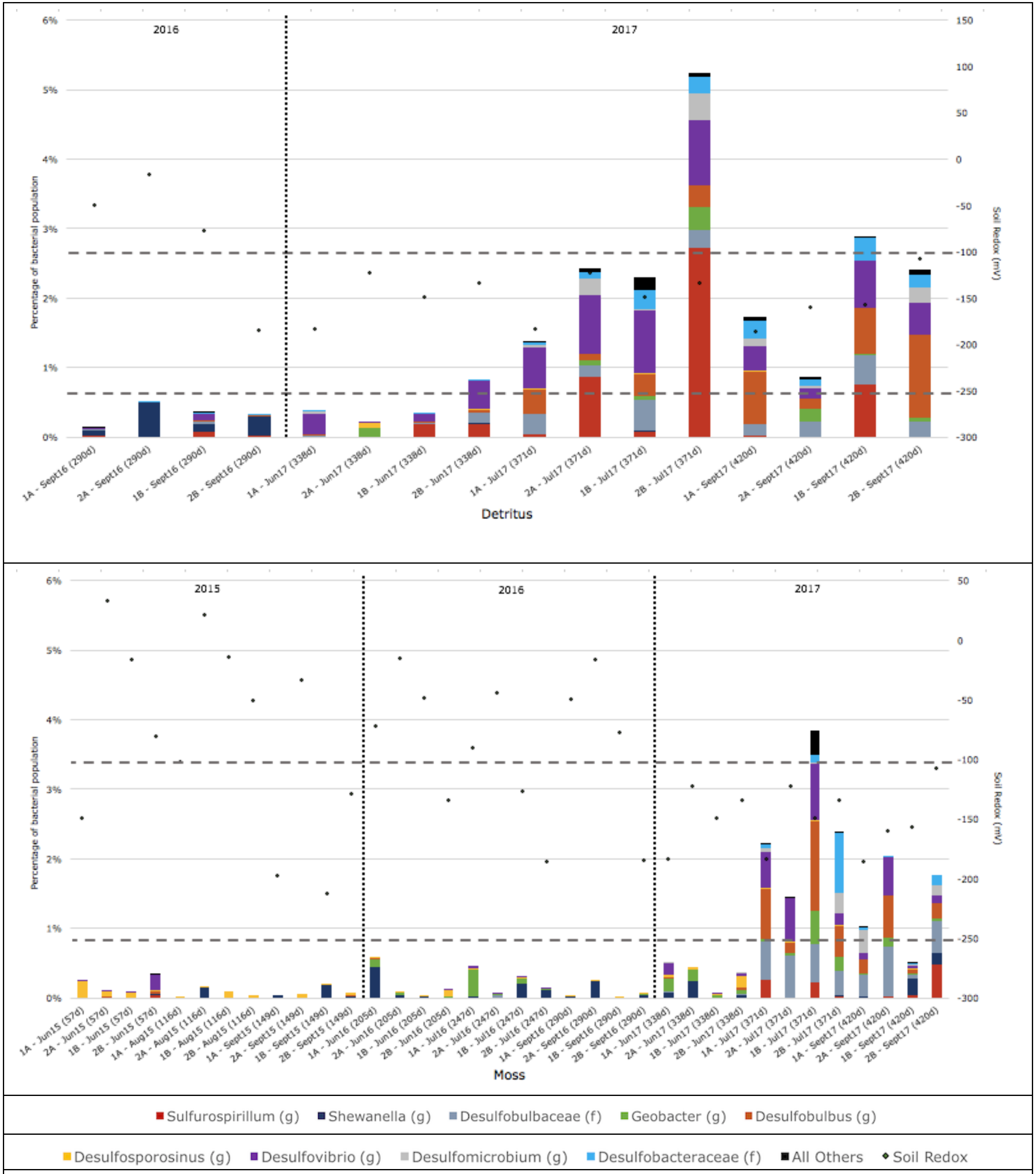


Figure 30 – Percentage and identity of sulphide-producing bacteria in detritus (top) and moss (bottom) demonstration-scale CWTS.

The horizontal dashed lines indicate the targeted soil redox range. Organism classifications and data analysis methods have been updated from Contango (March 2016). The y-axis provides the percentage of the bacterial community (relative abundance) that corresponds to sulphide-producing bacteria through the reduction of sulphate, sulphite, thiosulphate, and sulphur. Percentage is based on identification via genetic sequencing. Organisms are either classified to the genus (g) or family level (f).

5.9.2. Selenium-reducing Bacteria

The targeted selenium treatment pathways in the Minto CWTS include sorption to moss and soils, and subsequent microbial reduction of soluble (sorbed) selenate (Se(VI)) and selenite (Se(IV)) to insoluble elemental selenium (Se(0)). This reductive process can also be achieved directly in the water column, but is more effective when associated with mosses and biofilms due to their sorptive properties that bring the selenium in contact with beneficial selenium-reducing bacteria. Selenium reduction biogeochemical processes are achieved within the range of soil redox conditions targeted for sulphate-reduction as suggested by pilot-scale testing and literature (Contango, 2014).

Selenite-reducing organisms are ubiquitous in nature and as expected, were detected in all sample types, including algae, biofilm, moss, soil, sediment, roots, and detritus. Although organisms that reduce selenate to elemental selenium (rather than intermediary selenium compounds) are generally less abundant in the environment, they were found associated with all sample types, indicating that the conditions conducive to their proliferation have been created within the CWTS. Moreover, the abundance of selenite- and selenate-reducing organisms generally increased or remained stable over time in the demonstration-scale CWTS through the commissioning and operational periods in (Figure B30 in Appendix B). Aquatic mosses were found to initially host the highest abundance of both selenate- and selenite-reducing organisms, affirming the importance of the inclusion of moss in the CWTS. Over time, as the vegetation has established, selenium-reducing bacteria have increased in abundance on the roots of *C. aquatilis* (Figure B30 in Appendix B).

These findings indicate the commissioning period was successful and the demonstration-scale CWTS has established and maintained beneficial selenium-reducing microbes. Selenium is removed as it is sorbed to moss or detritus or by interacting directly with selenium in water that has been drawn into the root zone by plants. Abundance of selenium-reducing bacteria is similar to that found through 2016 and during pilot-scale soil testing, suggesting they have established as expected. Selenium-reducing microorganisms will continue to be monitored in 2018, alongside performance testing.

5.9.3. Nitrate-reducing Bacteria

Nitrate is sometimes a constituent of concern during operations and early closure owing to residuals from blasting activities. Even if not in exceedance of water quality guidelines in terms of receiving environment objectives, nitrate often requires treatment in order to subsequently achieve treatment of other constituents such as selenium and metals through sulphide production. Nitrate can be removed from water through denitrification by different types of microbes, including nitrate reducing bacteria which can reduce nitrate (NO_3) to nitrite (NO_2), and also denitrifying organisms that are capable of fully reducing nitrate to nitric oxide (NO), nitrous oxide (N_2O), and dinitrogen gas (N_2, which is the most abundant gas in air). Most-probable number (MPN) analysis was therefore used to quantify these organisms.

As observed in 2016, nitrate-reducing and denitrifying organisms were found associated with all sample types in the demonstration-scale CWTS (Figure 31; Contango, 2017). Roots and detritus had a high abundance of both nitrate and denitrifying organisms, with soil being similar to or slightly less than what was found during pilot-scale testing. These results indicate nitrate reducers have established in the CWTS during the commissioning period as expected. Nitrate-reducing microorganisms will continue to be monitored in 2018, alongside performance testing.

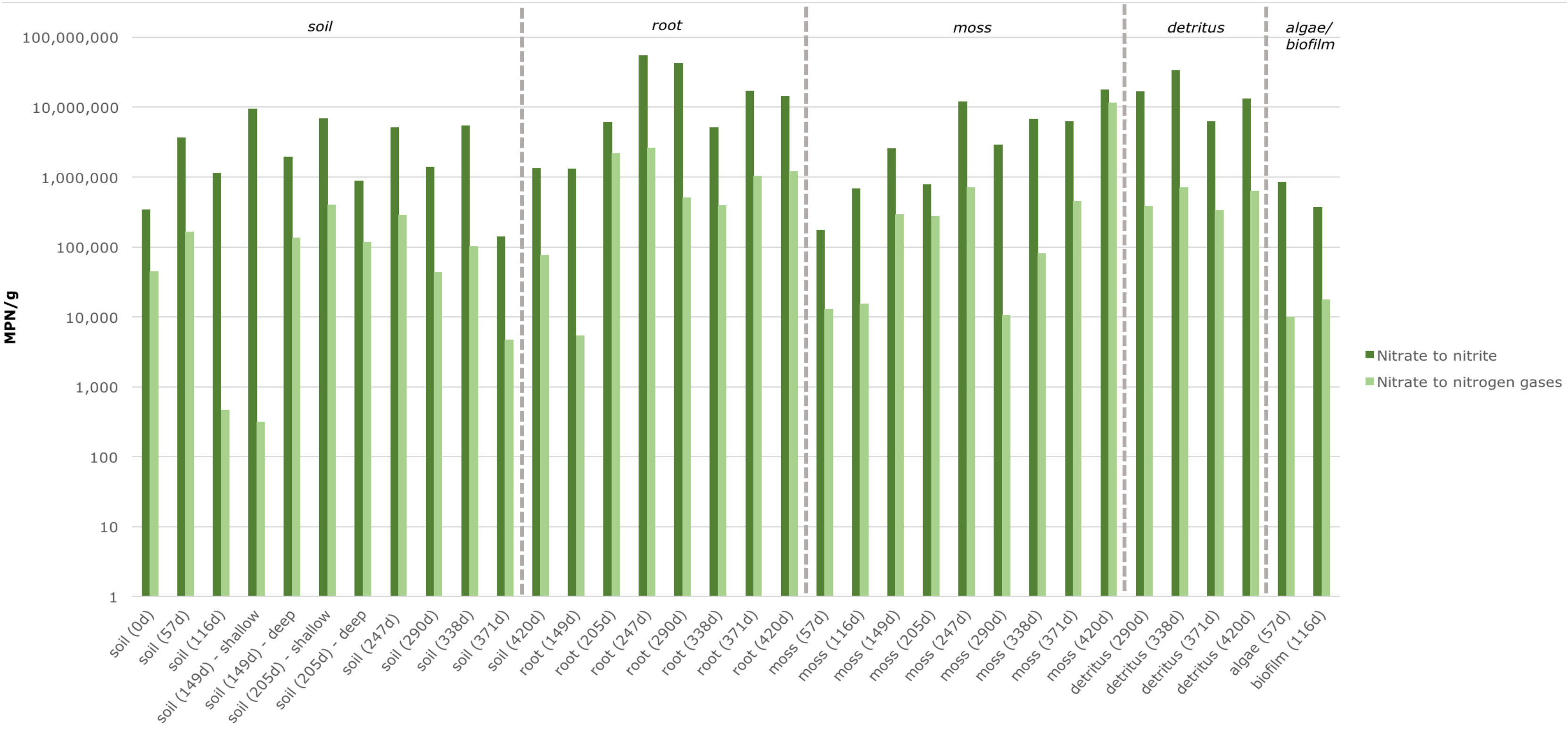


Figure 31 – Abundance of nitrate-reducing and denitrifying organisms in various CWTS sample types over time.
Nitrate-reducing = reduction of nitrate to nitrite; denitrifying = reduction of nitrate to nitrogen gases.
Shallow soil (0-5 cm); deep soil (10-20 cm); soil at 0d was that used for construction of CWTS.

6. Operational Challenges

The following are key findings regarding operational challenges, which are detailed further below:

- Aphids were again found in abundance on *C. aquatilis* in 2017.
- Efforts to control the aphid population on-site were made but an ongoing spraying regiment was not maintained and, therefore, aphids remained. However, no short-term detrimental effect on *C. aquatilis* viability was observed, despite the persistence of aphids.
- Damage to the above water vegetation was observed however new shoots were emerging in the CWTS and treatment COCs was not impacted by damage to the above water vegetation.
- Effects of aphids on *C. aquatilis* did not affect treatment.
- These issues with aphids are likely owing to the isolated nature of the demonstration-scale CWTS and not expected to affect the full-scale CWTS.

The Minto Mine's demonstration-scale CWTS, which is constructed of an emergent macrophyte monoculture of *Carex aquatilis*, experienced an aphid infestation in 2016 and 2017. The demonstration-scale CWTS is located in a relatively isolated area, away from other vegetation and potential sources of insects. It is known that aphids can migrate on air currents (Dixon, 1971), possibly over great distances (Riley et. al., 1995), which may be how they reached the demonstration-scale CWTS. Aphids are often monophagous, meaning they feed on one species of plant (Foottit and Maw, 1997) and it is likely that having additional vegetation available will not reduce the level of infestation on the *Carex* species planted in the CWTS. However, if additional surrounding vegetation is available, it could provide habitat for natural predators of aphids. With the demonstration CWTS currently located 50 m away from trees or other vegetation, there is little to no opportunity for natural predators to inhabit the area or incentive to travel the distance to the CWTS. The large buffer area (MVFE) around the demonstration-scale CWTS allows the aphids to colonize more robustly than anticipated in the full-scale CWTS onsite, which would not have the same buffer zone. This would not be an issue in the full-scale CWTS.

Aphids can be controlled, naturally, by predatory insects such as ladybugs, lacewings, and parasitic wasps (Flint, 2001). Ladybugs were observed in very small numbers on the *Carex* plants but in insufficient numbers to control the aphid population. Lacewings are found throughout North America and would be expected to be present in the Minto Mine region (Russel and Diaz, 2015). Several types of parasitic wasps that prey on aphids are known to be present in the Yukon (Finnamore, 1997). Other control methods involve the use of insecticidal soaps, which are recommended as they are non-toxic to most other insects and kill aphids through contact (the soft bodies are suffocated by the fatty acids in the soap; Ubl and Munnerlyn, 2009).

To quantify the aphid population on-site, sticky, yellow insect traps were installed at W10 and W15 as well as eight (two per cell) in the CWTS in 2017 (Figure 32). However, none of the traps at any of the locations were successful in trapping aphids and instead trapped numerous other insects. It was observed that the sticky traps at W10 and W15 trapped a larger quantity and diversity of insects compared to the traps installed in the CWTS. This suggests that the larger population and diversity at the W10 and W15 areas assisted with keeping aphid populations under control in these areas. Due to the isolated area of the CWTS, away from other vegetated areas, the CWTS hosted a smaller quantity and diversity of insects which were not able to keep the aphid population under control.

Efforts were made in 2017 to control the aphid population by applying a mild insecticidal soap (Scott's EcoSense Bug B Gone Insecticidal Soap concentrate mixed with water) or a soap solution using a hand-held sprayer. Although the insecticidal soap was more effective than the soap solution, an ongoing spraying regiment was not maintained long enough to decimate the population. Care must be taken when using insecticidal soap to spray all surfaces of plant leaves, as aphids frequently inhabit the underside of leaves. Applications should be repeated every 4-7 days (follow label instructions) until pests are eliminated (Ubl and Munnerlyn, 2009). A stronger insecticidal soap (Trounce's Yard and Garden Insecticide) was applied on September 13, 2017 in another effort to reduce aphid populations; however, no discernable change was noticed, perhaps due to the lateness in the season. Insecticidal soaps with natural plant-based pyrethrins may provide control with fewer negative impacts than insecticides like malathion, permethrin, and acephate because pyrethrins break down quickly (Flint, 2001).

Series 1 of the CWTS appeared to have a larger aphid infestation and resulted in more damage to the above water vegetation. Regrowth will be monitored in 2018 and replanting of Series 1 may be required. The aphids will continue to be monitored in 2018 and compared with other background areas (e.g., W10 and W15) to see if increases in aphid populations are specific to the CWTS, or general to the area. In 2018, it is recommended that a stronger insecticide be applied early in the season and on a frequent, predetermined schedule.

Figure 32 - Insect traps.
Insect traps installed in CWTS cells (left and right), insect trap installed at W15 (center) in 2017.

Figure 33 – Aphids observed in cell 1A and 2A in 2016 (top) and 2017 (bottom). Left pictures are of cell 1A. Right pictures are of cell 2A. Note the increased yellowing in cell 1A (2017) and cell 2A (2016, 2017) due to a denser aphid population.

Figure 34 – Aphids observed on *C. aquatilis.*
The left picture was taken in 2016 and the right picture was taken in 2017. Note the small green and black aphids on *C. aquatilis* leaves.

7. Summary of Results

When designed and implemented in a strategic and scientifically guided manner, CWTS can mitigate risks posed by many constituents. A treatment plan including processes to precipitate insoluble species of these constituents for sequestration into the soils of the wetland are very desirable as this mechanism captures the constituents and stores them in stable form in the soil, rather than transferring the constituents to an indeterminate fate (e.g., through plant uptake that can potentially bio accumulate in wildlife or be re-released in plant decomposition). This study addressed several important design considerations regarding implementation of a CWTS at full-scale for the treatment of metals and metalloids to meet the overriding objective of completing commissioning of the CWTS and progress through operational performance. A summary of key findings from the 2017 studies and recommendations to meet the objectives are listed below.

Monitor explanatory parameters and performance to determine when commissioning is complete and the operational period has begun:

- Dissolved oxygen (DO) decreased from an average of 8.4 mg/L during commissioning-B in 2016, to an average of 5.3 mg/L during operations in 2017. The DO in the water column is likely the result of photosynthesis of algae and mosses.
- Despite this DO level in the water column being in oxidizing ranges, stable reducing conditions were achieved in the CWTS soils within the targeted soil redox range (-100 to -250 mV).

Assess removal of constituents from the water:

- Copper treatment in the CWTS was masked by leaching from the soils used in construction of the CWTS into the water, but this has mostly been remedied now by the wetland treating this copper and turning it into more stable sulphide forms in the soil.
- During the operational period the demonstration-scale CWTS successfully achieved an average decrease in concentrations of 0.0169 µg/L for cadmium (from 0.0261 µg/L to 0.0092 µg/L), 31.8 µg/L for copper (from 49.1 µg/L to 17.3 µg/L), 3.6 µg/L for molybdenum (from 6.3 µg/L to 2.7 µg/L), 3.5 µg/L for selenium (from 4.0 µg/L to 0.5 µg/L), and 47.3 µg/L for zinc (from 49.2 µg/L to 1.9 µg/L).
- Molybdenum and selenium treatment in the operational period is notable as the removal rates were negligible within the margins of error of the testing method in the commissioning-A period.

Determine the hydraulic residence time (HRT) by tracer study and associated correction factor to apply to the nominal (calculated) HRT:

- The tracer study effectively demonstrated the HRT (2.25 days) and flow symmetry through the CWTS.
- There was a single flow path in the CWTS (shown by a single peak in the tracer study)
- Water is incorporating into the CWTS soils (shown by the long tail for depletion of the tracer).

- The nominal HRT is calculated from the area of the CWTS and the depth at the in-situ measuring points. This nominal HRT does not account for depth variations, embankment slopes, vegetation (using space in the water), or substrate pore space involvement. It was found that once all of these factors are in play, the correction factor from nominal to actual is only 0.01 added to the depth of the CWTS, which is incorporated into the HRT calculation as expressed in Equation 3.

Evaluate CWTS performance, and determine achievable concentrations of contaminants of concern (thermodynamic minimums):

- All targeted constituents are being treated by mineralization and sequestered to the soils (minimal plant uptake).
- The lowest concentrations consistently achievable for the treatment design (thermodynamic minimums) were reached by the end of the A cells for cadmium and copper.
- RRCs for cadmium and zinc in the 2017 demonstration-scale CWTS were artificially low because low flow rates did not provide the resolution needed to determine a RRC.
- Removal rate coefficients (RRCs, *k*) have been developed that can be used for full-scale sizing.
- Copper leaching from soils has decreased, but is still likely making the RRC artificially low in this CWTS; however, the RRC is expected to improve once copper leaching has subsided.

Update site-specific removal rate coefficients (from commissioning period) with data from operational period:

- Removal rate coefficients (RRCs, *k*) have been developed that can be used for full-scale sizing.
- Copper leaching from soils has decreased, but is still likely making the RRC artificially low in this CWTS.

Determine amount of water loss due to evapotranspiration and effect on outflow concentrations:

- The evapotranspiration studies revealed a significant loss of water, which will impact calculations of loads to the receiving environment (making them lower than previously estimated).
- In May and June, an average water loss of 5.3 L/day/m^2 was observed, which is equivalent to 18-20% of water (~700 L/day lost in the demonstration CWTS).
- During the evapotranspiration trials, copper leached into the water as it was transformed from an oxide mineral to a sulphide mineral (because of the copper in the soils used for construction). This is not representative of what would occur during periods with no flow in a full-scale CWTS, where soils with minimal leachable copper are used and copper is deposited in sulphide form (fraction 4) by the biogeochemical activity of the CWTS (Section 5.6).

Monitor metals leaching from mineralized soils used in construction:

- In 2017, leachable copper concentrations in soils decreased in the top 0-10cm while total copper concentrations increased.

Assess stability of constituents of concern in soils:

- Most constituents, including copper, have shifted primarily into stable reduced and residual minerals fractions in the soil.
- Acid volatile sulphides (AVS) were non-detectable in the CWTS in 2016. In 2017, small amounts of AVS were detected in cells 1A and 2A which indicates that residual sulphides are starting to become available for metal treatment and that copper in the soils are becoming rendered inert through sulphide mineralization.

Determine the rate and extent of detritus decomposition (*C. aquatilis* leaves) in the CWTS over time:

- The detritus study suggested that algae growth on the assay devices had reached a steady state (growth vs decomposition) by ~23 days of the study.
- After 83 days submerged in the CWTS, *C. aquatilis* decomposed on average 64%.

Assess treatment mechanisms (including microbes):

- Establishment of sulphide-producing bacteria (SPB) increased throughout 2017 and was highest after commissioning was completed.
- SPB were found in highest abundance in root and soil samples.
- The average number of different types of sulphide-producing bacteria increased over time in all sample types tested (root, soil, detritus, and moss).
- Selenium-reducing and nitrate-reducing bacteria increased over time with the highest abundances found in *C. aquatilis* roots.

Determine an appropriate method for insect pest control (aphids) in the CWTS:

- Aphids were again found in abundance on *C. aquatilis* in 2017.
- Efforts to control the aphid population on-site were made but an ongoing spraying regiment was not maintained and, therefore, aphids remained. However, no short-term detrimental effect on *C. aquatilis* viability was observed, despite the persistence of aphids.
- Damage to the above water vegetation was observed however new shoots were emerging in the CWTS and treatment COCs was not impacted by damage to the above water vegetation.
- Effects of aphids on *C. aquatilis* did not affect treatment.
- These issues with aphids are likely owing to the isolated nature of the demonstration-scale CWTS and not expected to affect the full-scale CWTS.

8. Next Steps for 2018

A conceptual testing plan was developed at the beginning of the demonstration-scale CWTS program, and has been refined and adapted based on performance and scientific findings during the commissioning and operational periods of the demonstration-scale CWTS. The demonstration-scale CWTS is expected to run until at least the end of 2018 to assess performance under a wider range of conditions. In 2018, a flow rate schedule will be developed targeting different HRTs based on predicted HRTs for full-scale performance. The overriding objective of the demonstration-scale program in 2018 is to assess performance under conditions that would be similar to the full-scale CWTS. Table 11 outlines the action plan for CWTS optimization and testing for 2018 based on the performance results through 2017.

A multi-year plan is provided in Appendix C, and includes work performed to date as well as a schedule of activities for 2018.

Table 11 – Minto 2018 CWTS demonstration-scale action items.

Timing	Task	Purpose
April 2018	Develop a flow rate schedule for 2018.	The flow rates will fluctuate based on expected amounts of water for full-scale wetland (scaled to size) in order to evaluate the performance of the wetland at different key periods.
	Develop sampling plan for 2018	The sampling plan will include sampling types, parameters, frequency, and locations. These results will inform the performance of the CWTS. Monthly sampling of the in, mid, and out locations will be added to the 2018 sampling plan to better assess removal of constituents through the CWTS cells.
	Develop aphid control and monitoring and plan for 2018	A consistent control and monitoring plan will aid efforts to control the aphid population residing in the demonstration-scale CWTS.
April/May 2018	Start water flow to CWTS	Begin 2018 demonstration-scale CWTS program
	Add sandbags on top of existing sandbags along edges of CWTS	Adding sandbags along edges of CWTS will minimize flow short circuiting. Use the sand that was confirmed to be a good borrow source in 2016 (i.e., low copper)
	Add sandbags to the end of the CWTS cells to increase the water depth to ~20 cm	Raising the water levels will promote the desired reducing conditions in the CWTS.
	Implement aphid control using insecticide on a routine schedule	Begin applications in early May when vegetation begins to become green, in order to control the aphid population before an infestation occurs.
Ongoing through 2018 sampling season	Routine sampling program	Follow sampling plan from May to September 2018 for routine collection of water, soil, microbial, plant, and detritus samples.
	Monitor for the presence of aphids in the CWTS and surrounding areas (W10 and W15 areas).	Determine if the aphid presence is isolated to the CWTS. Determine if more aggressive control measures are needed.

July/Aug 2018	Conduct a vegetation plot harvest. Collect all above water biomass of *C. aquatilis* in a 1m x 1m plot	To determine quantity of biomass per m^2
	Conduct evapotranspiration study	Although 2017 data suggests minimal release of metals from soils, another evapotranspiration trial during the operational period needs to be conducted to confirm metals leaching has subsided. Completing the evapotranspiration study in July/Aug in 2018 will provide information on evapotranspiration rates in warmer months and the effects of seasonality.
Sept 2018 (If needed)	Replant CWTS	Replant areas of the CWTS that were impacted by aphids if needed.
December 2018	Report	2018 Update Report

9. Closure

We trust the information herein satisfies your present requirements. Should you have any questions, please contact the persons listed below. We appreciate the opportunity to provide the services detailed in this report, and look forward to discussing any comments you may have.

Respectfully submitted,

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APPENDIX A - Methods

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A1. Demonstration-Scale Constructed Wetland Treatment System Design

A1.1. System Layout and Dimensions

The demonstration-scale CWTS includes two systems in parallel with two cells in each series and a final catchment basin that both systems flow into (Figure A1). Dimensions and construction details are available in the Minto Demonstration Scale Report Document 011_0315_01A (Contango, 2015). The two parallel systems serve as a replicate for data analysis, and as testing has progressed, the two systems have also allowed for comparison of different management techniques. Dimensions of the systems are provided here in Table A1.

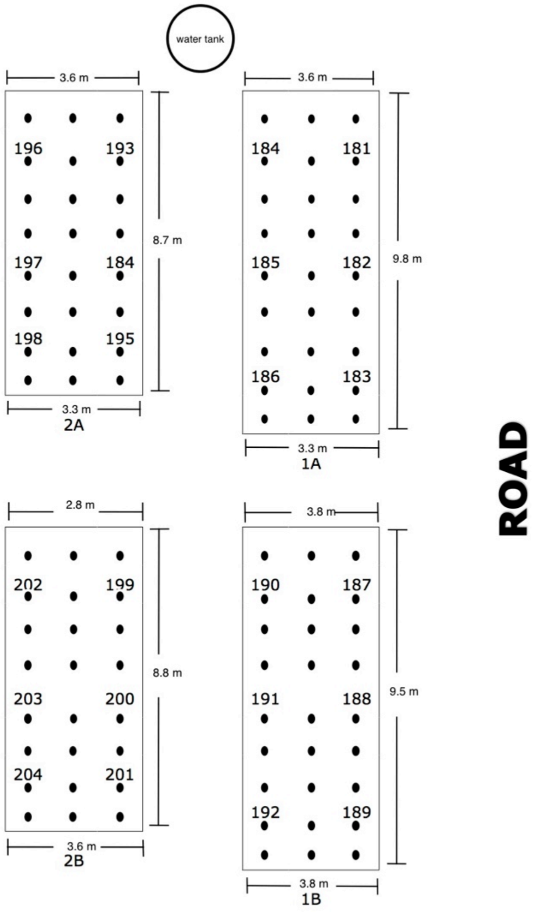

Figure A1 – Diagram of demonstration-scale CWTS.

Dimension measurements are indicated at soil surface. Black dots indicate initial construction grid marked by moss stakes, and locations of soil redox probes with identifying numbers.

Table A1 – Dimensions of demonstration-scale CWTS cells at soil surface and resultant areas of treatment systems.

Measurement		Series 1		Series 2	
		1A	1B	2A	2B
Width (m)	Inflow	3.6	3.8	3.6	2.8
	Outflow	3.3	3.8	3.3	3.6
Length (m)		9.8	9.5	8.7	8.8
Approximate surface area at soil (m^2)		33.8	36.1	30.0	28.2
Total area of system at soil (m^2)		69.9		58.2	

A1.2. Soils

Soils used to construct the CWTS are described in the initial report that outlines construction (Contango, 2015). In brief, the recommended soil for the CWTS was sand, with 2-7% by volume as organic material (e.g., woodchips, peat). In the pilot-scale systems, this resulted in a total organic carbon (TOC) content by weight of 0.2-0.6% (the sand itself was at 0.1% TOC prior to adding amendment). Ideally, this percentage could be higher, approximately 2-10% by weight to stimulate the desired reducing conditions. For the demonstration-scale system, the soil added to each of the four cells during construction was from a local borrow site. As is expected in a mining area, the soils are likely mineralized. Although a potential borrow source was tested prior to construction (“Tested Soil”; Table A2), a different borrow source was available upon construction of the demonstration-scale CWTS (“Soil used”; Table A2). The material used in the construction of the demonstration-scale CWTS was an organic peat, and analyses received after construction indicated an elevated concentration of leachable copper (Table A2). It should be noted that in a full-scale system, the variability in soil would be normalized by the larger volume of soil used. The soil in the CWTS (composed of the organic peat soil, wood chips, and straw) had a total organic carbon (TOC) content of 1.8-3.1%.

Table A2 – Comparison of copper concentrations in soils of pilot- and demonstration-scale CWTS.

Test method	Pilot-scale	Demonstration-scale	
	Initial soil	Tested soil (June, 2014)	Soil used (August, 2014)
SPLP Copper (mg/L)[1]	-	0.00546-0.0296[2]	0.148-0.608
Total Copper (mg/kg)	5.3-5.5	210-1400[2]	960-1400[3]

[1] SPLP - Synthetic Precipitation Leaching Procedure.
[2] For the June 2014 samples, the soil with the highest total copper concentration also had the lowest leachable copper concentration, and was therefore deemed acceptable for use.
[3] Total copper value for soils used was taken in June 2015 (no data for August 2014).

A1.3. Vegetation

The demonstration-scale CWTS was planted with *Carex aquatilis* (aquatic sedge) and aquatic mosses from the W10 area of the Minto Site. The plant selection and borrow source was previously determined through the site assessment (Contango, 2014a). Five *C. aquatilis* plants were planted per square meter, with moss tied to stakes that outlined the 1 m x 1 m grid for planting (details provided in Contango, 2015).

A1.4. Water Source

Water from the W36 area receiving seepage from the toe of the Mill Valley Fill Extension (MVFE) was selected for the demonstration-scale CWTS testing as the leachate is similar to that expected upon closure in the MVFE area. The chemistry of this water at the time of bringing the demonstration-scale CWTS online (September 18, 2014) is provided in Contango, 2015. In 2015 the water for the CWTS was pumped out of the sump at the toe of the MVFE. As the Mill Valley Fill Extension Stage 2 (MVFE2) progressed a new collection sump (W62 sump) was constructed as a replacement for the sump used in 2015. The W36 sump was decommissioned in February 2016 as part of the MVFE2 construction. The new sump approximately 30 m downslope was the supply water for the CWTS for the summer of 2016 and was the same source for 2017 (Figure A2).

Figure A2 – Water source for the demonstration-scale CWTS in 2017.

A2. Flow Rates

Flow rates as well as the totalizer values were recorded from the flow meter that feeds the demonstration-scale CWTS periodically throughout 2017. The flow rates (recorded by Minto) represent the flow that occurred at the time the flow rate was recorded off the flow meter and is represented by blue bars in Figure A3 below. The totalizer value was also recorded periodically and is the cumulative amount of water that passes through the flow meter between two given dates. Actual flow rates were also calculated based on the totalizer values and are represented by green dots in Figure A3 below. The flow rates calculated from the totalizer values represent the actual flow rates. The average actual flow rates calculated from the totalizer values during the operational period were 0.38 gallons per minutes (GPM) for series 1 and 0.29 GPM for series 2. Figure A3 shows the fluctuation in actual versus targeted flow rates throughout the 2017 operational period.

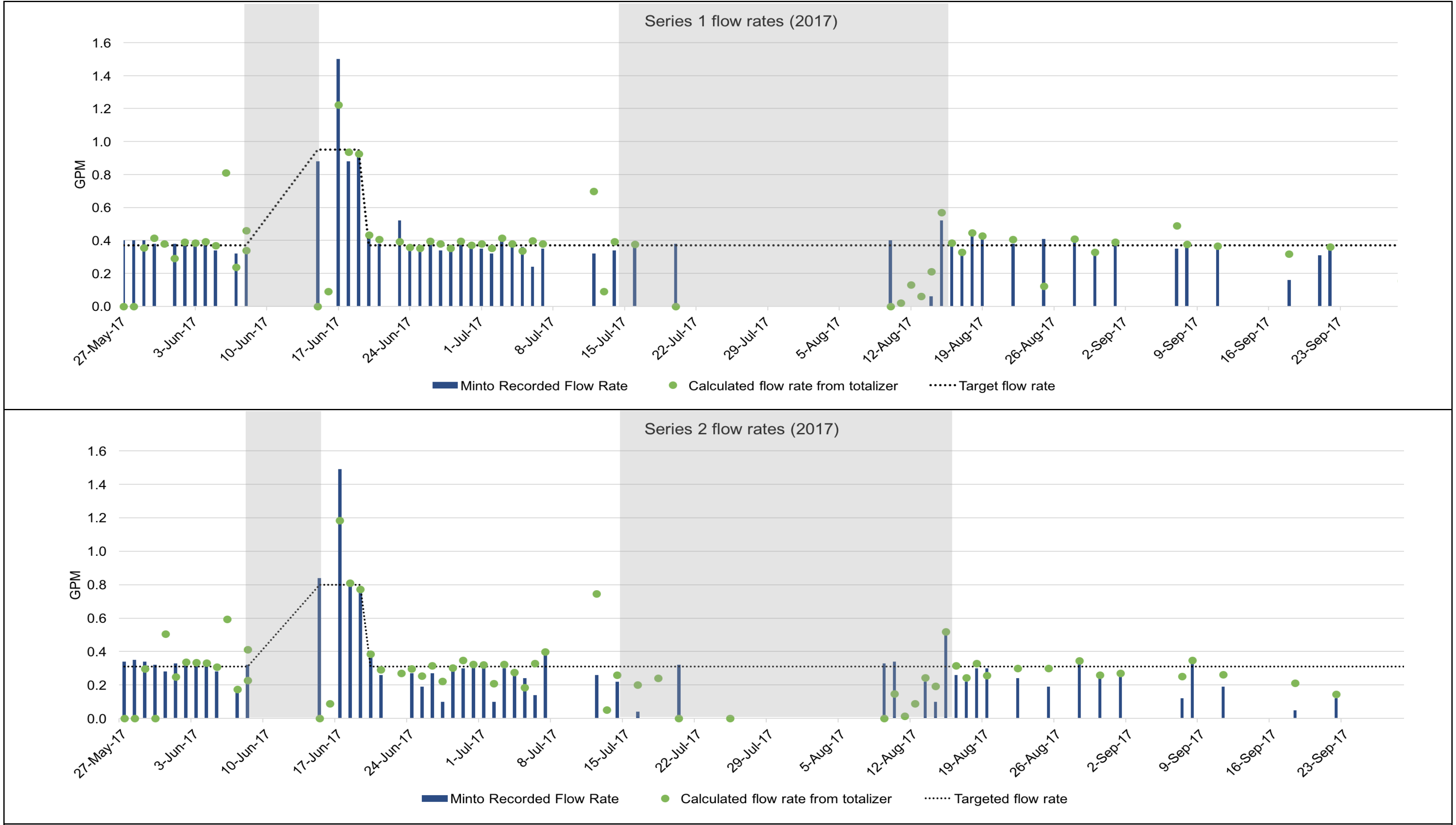

Figure A3 – Flow rates during CWTS operations in 2017.

Blue bars indicate flow rates displayed on flow meter, while green dots are flow rates calculated from the totalizer values (values from meter were recorded by Minto personnel). Targeted flow rates for series 1 and 2 were 0.37 and 0.31 gallons per minutes (GPM), respectively. Targeted flow rates are different for each series because the series differed in size. Series 2 was smaller than series 1 and therefore needed a slower flow rate to obtain the same HRT as series 1. The totalizer value is the cumulative volume of water passing through the flow meter between two measurement dates. Areas with no blue bars or green dots are time periods where flow rates and totalizer values were not recorded. Areas shaded grey indicate dates of interrupted flow. Further details can be found in Table 3 of the main report.

A2.1. Demonstration-Scale Commissioning Periods

Performance monitoring continued during commissioning although full treatment functionality of the demonstration-scale system was not expected. The information aided in guiding future development of the full-scale system in the following ways:

- Evaluated construction effectiveness and potential optimizations.
- Assessed timelines to reach targeted operational parameters to allow for effective phasing of implementation (e.g., soil redox, percentage and abundance of sulphate reducing bacteria).
- Assessed the effectiveness of *Carex aquatilis* and aquatic moss transplantation to assess planting density, time period to full density, and if plant propagation and/or a replanting schedule is necessary.

However, there were aspects of the demonstration-scale CWTS that were not directly transferrable to the planned construction of the full-scale CWTS. Notably, the demonstration-scale CWTS was built with a different soil type and chemistry than recommended for the full-scale system. Therefore; it took longer to commission the demonstration-scale system as the copper in the soils needed to be treated in addition to the copper and other constituents in the water.

Based on pilot-scale testing (Contango, 2014b), the estimated commissioning period for the Minto demonstration-scale CWTS was four months (i.e., period when water is flowing). In 2014, the demonstration-scale CWTS operated for less than one month prior to freezing, and was restarted along with spring thaw (freshet) in mid-May 2015. Based on these timelines, September 2015 was month four of commissioning, and the demonstration-scale system trended towards performance as expected during the commissioning period (Contango, 2016). However, as discussed further in sections 2.2 and 6.1 of the 2016 update report (Contango, 2017), the soil used in the CWTS had high concentrations of leachable copper, and therefore optimization opportunities were evaluated throughout 2015, and adjustments were implemented in 2015 and 2016. The last operational adjustment during the commissioning period was the addition of organic material in 2016, which marked the end of the commissioning-A period and the beginning of the commissioning-B period. Organic material will also be added during construction of the full-scale design to enhance desired reducing conditions to establish in the CWTS until vegetation is sufficient to provide for this required component. The end of the commissioning-B period was expected to be between July 16 and August 2, 2017. However, due to issues with the totalizer, the end of the commissioning-B period was August 17, 2017 and was marked by stabilization of flow rates and resolution of totalizer complications. Additionally, sandbags were added to the end of each cell on August 11, 2017 in order to raise the water level to obtain better treatment through enhancing reducing conditions. The operational period therefore began on August 18, 2017 and ran until September 22, 2017. Discussions in this report are based on the operational period.

A3. Sampling and Analyses

A3.1. Routine Monitoring of Explanatory Parameters

Explanatory parameters are quantifiable aspects of a CWTS environment that can be used to assess feasibility of treatment for a range of constituents, and therefore 'explain' the performance of a CWTS. These parameters, which often include acidity, alkalinity, conductivity, dissolved oxygen (DO), pH, oxidation-reduction potential (ORP), ion balance, available electrons donors (e.g., organic carbon, reduced elements), and temperature, can be used to predict, promote, and/or optimize the ability of the system to treat different constituents (Haakensen et al., 2015). A YSI ProPlus meter was used in the field to test for water temperature, DO, conductivity (and specific conductivity; SPC), pH, and ORP. In situ field readings were taken weekly in conjunction with water sampling using the YSI ProPlus.

A3.2. Water Sampling and Analyses

Water sampling occurred on a weekly basis from spring thaw in May 2017 to freeze up in September 2017. Frequencies and sampling parameters are outlined in Table A3. Grab samples were collected at the feed and outflow of each cell. Care was taken to avoid collecting plant matter, invertebrates, and other debris in the grab samples. Samples were collected from downstream to upstream to ensure that water sampling did not affect sample collection from the next cell (e.g., disrupting flow rates or suspending solids).

Due to copper and aluminum being found to be released from the CWTS substrates into the water in 2015, an additional sampling structure was designed. For two timepoints in 2015 (August 15, 2015 and September 17, 2015), two timepoints in 2016 (June 14, 2016 and September 7, 2016), and three timepoints in 2017 (June 20, 2017, August 18, 2017, and September 11, 2017) water was sampled not only at the feed and the outflow of each cell, but also through the cell. Beginning at the outflow of cell B and working upwards towards the feed, samples were taken at the B cell outflow, B cell mid-point, and B cell inflow, and then the same three points for the A cell (Figure A4). In each case, the sample was taken from within reaching distance of the side shore to ensure that sediments were not suspended in sampling.

Table A3 – Summary of 2017 analytical water sampling types, frequencies and locations.

Water	
Dissolved and total metals	Weekly, outflow of each cell and feed
Ammonia	
Nitrate	
Nitrite	
Flow rate	Weekly, feed
pH, DO, ORP, Conductivity (in situ)	Weekly, all cells and feed
Anion Sum	Monthly, outflow of each cell and feed
Cation Sum	
Hardness ($CaCO_3$)	
Ion Balance	
Total Dissolved Solids (TDS)	
Chloride (Cl)	
Sulphate (SO_4)	
Nitrogen (Total)	
Alkalinity	
pH	
Conductivity	
Chemical Oxygen Demand (COD)	
Total Organic Carbon (TOC)	
Total Kjeldahl Nitrogen (TKN)	
Total Suspended Solids (TSS)	
Dissolved Organic Carbon (DOC)	
Bicarbonate (HCO_3)	
Carbonate (CO_3)	
Hydroxide (OH)	

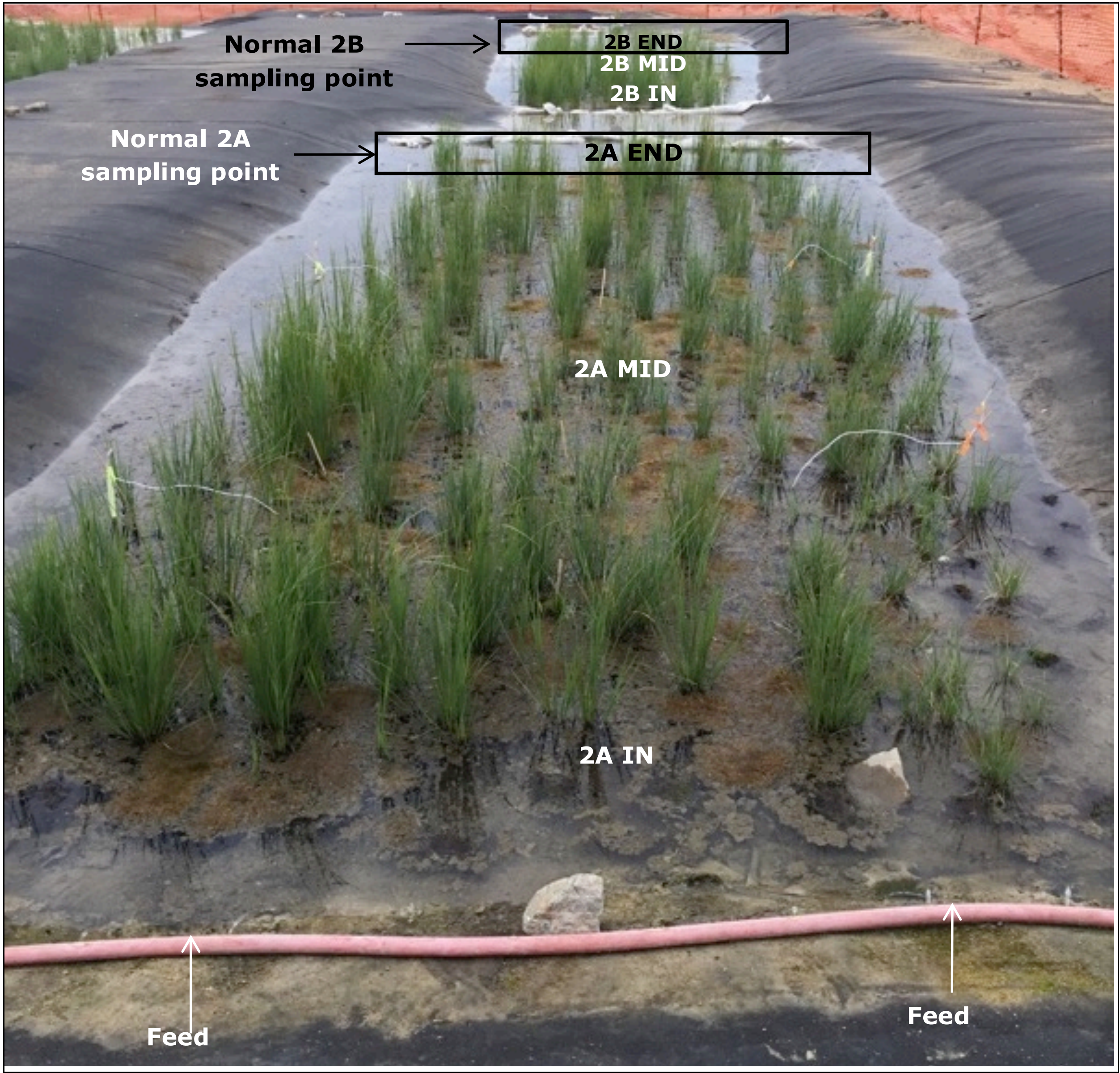

Figure A4 – Sampling points through the CWTS (Photo taken August 16, 2015).

A3.3. Soil Sampling and Analyses

Soil sampling was conducted three times in 2017 (June, July, September). A sample of the top 0-10 cm of CWTS soil was collected into a 1L glass jar for analyses. Analyses are outlined in Table A4. Each CWTS cell was sampled during each sampling event.

Table A4 – Summary of 2017 analytical soil sampling types, frequencies and locations.

Soil	
Relative soil redox (in situ)	Monthly, all probes (6 per cell)
Analyses completed on soil sample	
SAR, pH, EC, %sat, Ca, F, Mg, Na, K, Cl, SO4	Seasonally (3x per year) from a depth of 0-10 cm.
Available NPK and sulphur	
Alkalinity	
Bicarbonate (HCO_3)	
Carbonate (CO_3)	
Total Organic Carbon (TOC)	
Metals Analysis (Total)	
Sulfur by LECO	
Metals Leach	
AVS+SEM	
Sequential Leaching (5 Acid Test)	
Metals SPLP	Spring Sampling (1x per year).
Analyses completed on special leach	
Bromide (Br)	Seasonally (3x per year)
Chloride (Cl)	
Sulphate (SO_4)	
Fluoride (F)	
Alkalinity	
Bicarbonate (HCO_3)	
Carbonate (CO_3)	
Hydroxide (OH)	
Dissolved Organic Carbon (DOC)	
Ammonia	
Nitrate	
Nitrite	
Total Dissolved Solids (TDS)	
Anion Sum	
Cation Sum	
Cation/EC ratio	
Ion Balance	

Although unintentional, the use of soils in the CWTS with high initial leachable copper concentrations (Table A2) allowed for additional types of testing to be carried out on these systems. To assess the effect of the elevated metals (aluminum and copper) in the soils used in construction on CWTS functionality, four soil analytical test methods were used:

- Total concentration of elements in the soils by CRC ICPMS (EPA 200.2/6020A). This method uses a heated strong acid digestion with HNO_3 and HCl and is intended to liberate metals that may be environmentally available.

- In 2015 and 2017, leachable concentrations of elements in the soils by Synthetic Precipitation Leaching Procedure (SPLP), which is a method to assess the mobility of elements in soils at the pH of rain water (i.e., if the CWTS were to entirely dry out, then be subjected to leaching by rain water) (EPA 1312/6010B).
- In 2016 and 2017 a leach method was used (EPA 6020A). This analysis was carried out using a leaching procedure which involved the gentle tumbling of a sample in a specified leaching solution (water from the CWTS) for two hours. This method is typically carried out by tumbling the sample in deionized water, however this method was adjusted to use water from the CWTS to be more representative of the actual leachability of the soils into the overlaying water of the CWTS. The resulting extract is then analyzed by inductively coupled plasma – optical emission spectrophotometry (EPA 300.1). This method was selected in 2016 to determine the concentration of metals that are being released from the soil into the overlying water column. The leach method is more representative of actual potential leachability of the soils into the CWTS than is the SPLP method.
- Sequential extraction procedure for the speciation of particulate trace metals (Tessier et al., 1979, EPA 6020A) to assess the stability and form of elements in soils.

A3.4. Plant Sampling and Analyses

Both *C. aquatilis* and moss samples were collected for metals analysis at the final sampling period of the demonstration-scale CWTS. Above water vegetation for *C. aquatilis* samples were collected from each cell in the CWTS. Green, living moss samples (rather than black, decomposing moss) were collected from each cell in the CWTS. Analyses are outlined in Table A5. Analyses of the tissue samples followed EPA 200.3/6020A and were reported in mg/kg dry weight. The tissue samples were homogenized and sub-sampled prior to digestion.

Table A5 - Summary of 2017 analytical plant sampling types, frequencies and locations.

Plant tissue samples	
Total Metals by ICPMS (Co, Cu, Fe, Pb, Li, Mg, Mn, Mo, Ni, P, K, Se, Ag, Na, Sr, Tl, Sn, Ti, U, V, Zn, Zr)	*Carex aquatilis* and aquatic moss, each cell, year end

A3.5. Microbial Sampling

Soil, roots, detritus, and moss were collected from each cell in the CWTS for microbial analysis three times in 2017 (June, July, Sept). The soil was collected by scooping the surface, from 0-10 cm, in various parts of the cell and pouring off any excess water after collection. The roots were collected from various plants in each cell at different depths of soil and pooled together in a 50mL falcon tube. Detritus samples were collected from various areas of the cells and included the decomposing straw material within the water. Moss samples were collected from various parts of the cell from the green new growth as well as the decomposing black areas of the moss and pooled together in a 50mL falcon tube. Microbial analyses are outlined in Section A3.6.

A3.6. Methods for Microbial Analyses

A3.6.1. Growth-based Analyses (MPN)

The most-probable number (MPN) of bacteria was determined for all microbial samples. The MPN test allows for an estimation of the number of bacteria that can grow in a specific laboratory medium (i.e., quantification method). MPN of heterotrophic organisms (grown with R2A medium; HiMedia Labs) were quantified in both aerobic and anaerobic conditions. MPN tests for selenate and selenite reduction were performed as per Siddique et al. (2006). The nitrate reduction MPN was performed as per the Nitrate Reduction Test (supplied by Sigma-Aldrich).

In brief, samples were weighed and/or measured into a 0.1% peptone solution and then serially diluted along a sterile 96-microwell round-bottom plate containing the growth media. All tests were conducted in triplicate. Wells were incubated without light at room temperature (21-22°C) and assessed for visible growth (formation of a pellet) and/or colour change specific to the type of media after 27-29 days. A colour change to red indicated selenite or selenate reduction, while nitrate reduction was assessed per the manufacturer's instructions. The most probable number of microbes was then calculated as described by Blodgett (2010).

A3.6.1. DNA-based Analyses

DNA was extracted from all samples using the MO BIO PowerLyzer PowerSoil DNA Isolation kit. Targeted DNA sequencing was used to identify bacteria present in each sample via polymerase chain reaction (PCR) amplification of the v3/v4 region of the 16S ribosomal RNA gene (Klindworth et al., 2013). Library preparation and sequencing was performed as per the manufacturer's instructions for MiSeq v3 paired-end 300 bp sequencing (Illumina) for all samples and positive and negative controls. After sequencing, the forward and reverse reads were merged and all sequences were quality filtered before processing into Operational Taxonomic Units (OTUs) and classified.

A3.7. Hydraulic Retention Time Tracer Study

The Minto Demonstration Scale 2016 Update Report (Contango, 2017) provides details on the methods used in the HRT tracer study in 2016. In 2017, a 1 m^3 tank was added to the CWTS area, and another HRT tracer study was conducted. The 1 m^3 tank provided a way to mix a lower concentration salt solution, and dose it into the CWTS over a longer period at a constant flow using a metering pump. This allowed the flow rate to be calculated for the duration of time the salt solution was dosed into the CWTS. To conduct the HRT tracer study over a longer period, the YSI unit was connected to a power source due to a limited battery life. By conducting the tracer study in 2017 as described above only one breakthrough occurred, as opposed to the two breakthroughs that were observed in 2016, providing more accurate results.

The 1 m^3 tank used in the HRT tracer study was filled with 600 L of influent water with 1.26 kg of salt dissolved into the water to create the tracer. The salt solution was mixed thoroughly with a mixing pump in the tank prior to use. The salt solution was dosed into cell 1A at a rate of 1.8 L/min. The tracer was dosed over a period of approximately four hours, at which time approximately 400 L of salt solution had been dosed into cell 1A. The volume of water and weight of salt was calculated based on the amount required to increase the specific conductance (SPC) of cell 1A to approximately twice its background level (i.e., from 850 µs/cm, to 1,700 µs/cm) (Oakton Instruments, 1997). When using this method in 2016 the SPC was raised by 38% higher than desired, therefore in 2017 38% less salt was used for the tracer. The volume of water used was then selected to ensure the concentration of the salt solution was sufficiently diluted and would mix with the water of the CWTS (i.e., the solution wasn't so dense that it would stratify and sink to the bottom of the CWTS).

In situ monitoring was carried out from June 21, 2017 until July 2, 2017. This time period was selected to allow sufficient time for the entire salt tracer to pass through the CWTS and return to background SPC levels. The YSI unit was placed in the CWTS for approximately two hours prior to dosing of the tracer to record background readings. The background SPC prior to commencing the HRT tracer study was approximately 829 µS/cm, and the SPC peaked at 1107 µS/cm, 2.25 days after the tracer was dosed into the CWTS (Figure 20, in main document). The increase in conductivity did not reach the desired amount of double the background SPC level, however the peak was sufficient to observe the tracer pass through the system and determine the maximum.

A3.8. Detritus Decomposition Trials

A detritus decomposition trial was developed and conducted in 2017 to assess decomposition rates of *C. aquatilis* in the CWTS over time, as well as the algae growth on CWTS organic materials within the water column (Chimney and Pietro, 2006; Hammerly et al.,1989). Twenty-four 12-inch by 4-inch mesh bags were filled with 5 grams of oven dried *C. aquatilis* material (dried at 50°C). On June 21, 2017, six bags were then submerged into each of the four CWTS cells to determine the rate of decomposition of *C. aquatilis* over time. An additional 24 mesh bags were filled with 3.8 grams of polyester filter fiber material. On the same day (June 21, 2017) six bags were submerged into each of the four CWTS cells to determine the amount of algae growth on material in the CWTS during the course of the trial. On July 25, 2017, after 34 days of submersion in the CWTS, and on September 11, 2017 after 82 days of submersion in the CWTS, one bag filled with polyester filter fiber and one bag filled with *C. aquatilis* was removed from each CWTS cell. The contents of the bags were then rinsed with deionized water to remove any sediment from the sample and dried in an oven at 50^{o}C. The dried weights after 34 days and 82 days were compared to the initial weights of the sample. It was assumed that the increase in weight on the polyester fiber fill sample would be representative of the algae that grew on the *C. aquatilis* samples that could not be removed by rinsing the samples. Therefore, the increase in dry weight of the polyester fiber was subtracted from the dry weight of the *C. aquatilis* to determine the amount of decomposition that occurred over a specific time period.

In total, six bags of each material were submerged in each cell and two bags of each material were removed over the 2017 sampling periods. The remaining four bags of each material were left in each cell for future analysis. Each removal of four bags (one from each cell) were treated as replicates for the sample material and date removed.

A3.9. Evapotranspiration Trials

Total evapotranspiration from the system is the combined effects of open water evaporation and plant transpiration (Beebe et al, 2014). The purpose of calculating the evapotranspiration of a system is to understand the amount of water lost, which in turn concentrates elements and should be considered in the context of the difference of decrease in outflow concentration (or not) and outflow load reduction. In 2016, an off-site and on-site evapotranspiration study was conducted (Contango, 2017); however, rain occurred during the on-site study and the Minto weather station was not functioning, therefore evapotranspiration rates could not be determined and it was recommended the study be repeated in 2017.

To add to the information gathered from the off-site evapotranspiration trials conducted in 2016 (Contango, 2017), three trials were conducted on-site to refine site-specific evapotranspiration rates. In 2017, the evapotranspiration studies were performed on-site from May 16-24 (trial 1), June 8-11 (trial 2), and June 11-15, 2017 (trial 3). Approximately 17.5 mm of rain occurred on-site during trial 2 on June 11, 2017 and therefore trial 2 was terminated and trial 3 began to account for the precipitation. In trial 1, the flow to the CWTS was shut off on May 16 and the water level was recorded in each cell of each series using depth measuring sticks, which were installed at each end of the CWTS in 2016 (Figure A5). The water level was recorded again on May 24 to determine the water lost due to evapotranspiration in the CWTS throughout the study. The same method to determine water lost was also used in trials 2 and trial 3 and the flow to the CWTS was shut off on June 8 to June 11 and June 11 to June 15, respectively.

Figure A5 – Depth sticks in CWTS cell 1A to record evapotranspiration in 2016 (left) and 2017 (right).

Depth sticks were installed in all CWTS cells June 2016 and used throughout the demonstration-scale study.

A4. Thermodynamic Minimum Calculations

The thermodynamic minimum is the lowest concentration consistently achievable for a given treatment design and water chemistry. Once reached, making the CWTS bigger will not result in further decrease of concentration (although it will continue to decrease the load). Therefore, this is a useful parameter to aid in determining appropriate sizing and outflow water quality objectives of a CWTS. The CWTS was analyzed at three points to determine whether the thermodynamic minimum had been reached. Concentrations of constituents were measured at three sampling points (CWTS feed, cell A-outflow, and cell B-outflow) in the series and compared to determine if the thermodynamic minimum had been reached. To determine if a concentration was significantly different or not, statistical analyses were done (paired samples t-test, $\alpha=0.05$) to determine if the concentration had stabilized across two sampling points. Once a concentration had stabilized across two points in a series, the thermodynamic minimum was considered to have been met.

A5. Load Removal Calculations

The load removed shows how much of the load of a constituent entering the pilot-scale CWTS was removed during each flow period. Equation A1, Equation A2, and Equation A3 show how the nominal load in, load out, and load removal (non-evapotranspiration adjusted) is calculated.

$$Load_{in} = C_i \times V$$

Equation A1 – Equation for the calculation of load of a constituent into a CWTS over a period of time.

$Load_{in}$ is the mass of a constituent that enters a CWTS over a period of time, C_i is the inflow concentration of the constituent, V is the volume of water that enters a CWTS over a period of time.

$$Load_{out} = C_f \times V$$

Equation A2 – Equation for the calculation of the load of a constituent out of a CWTS over a period of time.

$Load_{out}$ is the mass of a constituent that exits a CWTS over a period of time, C_f is the outflow concentration of the constituent, V is the volume of water that enters a CWTS over a period of time.

$$Load\ Removed = Load_{in} - Load_{out}$$

Equation A3 – Equation for the calculation of the load removed over a period of time.

A5.1. Load Removal Calculations Adjusted for Evapotranspiration

The results of the evapotranspiration trial (Section A3.9) were integrated with the load removal calculations (Section A4) to determine the actual amount of load removed taking into consideration the amount of water lost from the pilot-scale CWTS through evapotranspiration (Equation A4). Equation A5 describes how the outflow water volume from a CWTS is adjusted for evapotranspiration. Equation A5 uses a value for evapotranspiration in L/day/m^2, which was calculated using the results of the evapotranspiration trial (main report), which is multiplied by the surface area of the CWTS. For series 1 the surface area is 69.7 m^2, and for series 2 the surface area is 58.2 m^2. Equation A6 describes how the load out adjusted for evapotranspiration is calculated using the evapotranspiration adjusted outflow volume calculated in Equation A5. Equation A7 was used to calculate the outflow concentration (mg/L) adjusted for evapotranspiration using the load out calculated in Equation A6. Equation A8 describes how the load removal adjusted for evapotranspiration is calculated using the load in calculated in Equation A1 and load out adjusted for evapotranspiration in Equation A6.

$$Water\ loss\ (\%) = \frac{ET}{Q} \times 100$$

Equation A4 – Equation for the calculation of the water loss due to evapotranspiration.
Q is the flow rate (L/day), *ET* is the evapotranspiration rate (L/day).

$$V_{ET} = Q - ET$$

Equation A5 – Equation for the calculation of the outflow water volume adjusted for evapotranspiration.
V_{ET} is the outflow water volume adjusted for evapotranspiration, *Q* is the flow rate (L/day), *ET* is the evapotranspiration rate (L/day).

$$Load_{out(ET)} = V_{ET} * C_f$$

Equation A6 – Equation for the calculation of the load out of a constituent adjusted for evapotranspiration.
$Load_{out(ET)}$ is the load out adjusted for evapotranspiration, V_{ET} is the outflow water volume adjusted for evapotranspiration, C_f is the outflow concentration of the constituent.

$$Cf_{ET} = \frac{Load_{out(ET)}}{Q}$$

Equation A7 - Equation for the calculation of outflow concentration adjusted for evapotranspiration.
Cf_{ET} is the outflow concentration of the constituent adjusted for evapotranspiration, $Load_{out(ET)}$ is the load out adjusted for evapotranspiration, *Q* is the flow rate (L/day).

$$Load\ Removed\ Adjusted\ for\ Evapotranspiration = Load_{in} - Load_{out(ET)}$$

Equation A8 – Equation for the calculation of the load removed adjusted for evapotranspiration.
$Load_{out(ET)}$ is the load out adjusted for evapotranspiration

A6. Removal Rate Coefficients and Calculations

An important factor for CWTS design is the rate of treatment, also known as the removal rate coefficient (*k*). The removal rate coefficient is based on the treatability of a specific compound and the hydraulic retention time of the CWTS, both of which are site-specific based on water chemistry, CWTS designs, and characteristics of the CWTS.

Once hydraulic retention time is calculated (main report), it can be used to solve for the removal rate coefficients (*k*) using the inflow (*Ci*) and outflow (*Cf*) concentrations of a given constituent (Equation A9 and Equation A10). Equation A9 was utilized to calculate first-order removal rate coefficients, while Equation A10 was utilized to calculate zero-order removal rate coefficients.

$$k = \frac{-\ln\left(\frac{Cf}{Ci}\right)}{\mathrm{HRT}}$$

Equation A9 – Equation for calculation of first-order removal rate coefficient.
k is the removal rate coefficient, *Cf* is the final concentration, *Ci* is the initial concentration, and HRT is the hydraulic retention time.

$$k = \frac{(Ci - Cf)}{\mathrm{HRT}}$$

Equation A10 – Equation for calculation of zero-order removal rate coefficient.
k is the removal rate coefficient, *Cf* is the final concentration, *Ci* is the initial concentration, and HRT is the hydraulic retention time.

A7. References

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Appendix B – Additional Tables & Figures

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Table B1 - Summary of extractable fractions from sequential extraction procedure for the speciation of metals[1].

Fraction	Description	COCs unstable when
1	Exchangeable fraction for adsorbed minerals	Readily released (i.e., soluble and exchangeable)
2	Mineral fraction bound to carbonates or solubilized at pH 5	Decreased pH
3	Oxidized mineral fraction bound to Fe-Mn oxides	Reducing conditions
4	Reduced mineral fraction and sulphides	Oxidizing conditions
5	Residual mineral fraction (primary and secondary minerals)	Not expected to be released in solution over time under conditions normally encountered in nature

[1] Method based on Tessier et al., 1979.

Table B2 – Total and leachable soil copper concentrations in first year of operations.

CWTS Cell	Sampling Date	Days in Operation	Sample Depth (cm)	Total Cu (mg/kg)	SPLP Cu (mg/L)	Leachable Cu (mg/kg)
1A	28-Aug-14	1	Initial Composite	-	0.298 (0.148-0.608)	-
	19-Jun-15	58	0-5	960	0.055[1]	-
	16-Aug-15	116	10-20	950	0.187	-
	18-Sep-15	149	10-20	1300	0.049	-
	29-Sep-15	160	10-20	910	0.069	-
	15-Jun-16	194	0-10	1440	-	0.953
	15-Jun-16	194	10-20	1210	-	0.66
	8-Jul-16	217	0-10	1430	-	0.603
	8-Jul-16	217	10-20	1730	-	0.832
	7-Sep-16	247	0-10	1290	-	0.449
	20-Jun-17	336	0-10	1470	0.315	0.308
	25-Jul-17	371	0-10	1630	0.529	0.463
	12-Sep-17	420	0-10	1490	0.590	0.481
1B	28-Aug-14	1	Initial Composite	-	0.298 (0.148-0.608)	-
	19-Jun-15	58	0-5	1400	0.033[1]	-
	16-Aug-15	116	10-20	1400	0.209	-
	18-Sep-15	149	10-20	830	0.065	-
	29-Sep-15	160	10-20	880	0.059	-
	15-Jun-16	194	0-10	1130	-	1.01
	15-Jun-16	194	10-20	1240	-	0.822
	8-Jul-16	217	0-10	1250	-	1.11
	8-Jul-16	217	10-20	1620	-	1.21
	7-Sep-16	247	0-10	1190	-	0.197
	20-Jun-17	336	0-10	1290	0.450	0.338
	25-Jul-17	371	0-10	1100	0.290	0.165
	12-Sep-17	420	0-10	1100	0.716	0.492

[1] Samples collected in June 2015 were at a shallow depth (0-5 cm) and copper content had therefore likely already been removed by washing from the faster flows of the CWTS system. The blue shading indicated samples that were taken from a shallower depth (0-10).

Table B2 continued – Total and leachable soil copper concentrations in first year of operations.

CWTS Cell	Sampling Date	Days in Operation	Sample Depth (cm)	Total Cu (mg/kg)	SPLP Cu (mg/L)	Leachable Cu (mg/kg)
2A	28-Aug-14	1	Initial Composite	-	0.298 (0.148-0.608)	-
	19-Jun-15	58	0-5	1175	0.037[1]	-
	16-Aug-15	116	10-20	660	0.139	-
	18-Sep-15	149	10-20	880	0.081	-
	29-Sep-15	160	10-20	1000	0.073	-
	15-Jun-16	194	0-10	1100	-	0.823
	15-Jun-16	194	10-20	1280	-	0.900
	8-Jul-16	217	0-10	1450	-	0.963
	8-Jul-16	217	10-20	1150	-	1.68
	7-Sep-16	247	0-10	1290	-	0.838
	20-Jun-17	336	0-10	1820	0.381	1.24
	25-Jul-17	371	0-10	1290	0.419	0.927
	12-Sep-17	420	0-10	1440	0.389	0.381
2B	28-Aug-14	1	Initial Composite	-	0.298 (0.148-0.608)	-
	19-Jun-15	58	0-5	1100	0.039[1]	-
	16-Aug-15	116	10-20	1000	0.201	-
	18-Sep-15	149	10-20	830	0.078	-
	29-Sep-15	160	10-20	540	0.059	-
	15-Jun-16	194	0-10	1040	-	0.771
	15-Jun-16	194	10-20	1310	-	1.16
	8-Jul-16	217	0-10	1070	-	1.38
	8-Jul-16	217	10-20	1180	-	1.25
	7-Sep-16	247	0-10	1520	-	0.123
	20-Jun-17	336	0-10	1110	0.283	0.523
	25-Jul-17	371	0-10	1240	0.477	0.540
	12-Sep-17	420	0-10	1140	0.596	0.809

The blue shading indicated samples that were taken from a shallower depth (0-10).

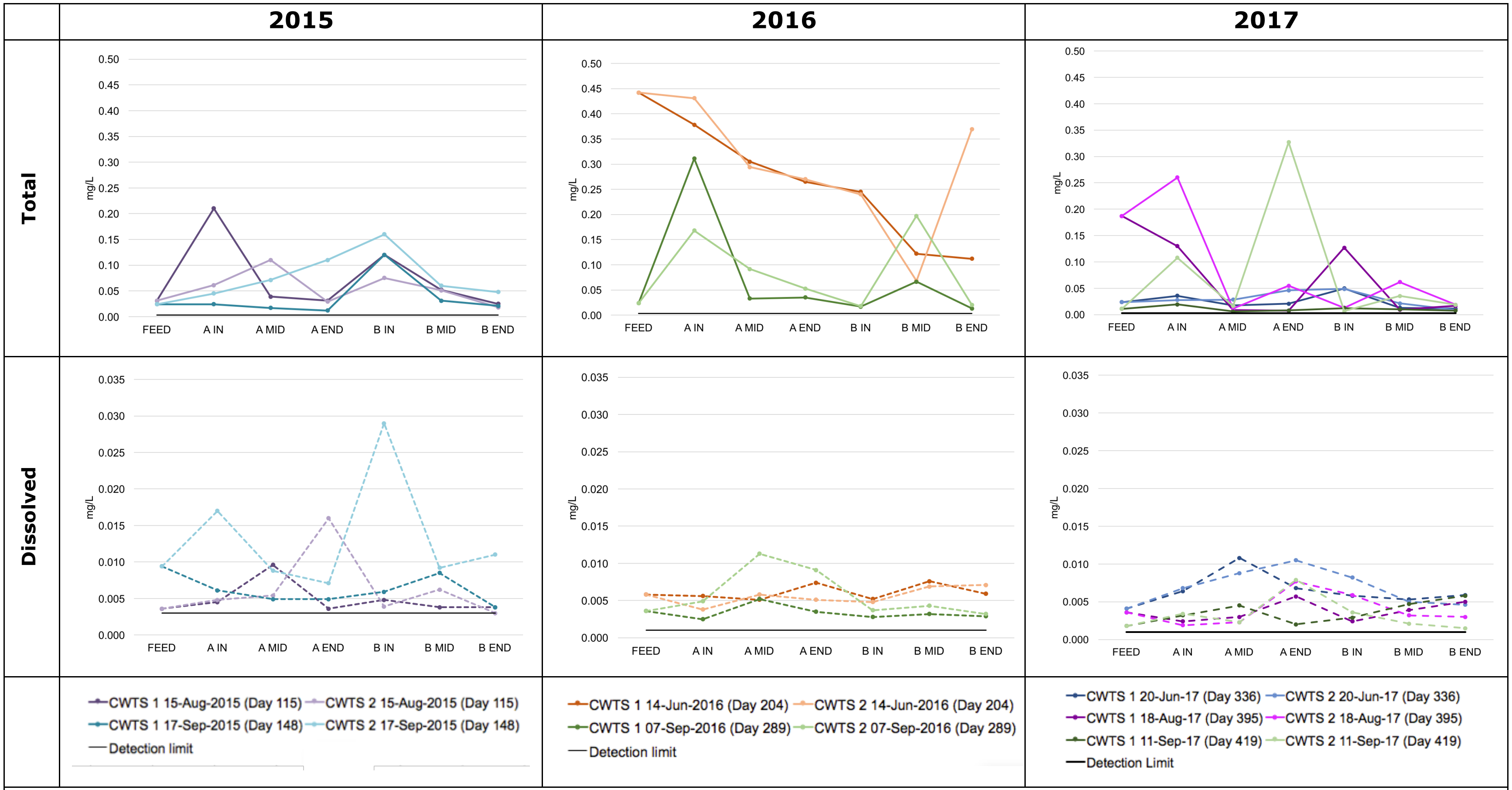


Figure B1 – Aluminum concentrations through the CWTS.
2015 (left), 2016 (middle), and 2017 (right) total (top) and dissolved (bottom) aluminum concentrations. Data shown for seven timepoints, where water was sampled at 7 locations through the flow path of the CWTS to assess for treatment fronts within the wetland, or possible leaching of elements from the soils into the CWTS. The Maxxam (2015 results) detection limit (DL; black line) for aluminum is 0.0030 mg/L. The ALS (2016 and 2017 results) DL for dissolved and total aluminum are 0.0010 mg/L and 0.0030 mg/L, respectively.

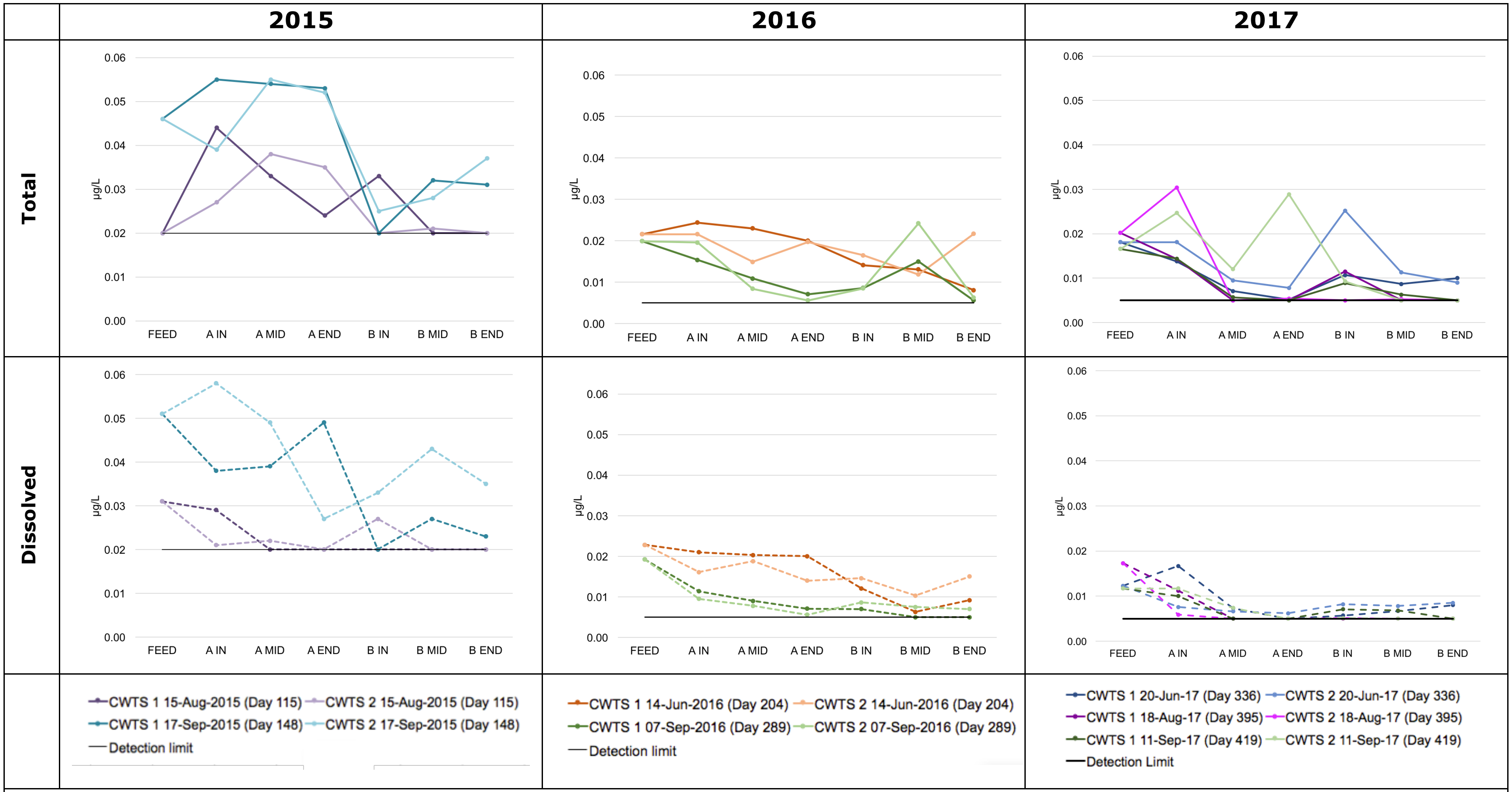


Figure B2 – Cadmium concentrations through the CWTS.

2015 (left), 2016 (middle), and 2017 (right) total (top) and dissolved (bottom) cadmium concentrations. Data shown for seven timepoints, where water was sampled at 7 locations through the flow path of the CWTS to assess for treatment fronts within the wetland, or possible leaching of elements from the soils into the CWTS. The Maxxam (2015 results) detection limit (DL; black line) for cadmium is 0.020 µg/L. The ALS (2016 and 2017 results) DL for cadmium is 0.005 µg/L.

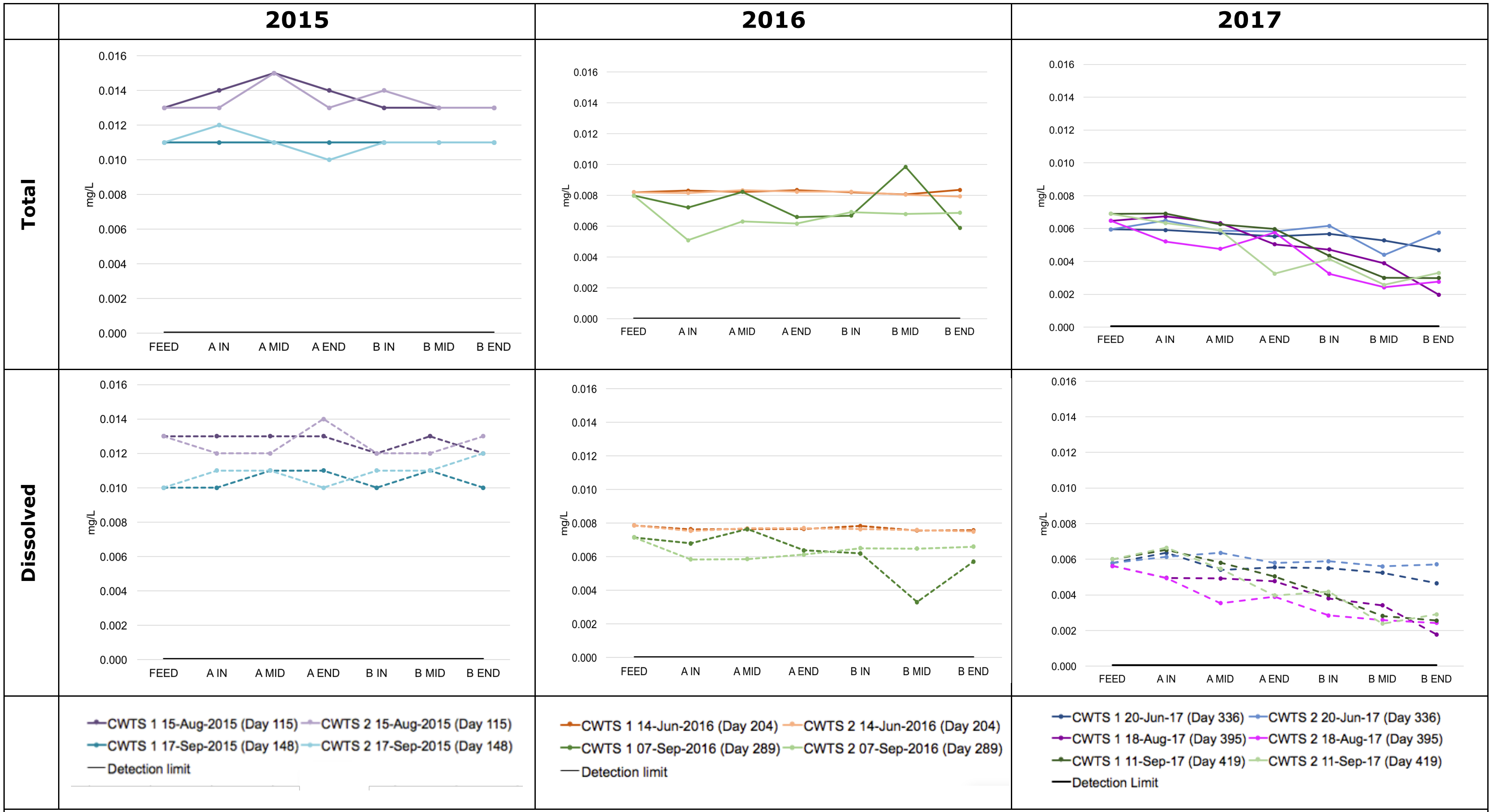


Figure B3 – Molybdenum concentrations through the CWTS.
2015 (left), 2016 (middle), and 2017 (right) total (top) and dissolved (bottom) molybdenum concentrations. Data shown for seven timepoints, where water was sampled at 7 locations through the flow path of the CWTS to assess for treatment fronts within the wetland, or possible leaching of elements from the soils into the CWTS. The Maxxam (2015 results) detection limit (DL; black line) for molybdenum is 0.0002 mg/L. The ALS (2016 and 2017 results) DL for molybdenum is 0.000050 mg/L.

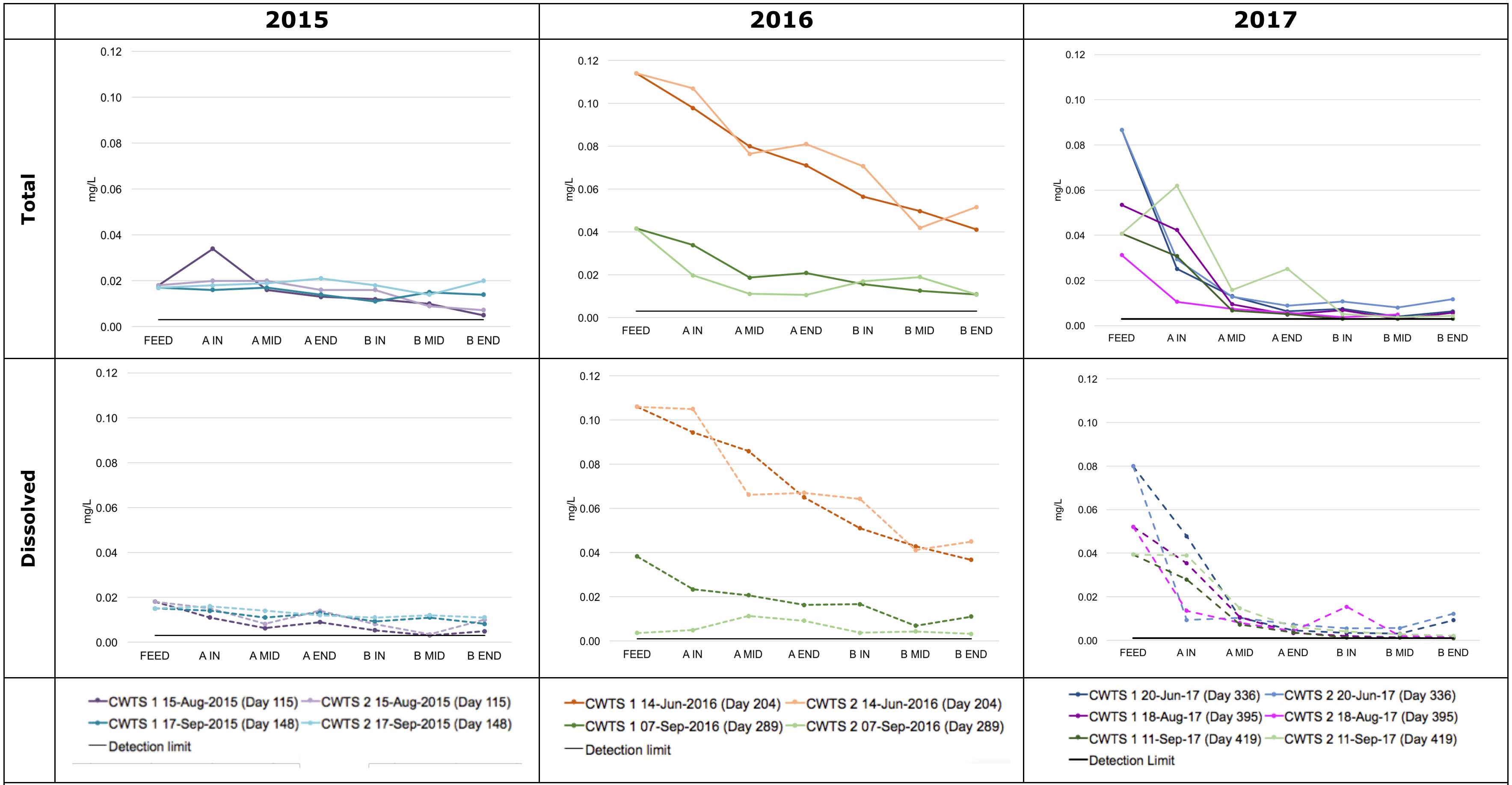


Figure B4 – Zinc concentrations through the CWTS.
2015 (left), 2016 (middle), and 2017 (right) total (top) and dissolved (bottom) zinc concentrations. Data shown for seven timepoints, where water was sampled at 7 locations through the flow path of the CWTS to assess for treatment fronts within the wetland, or possible leaching of elements from the soils into the CWTS. The Maxxam (2015 results) detection limit (DL; black line) for zinc is 0.0030 mg/L. The ALS (2016 and 2017 results) DL zinc is for 0.0010 mg/L.

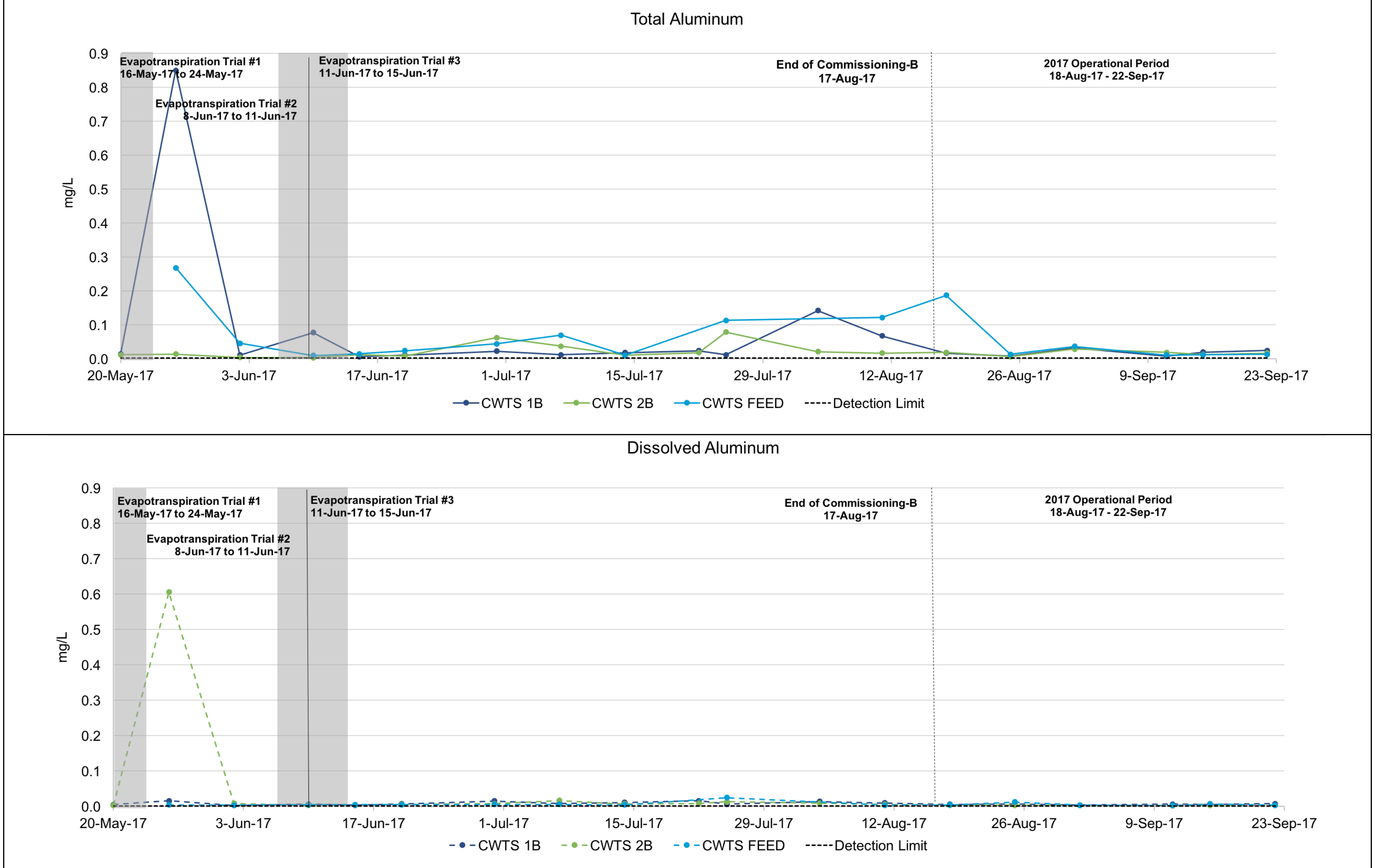


Figure B5 – Aluminum concentrations in the demonstration-scale wetland in 2017.
The evapotranspiration trials are indicated by grey shading and the duration in days. The ALS detection limit for dissolved and total aluminum is 0.001 mg/L and 0.003 mg/L, respectively. Flow to the CWTS was turned off on September 30, 2017. However, the last sampling date in the operational period was September 22, 2017 due to variable flow rates in the CWTS following this date.

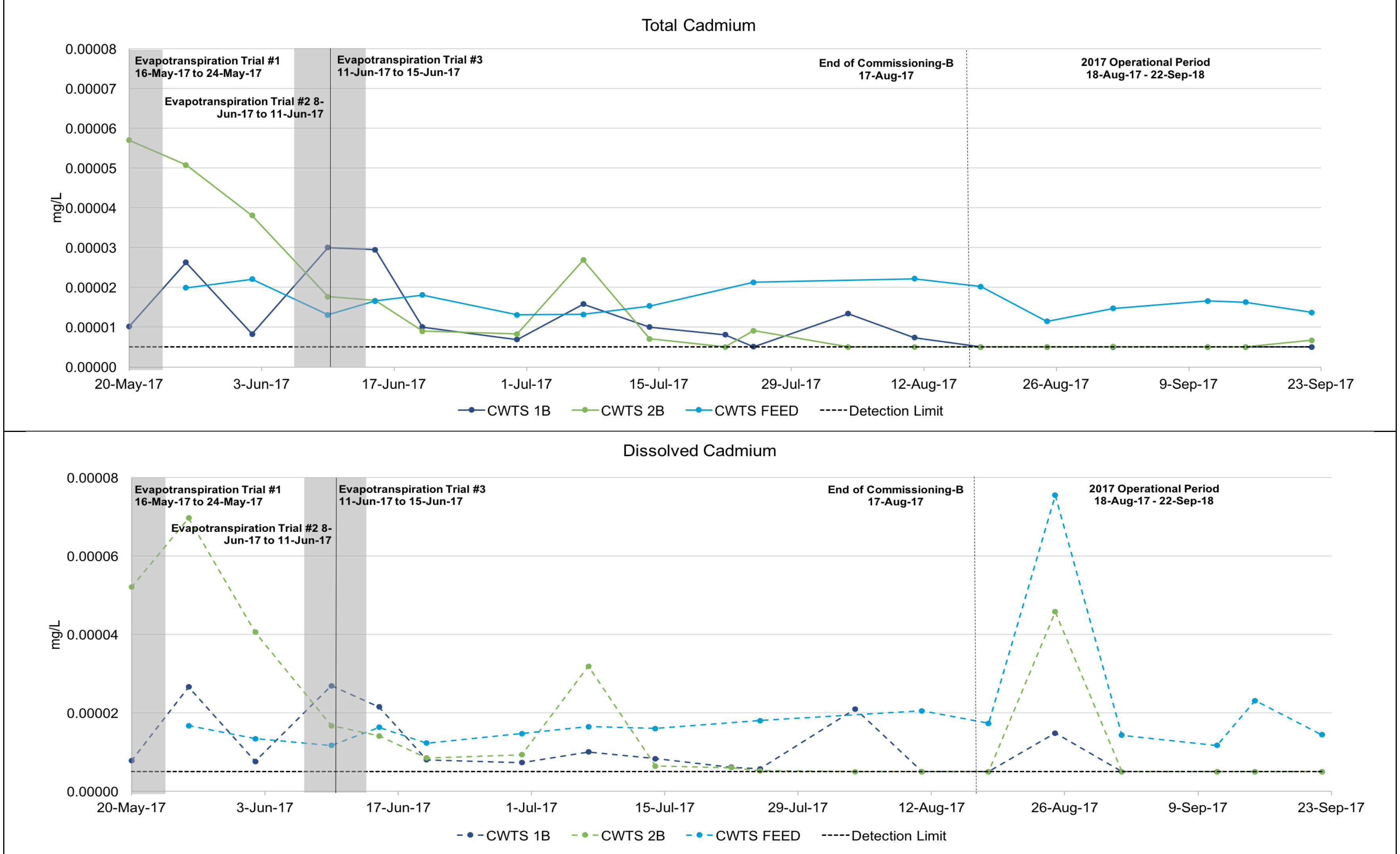


Figure B6 – Cadmium concentrations in the demonstration-scale wetland in 2017.
The evapotranspiration trials are indicated by grey shading and the duration in days. The ALS detection limit for cadmium is 0.000005 mg/L. Flow to the CWTS was turned off on September 30, 2017. However, the last sampling date in the operational period was September 22, 2017 due to variable flow rates in the CWTS following this date.

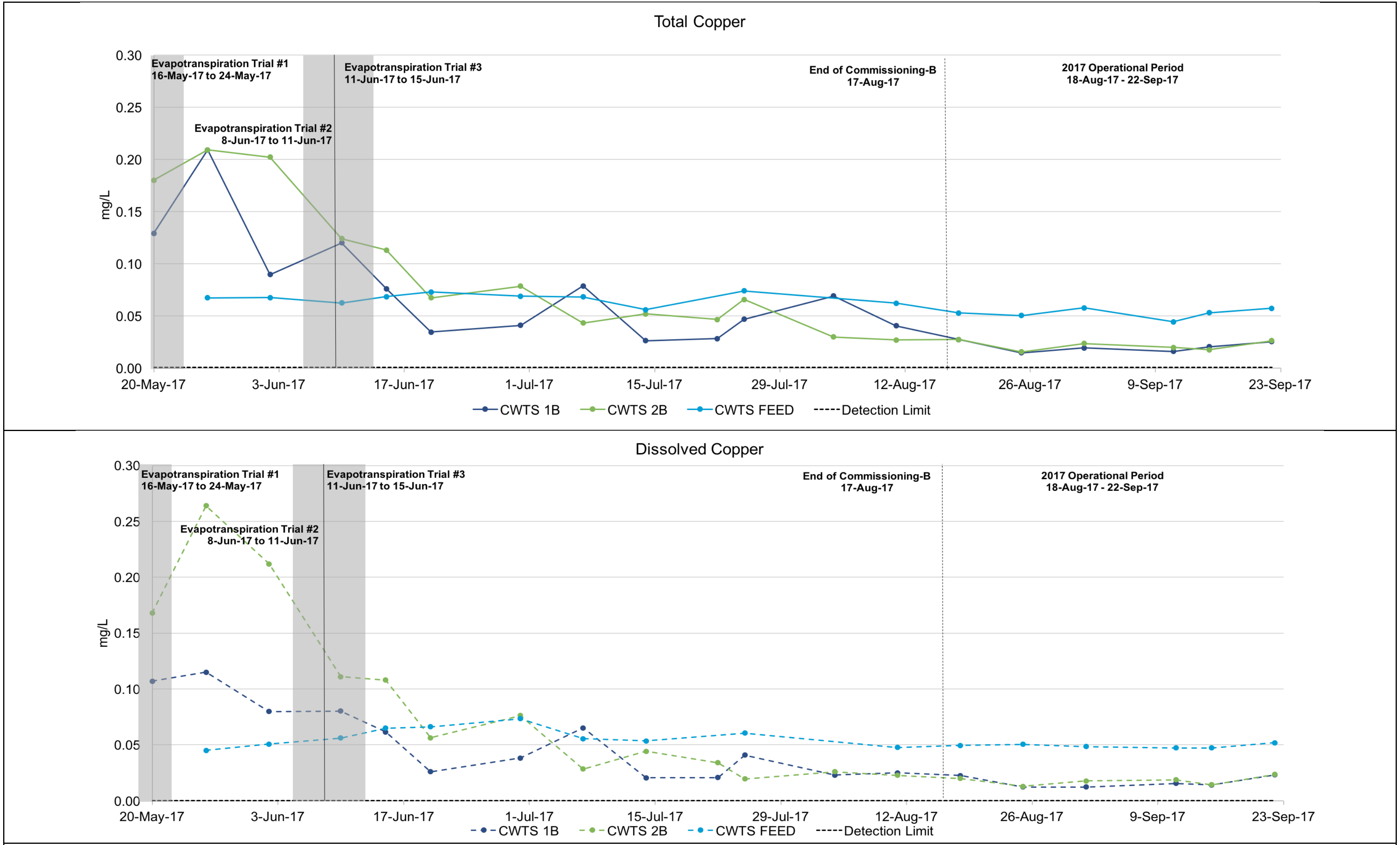
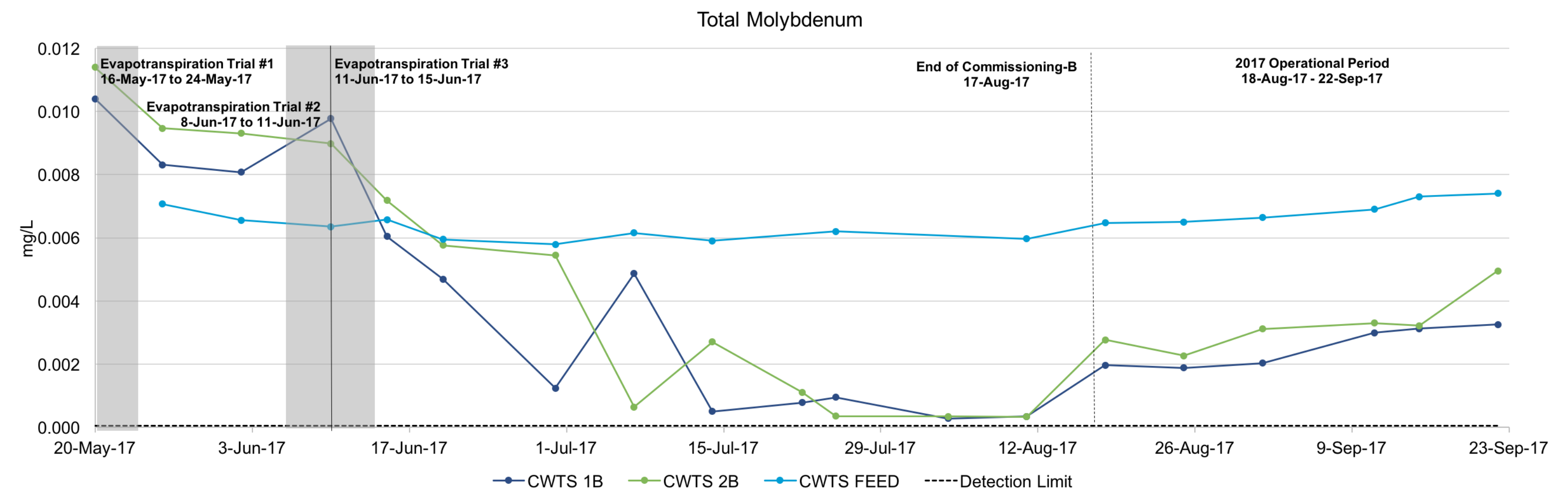


Figure B7 – Copper concentrations in the demonstration-scale wetland in 2017.
The evapotranspiration trials are indicated by grey shading and the duration in days. The ALS detection limit for dissolved and total copper is 0.0002 mg/L and 0.0005 mg/L, respectively. Flow to the CWTS was turned off on September 30, 2017. However, the last sampling date in the operational period was September 22, 2017 due to variable flow rates in the CWTS following this date.



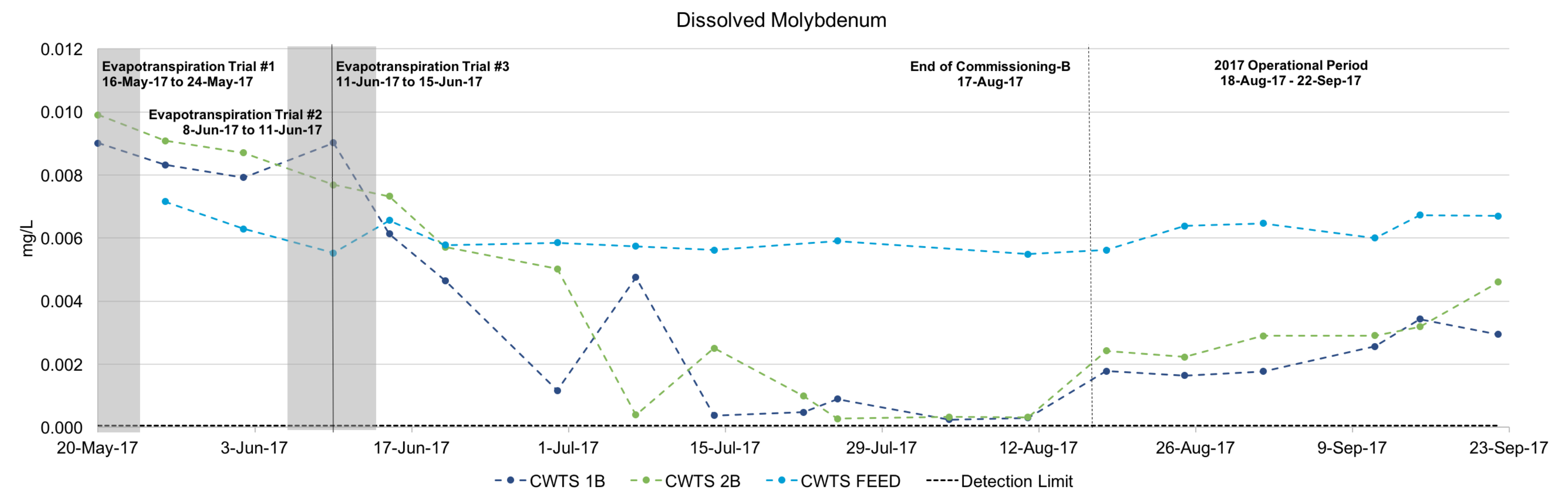


Figure B8 – Molybdenum concentrations in the demonstration-scale wetland in 2017.
The evapotranspiration trials are indicated by grey shading and the duration in days. The ALS detection limit for molybdenum is +/- 0.000050 mg/L. Flow to the CWTS was turned off on September 30, 2017. However, the last sampling date in the operational period was September 22, 2017 due to variable flow rates in the CWTS following this date.

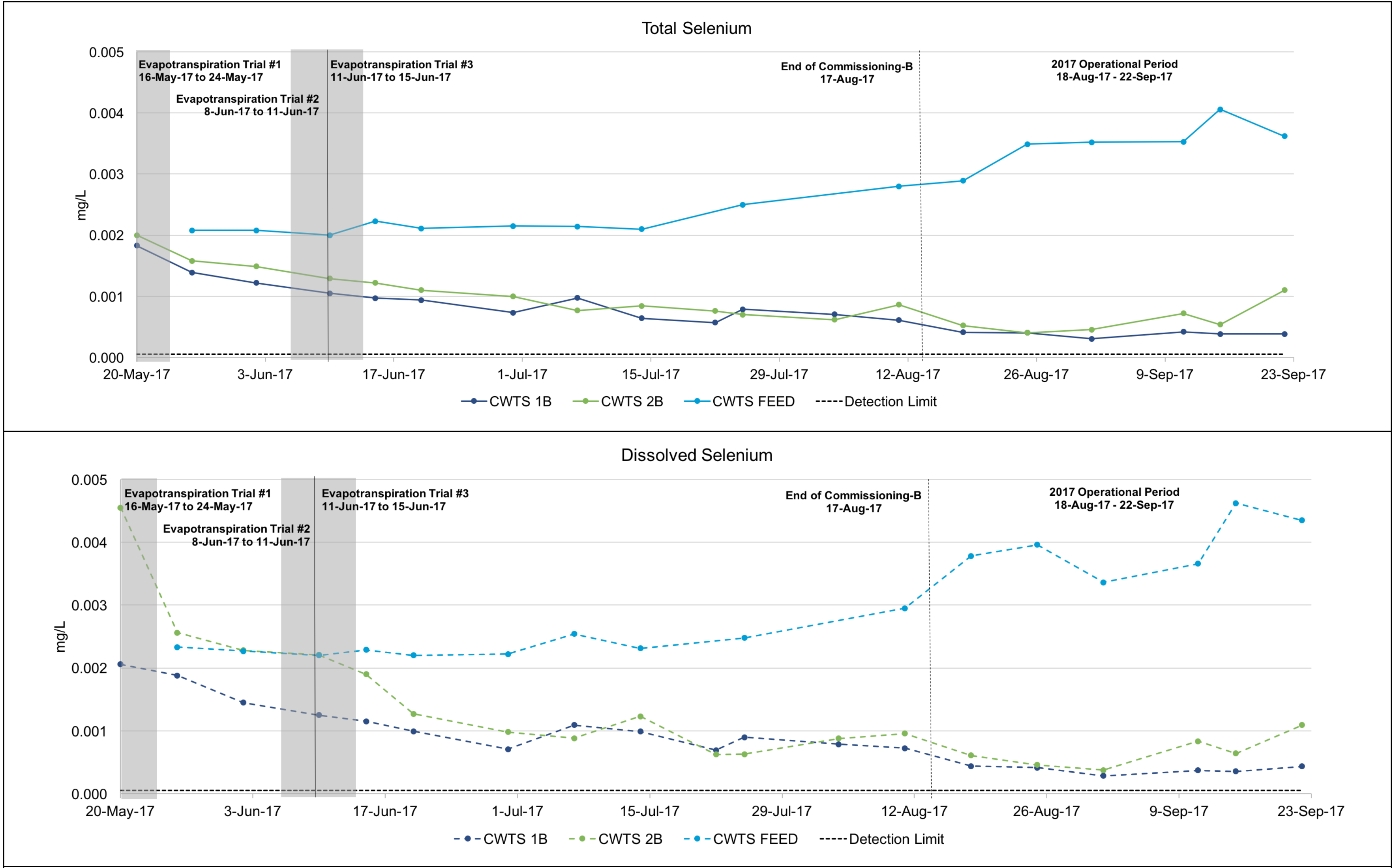


Figure B9 – Selenium concentrations in the demonstration-scale wetland in 2017.
The evapotranspiration trials are indicated by grey shading and the duration in days. The ALS detection limit for selenium is 0.00005 mg/L. Flow to the CWTS was turned off on September 30, 2017. However, the last sampling date in the operational period was September 22, 2017 due to variable flow rates in the CWTS following this date.

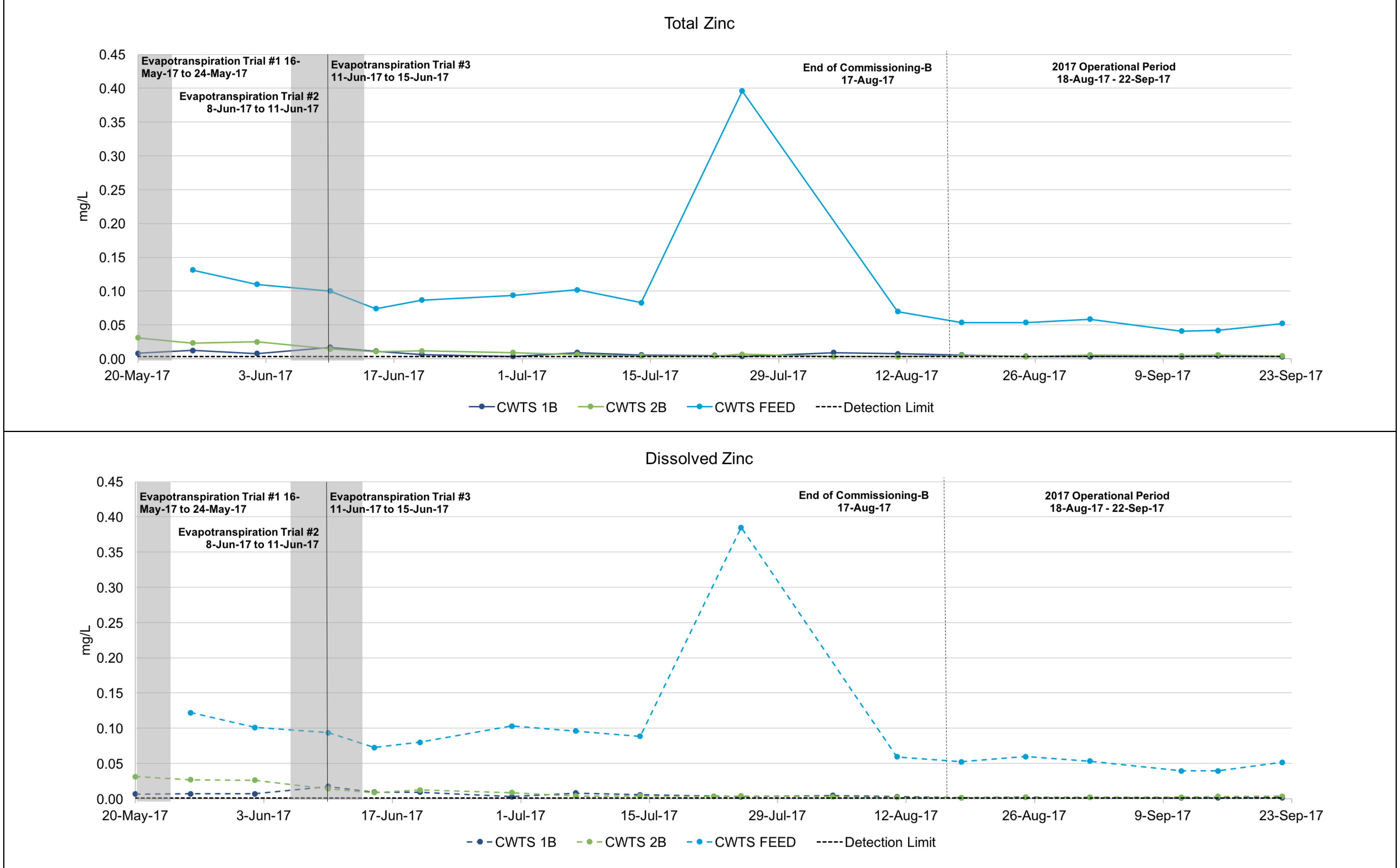


Figure B10 – Zinc concentrations in the demonstration-scale wetland in 2017.
The evapotranspiration trials are indicated by grey shading and the duration in days. The ALS detection limit for dissolved zinc is 0.001 mg/L. The detection limit for total zinc is 0.003 mg/L. Flow to the CWTS was turned off on September 30, 2017. However, the last sampling date in the operational period was September 22, 2017 due to variable flow rates in the CWTS following this date.

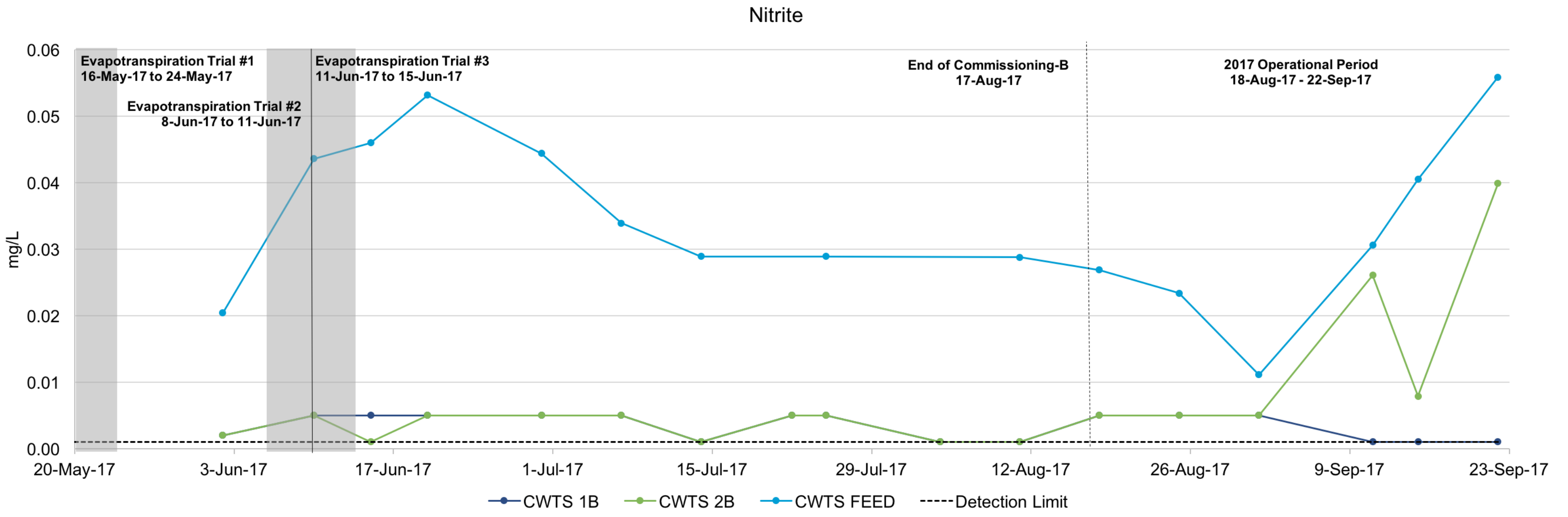


Figure B11 – Nitrite as N (NO_2) concentrations in the demonstration scale wetland in 2017.
The evapotranspiration trials are indicated by grey shading and the duration in days. The ALS detection limit for nitrite is 0.0010 mg/L. Flow to the CWTS was turned off on September 30, 2017. However, the last sampling date in the operational period was September 22, 2017 due to variable flow rates in the CWTS following this date.

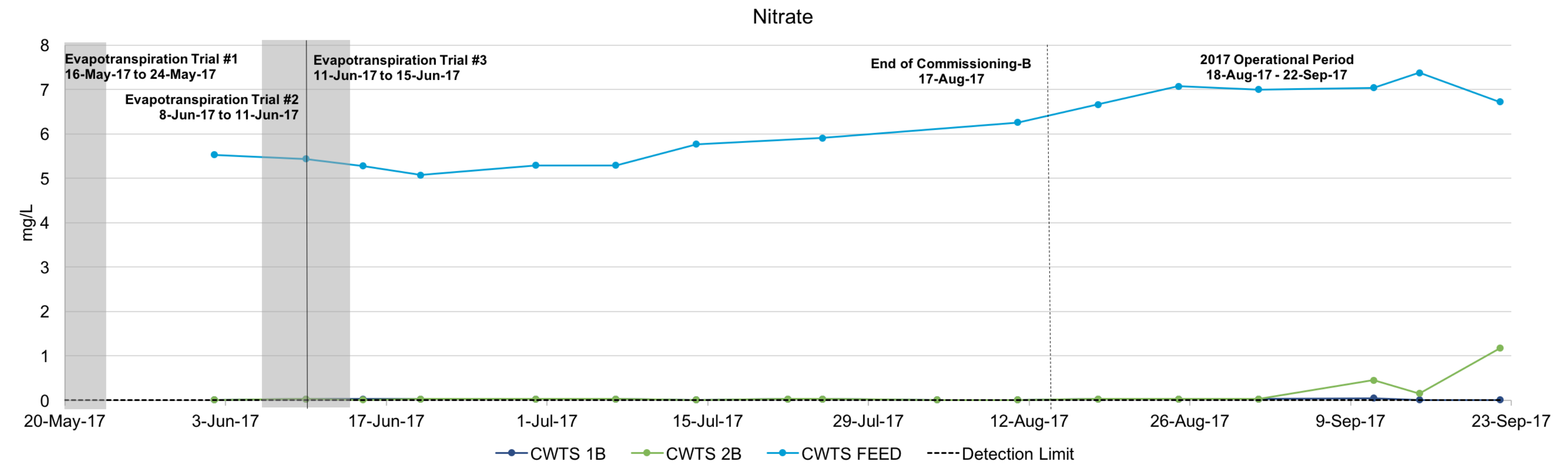


Figure B12 –Nitrate as N (NO_3) concentrations in the demonstration-scale wetland.
The evapotranspiration trials are indicated by grey shading and the duration in days. The ALS detection limit for nitrate is 0.0050 mg/L. Flow to the CWTS was turned off on September 30, 2017. However, the last sampling date in the operational period was September 22, 2017 due to variable flow rates in the CWTS following this date.

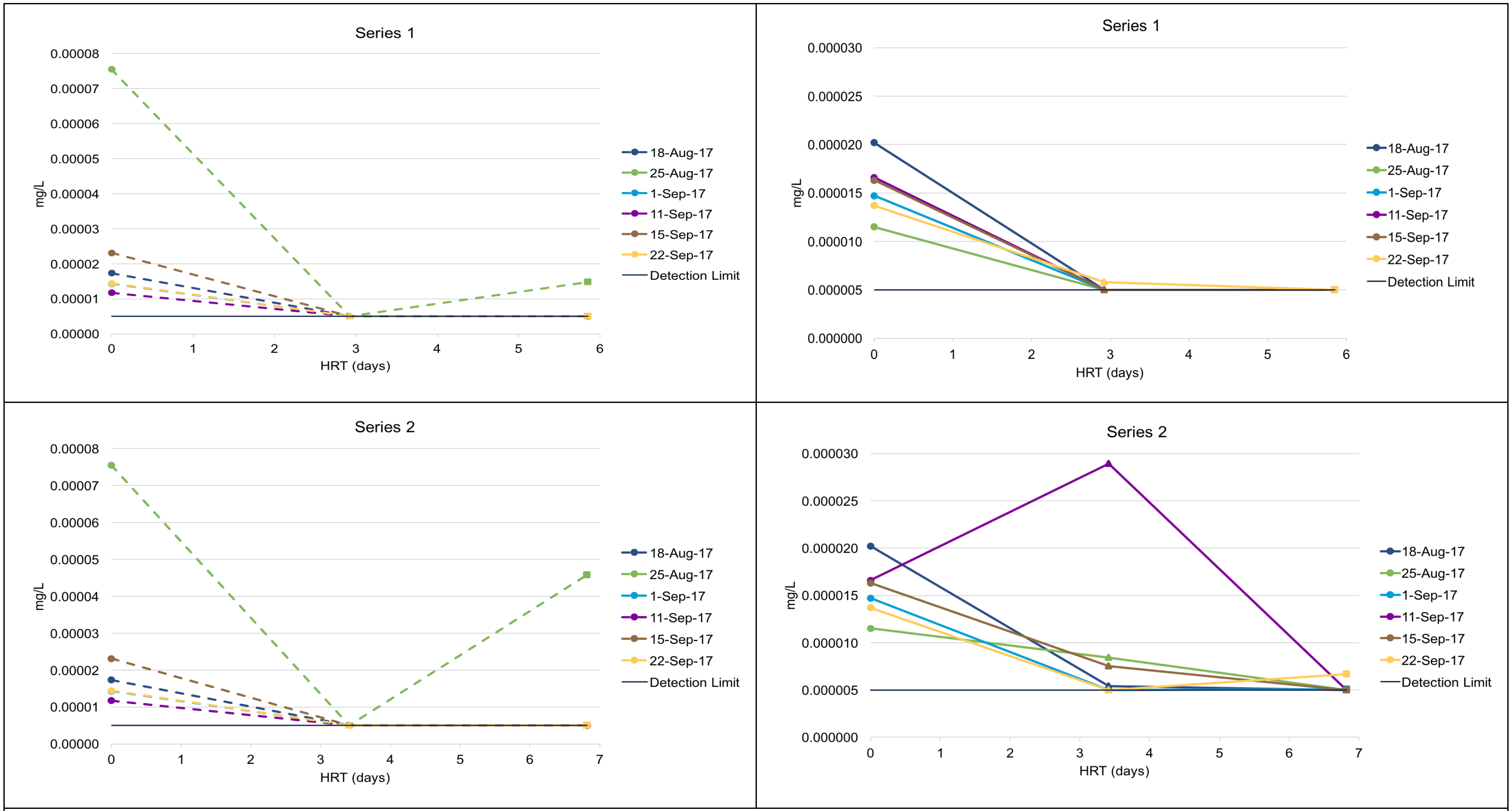


Figure B13 – Dissolved and total cadmium concentrations through series 1 and series 2.

Dashed lines represent dissolved concentrations (left) while solid lines represent total concentrations (right). Circles represent the feed water entering the wetland, diamonds represent the outflow of cell A and squares represent the outflow of cell B. The ALS detection limit for cadmium is 0.000005 mg/L.

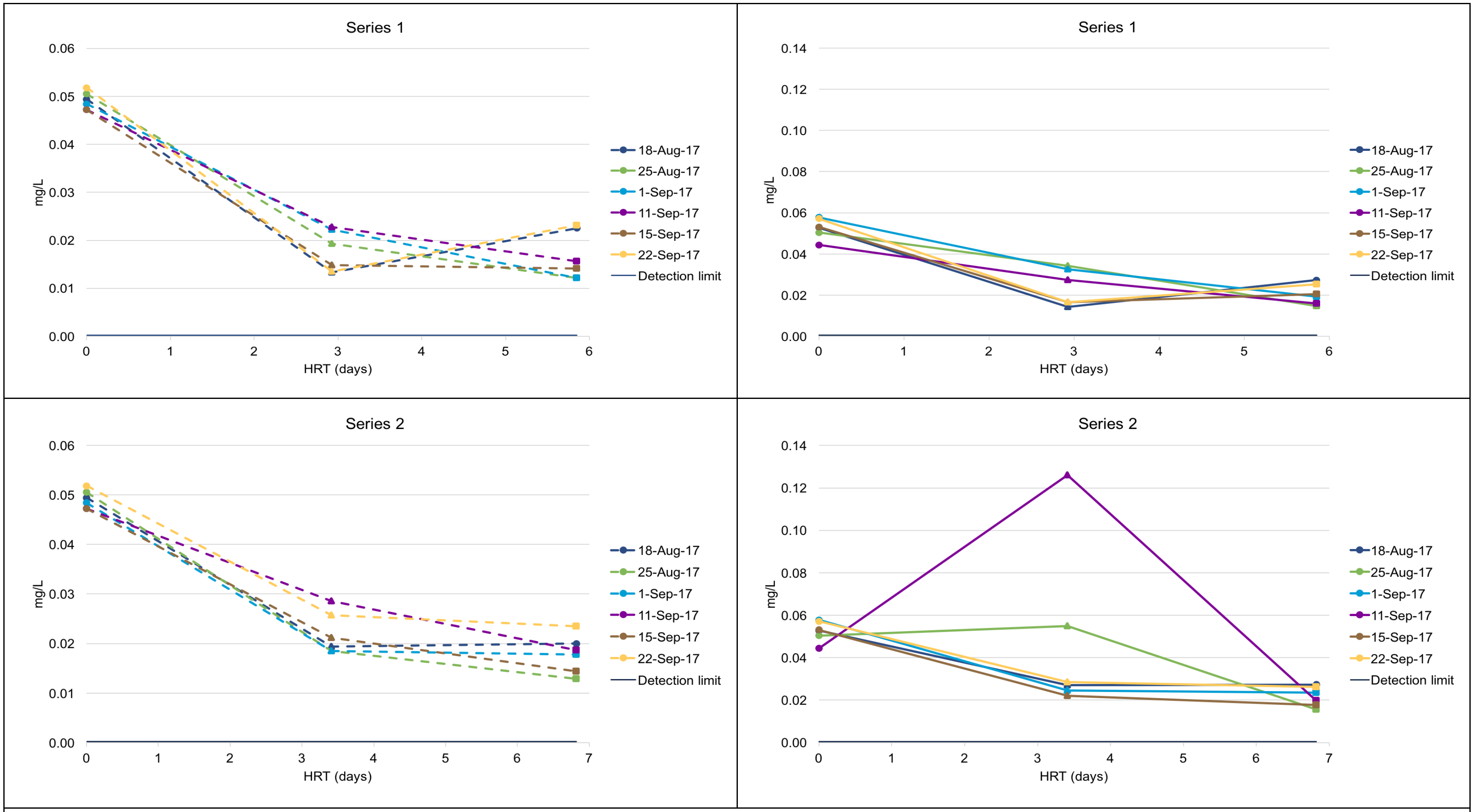


Figure B14 - Dissolved and total copper concentrations through series 1 and series 2.
Dashed lines represent dissolved concentrations (left) while solid lines represent total concentrations (right). Circles represent the feed water entering the wetland, diamonds represent the outflow of cell A and squares represent the outflow of cell B. The ALS detection limit for dissolved copper is 0.0002 mg/L. The detection limit for total copper is 0.0005 mg/L.

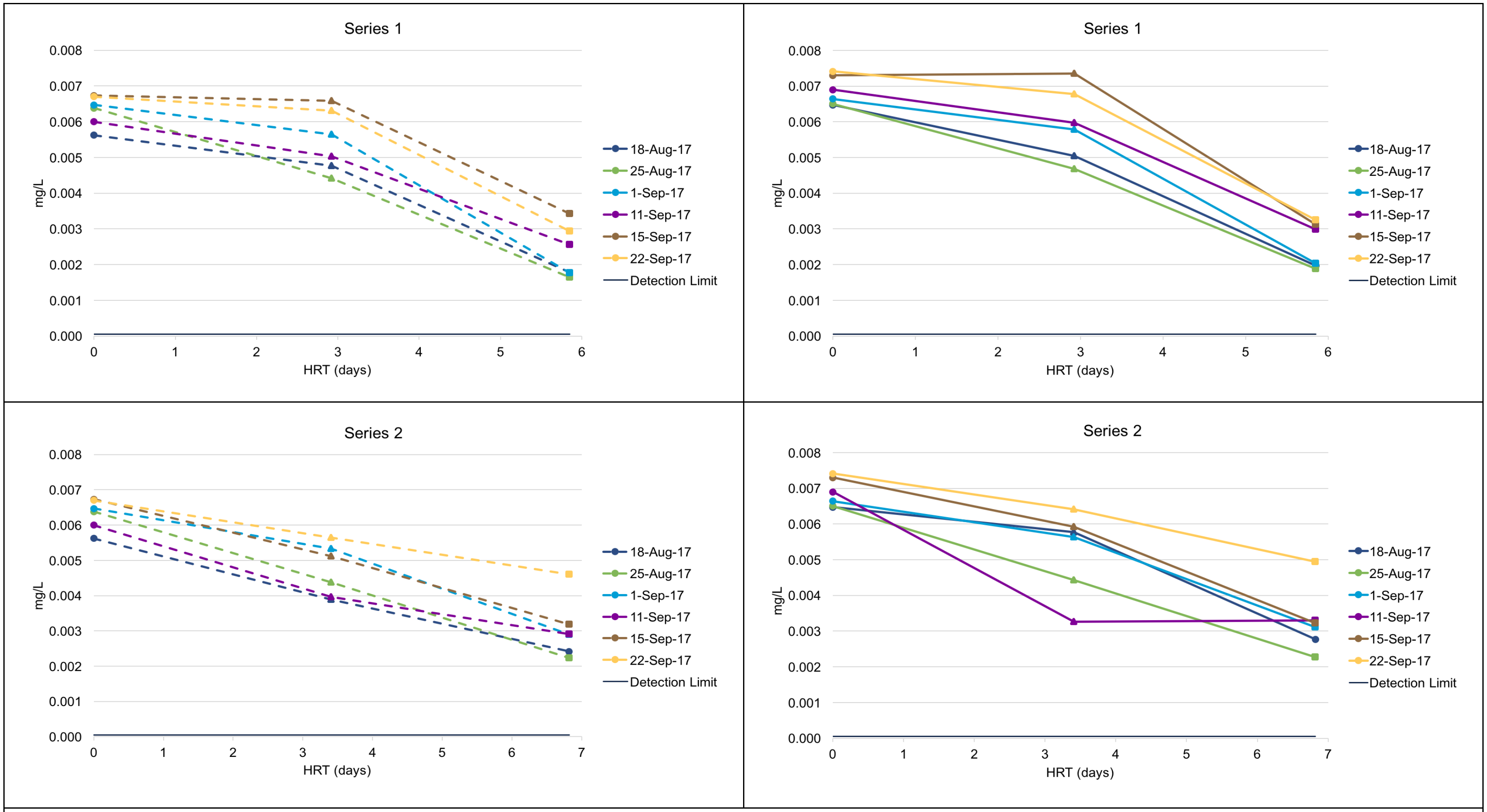


Figure B15 - Dissolved and total molybdenum concentrations through series 1 and series 2.
Dashed lines represent dissolved concentrations (left) while solid lines represent total concentrations (right). Circles represent the feed water entering the wetland, diamonds represent the outflow of cell A and squares represent the outflow of cell B. The ALS detection limit for molybdenum is 0.00005 mg/L.

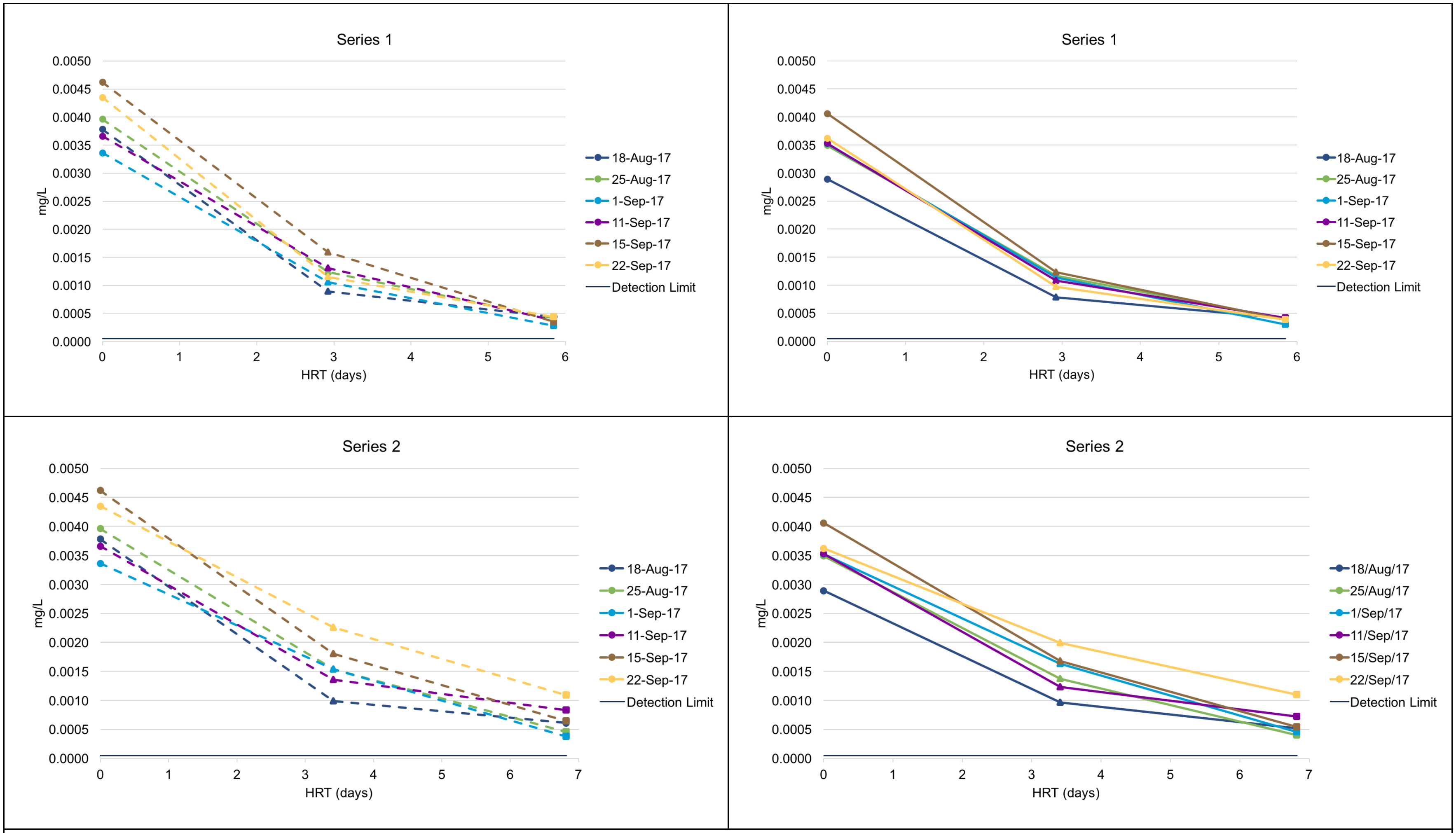


Figure B16 – Dissolved and total selenium concentrations through series 1 and series 2.
Dashed lines represent dissolved concentrations (left) while solid lines represent total concentrations (right). Circles represent the feed water entering the wetland, diamonds represent the outflow of cell A and squares represent the outflow of cell B. The ALS detection limit for selenium is 0.00005 mg/L.

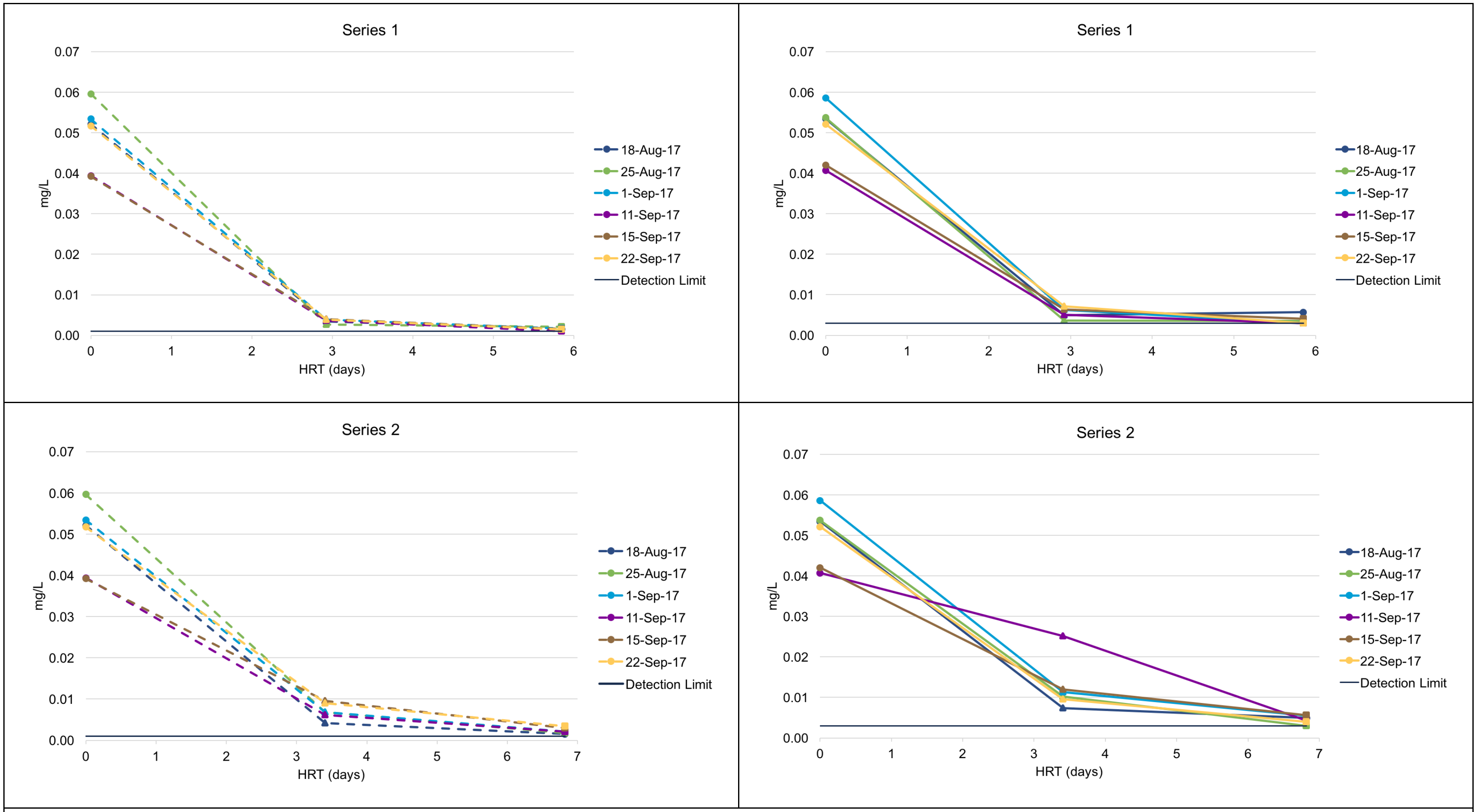


Figure B17 - Dissolved and total zinc concentrations through series 1 and series 2.
Dashed lines represent dissolved concentrations (left) while solid lines represent total concentrations (right). Circles represent the feed water entering the wetland, diamonds represent the outflow of cell A and squares represent the outflow of cell B. The ALS detection limit for dissolved zinc is 0.001 mg/L. The detection limit for total zinc is 0.003 mg/L.

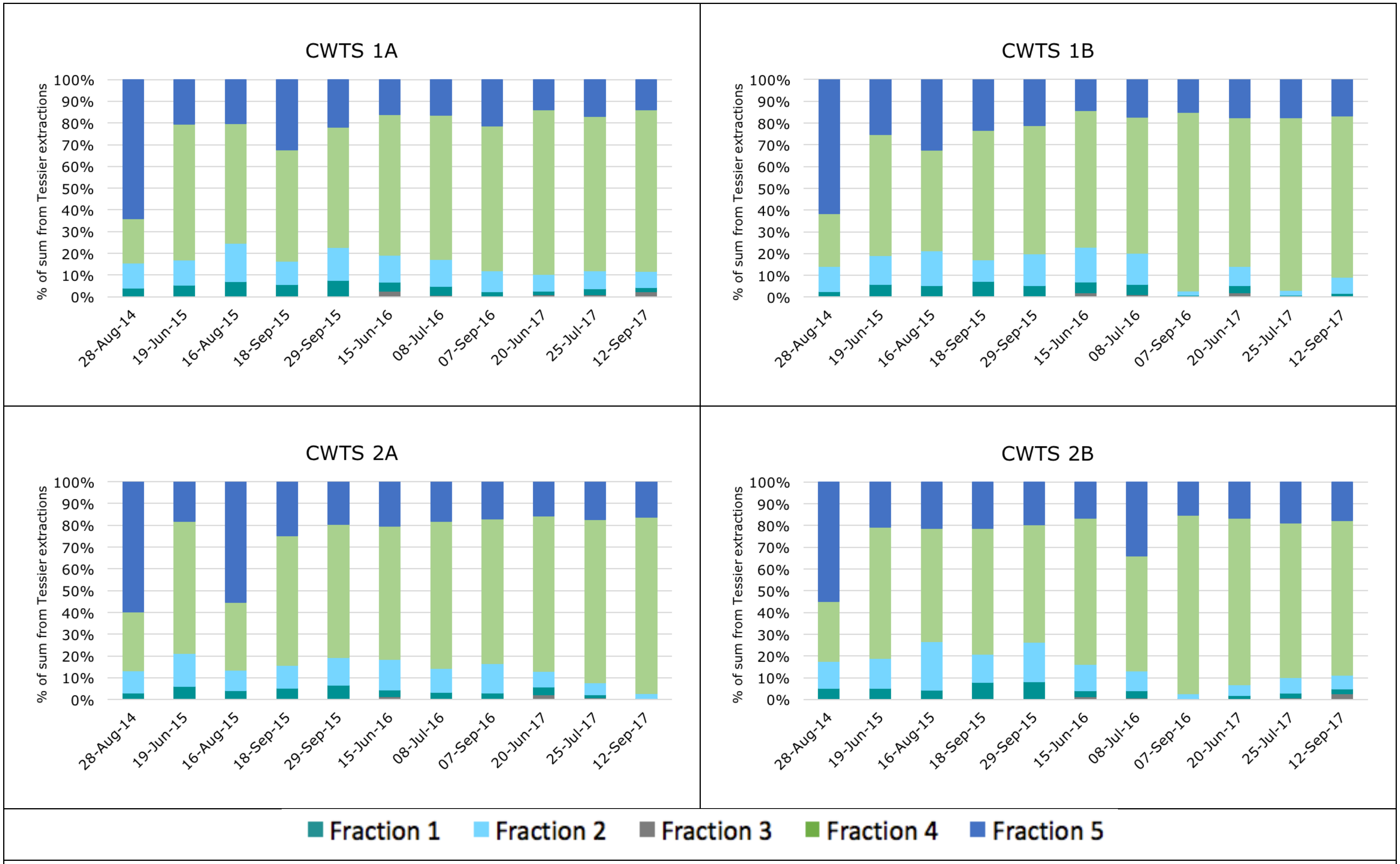


Figure B18 – Fraction distribution of copper expressed as percent over time (2014 – 2017).
Fractions are defined in Table B1.

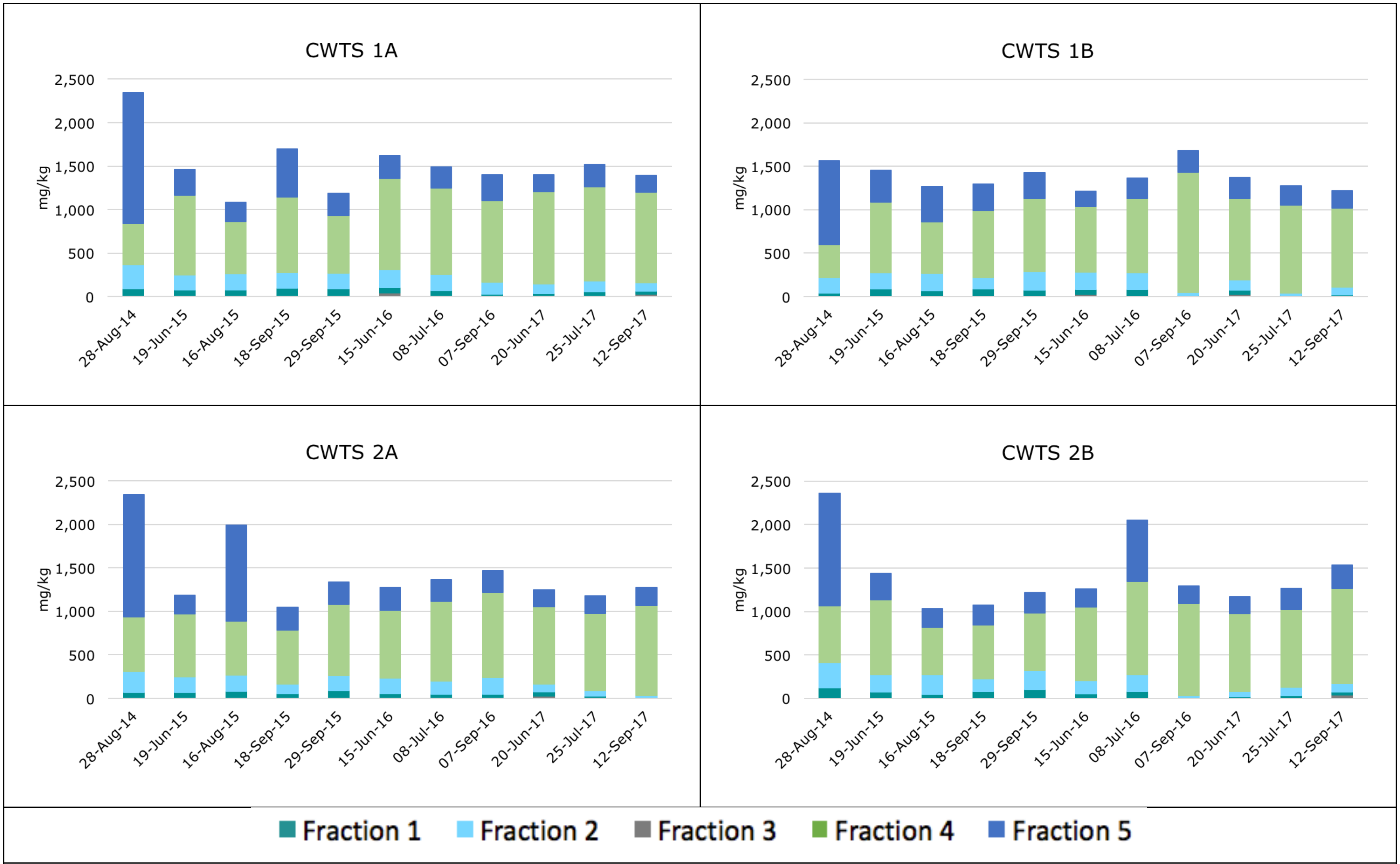


Figure B19 – Fraction distribution of copper expressed as mg/kg over time (2014 – 2017).
Fractions are defined in Table B1. The detection limit for copper is 0.50 mg/kg for all fractions.

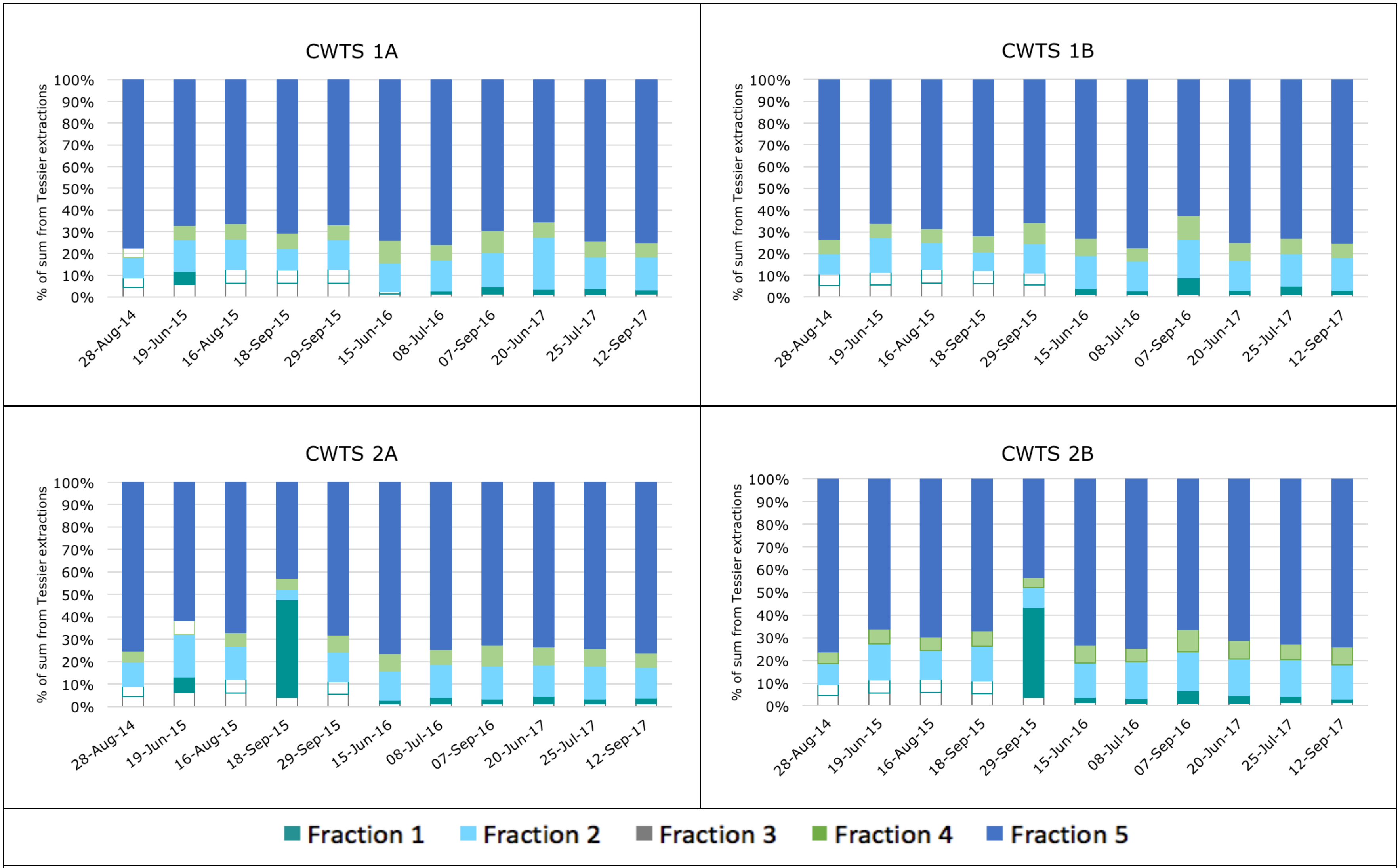


Figure B20 – Fraction distribution of zinc expressed as percent over time (2014 – 2017).
Unfilled areas are values at or below detection limits. Fractions are defined in Table B1.

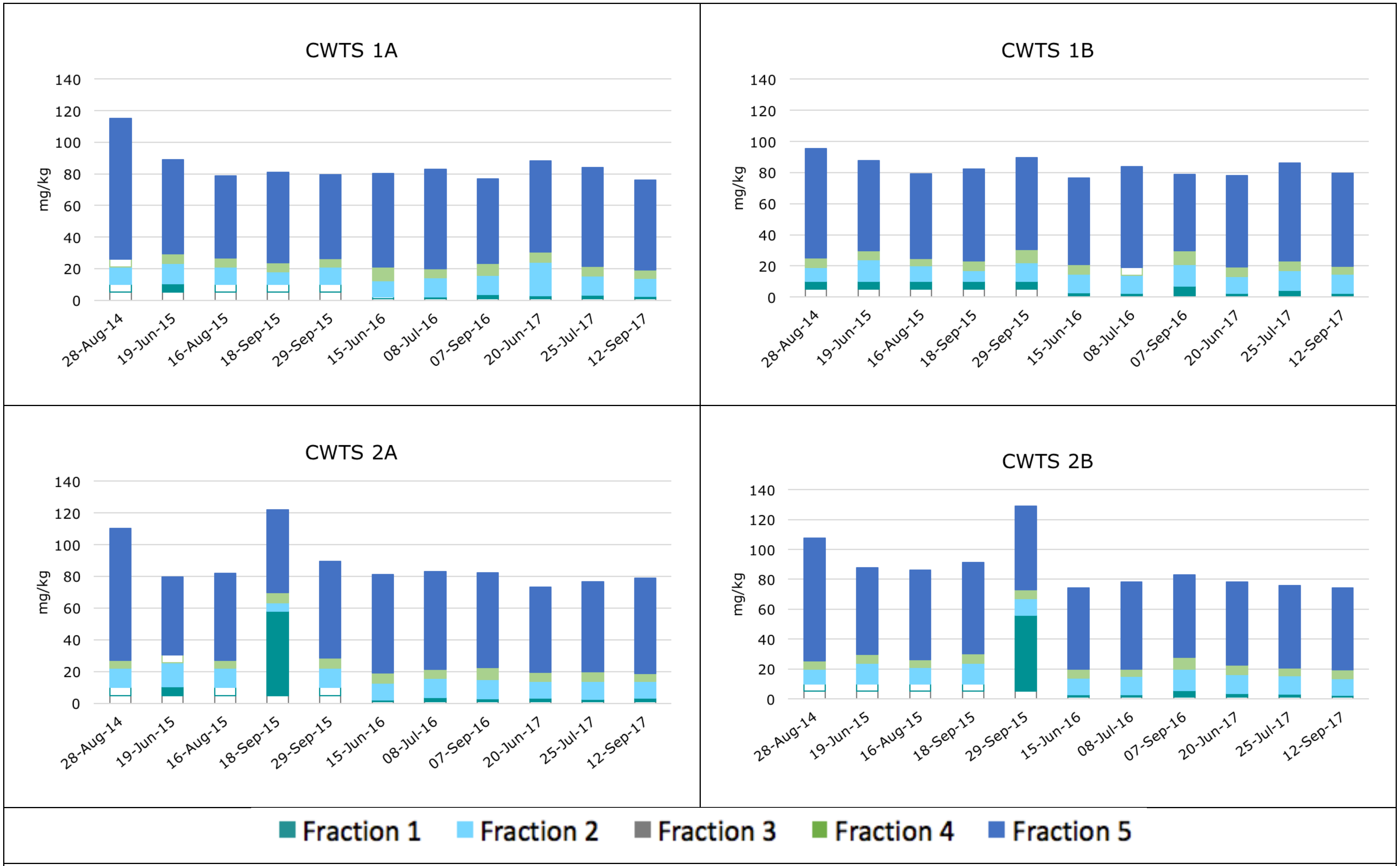


Figure B21 – Fraction distribution of zinc expressed as mg/kg over time (2014 – 2017).
A cells and B cells are on different y-axes. Unfilled areas are values at or below detection limits. Fractions are defined in Table B1. The detection limit for zinc is 1.0 mg/kg for all fractions.

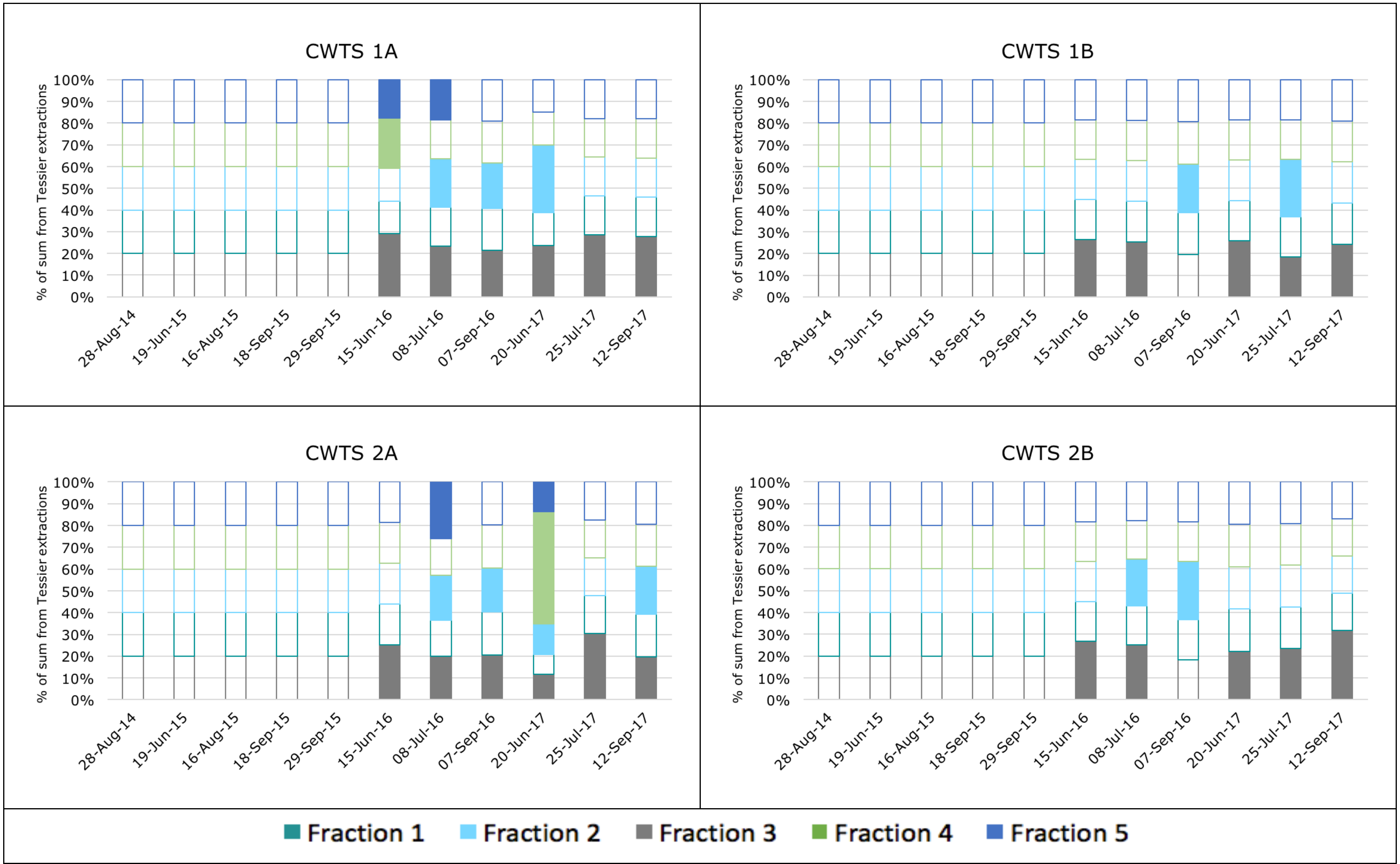


Figure B22 – Fraction distribution of cadmium expressed as percent over time (2014 – 2017).
Unfilled areas are values at or below detection limits. Fractions are defined in Table B1.

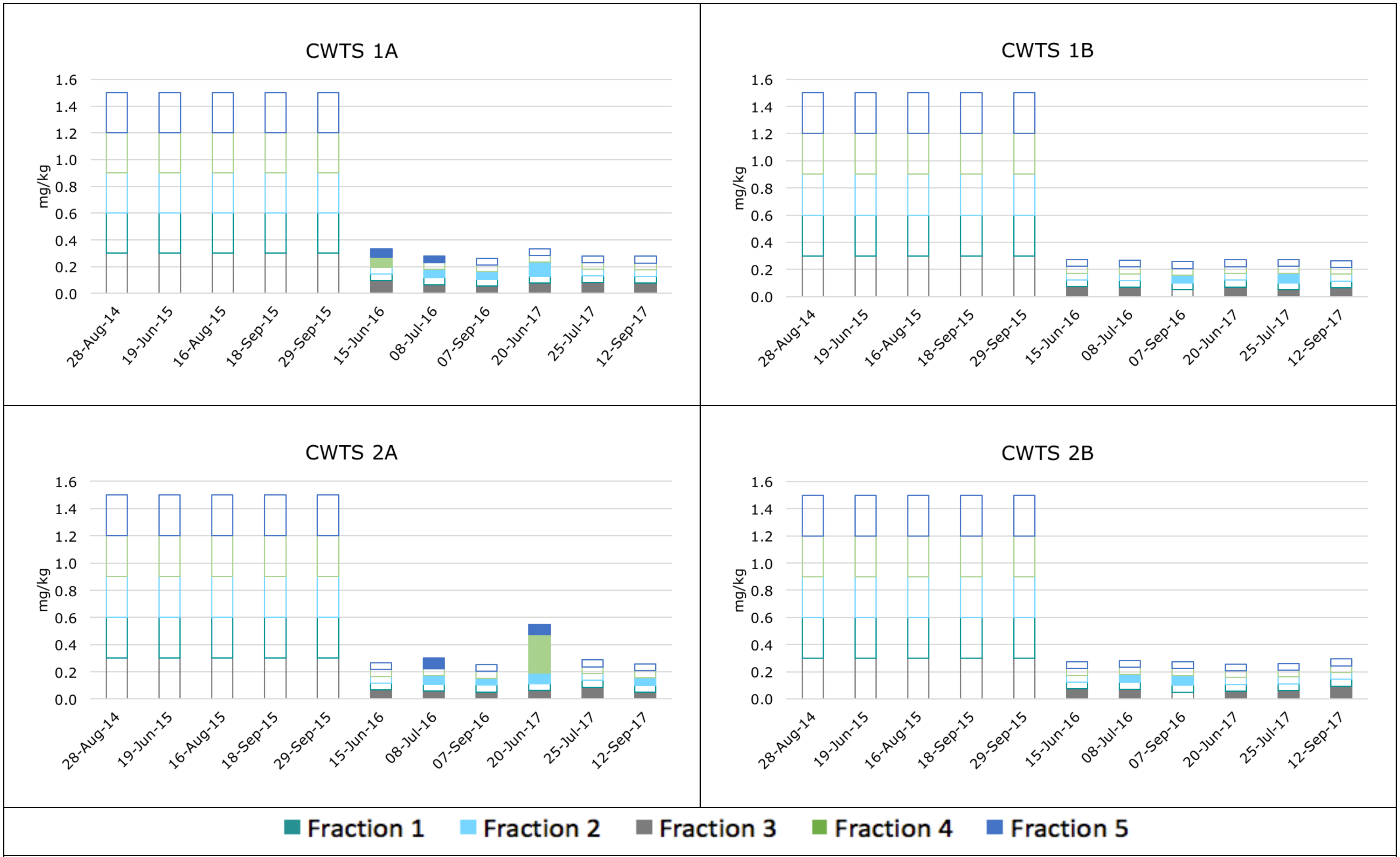


Figure B23 – Fraction distribution of cadmium expressed as mg/kg over time (2014 – 2017).
Unfilled areas are values at or below detection limits. Detection limits changed in 2016 and 2017, which is indicated by the smaller bars after 2015. The detection limit for cadmium in 2014 and 2015 was 0.30 mg/kg for all fractions. The detection limit for cadmium in 2016 and 2017 is 0.050 mg/kg for all fractions. Fractions are defined in Table B1.

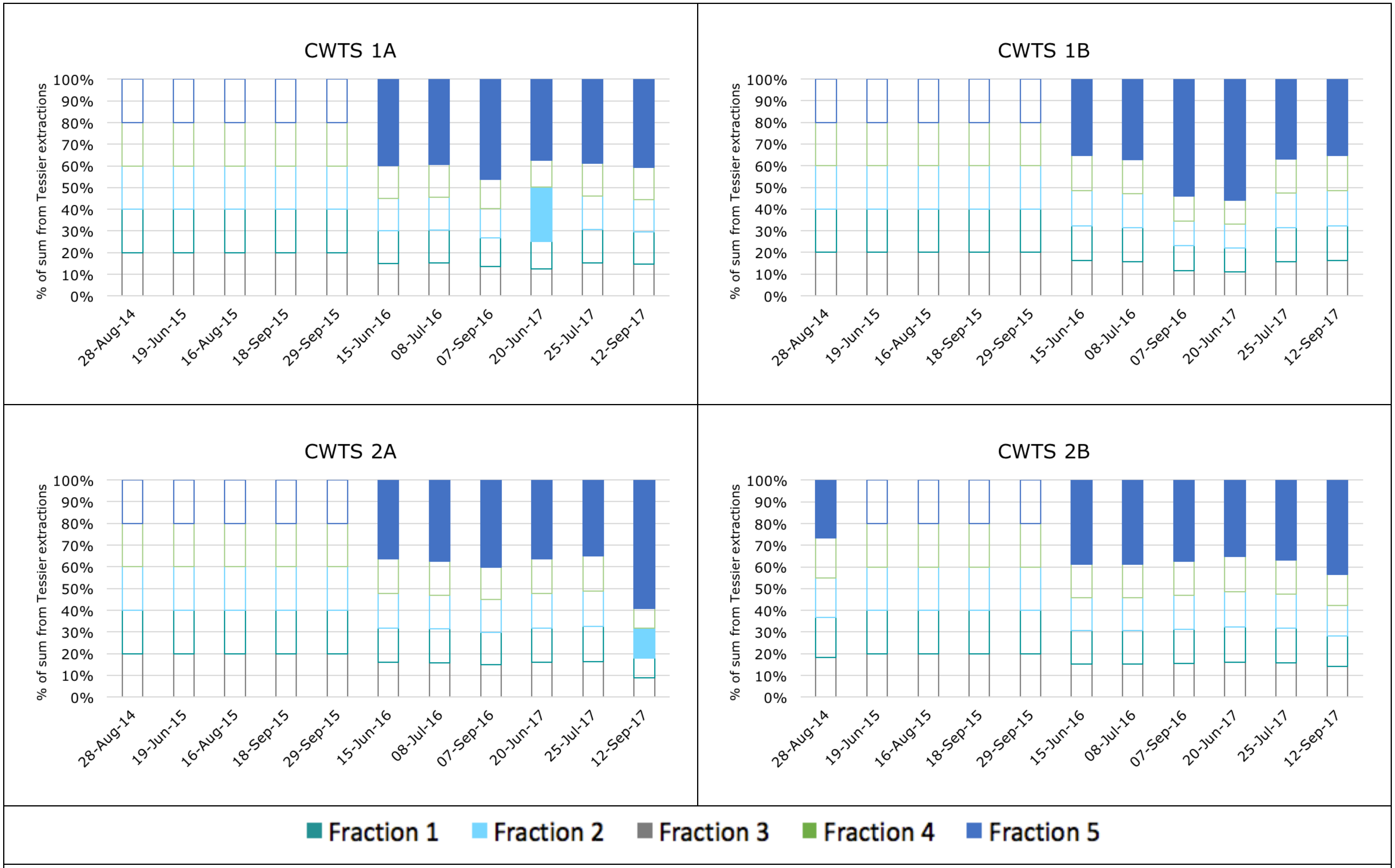


Figure B24 – Fraction distribution of molybdenum expressed as percent over time (2014 – 2017).
Unfilled areas are values at or below detection limits. Fractions are defined in Table B1.

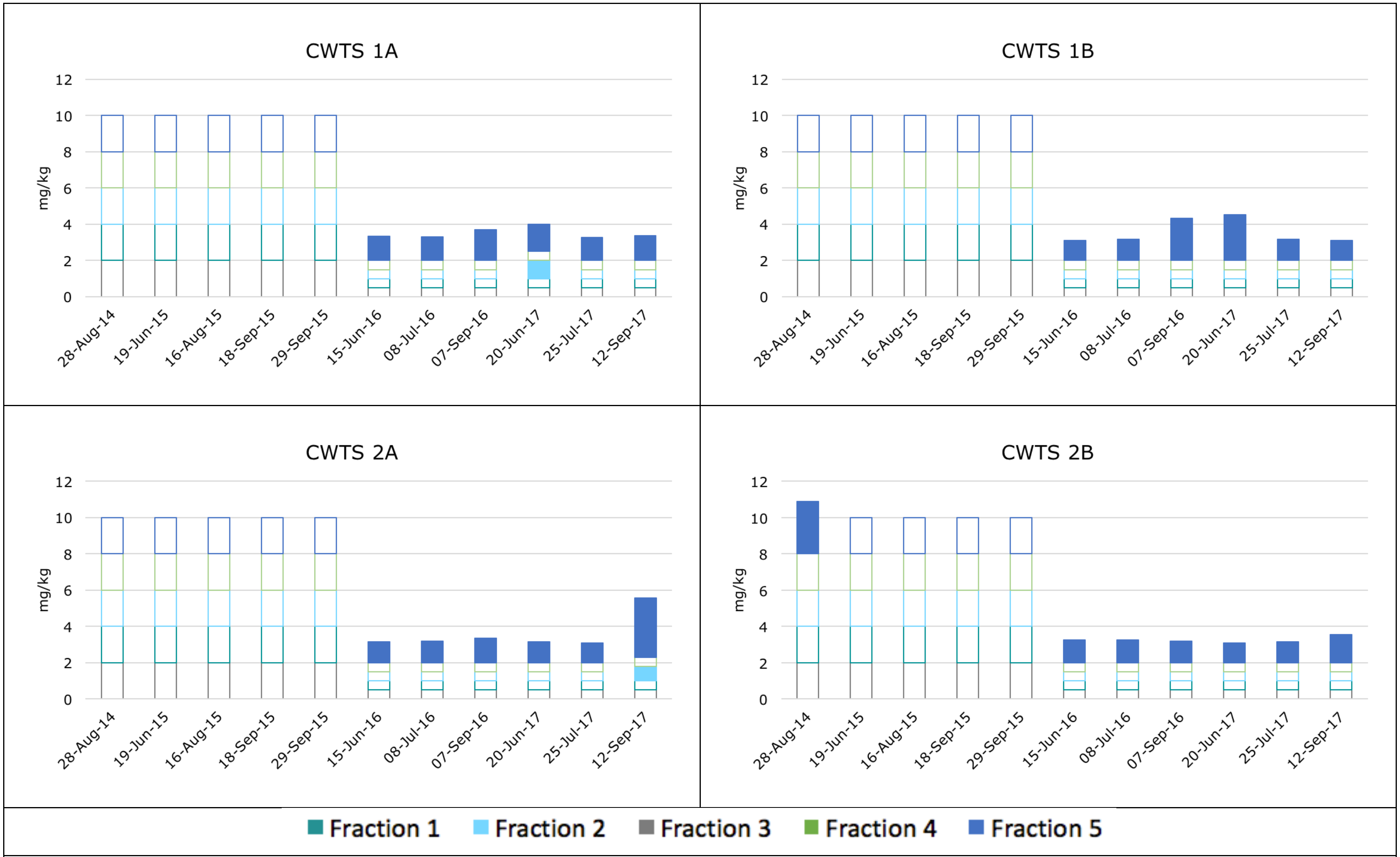


Figure B25 – Fraction distribution of molybdenum expressed as mg/kg over time (2014 – 2017).
Unfilled areas are values at or below detection limits. Fractions are defined in Table B1. Detection limits changed in 2016 and 2017, which is indicated by the smaller bars after 2015. The detection limit for molybdenum in 2014 and 2015 was 2.0 mg/kg for all fractions. The detection limit for molybdenum in 2016 and 2017 is 0.50 mg/kg for all fractions.

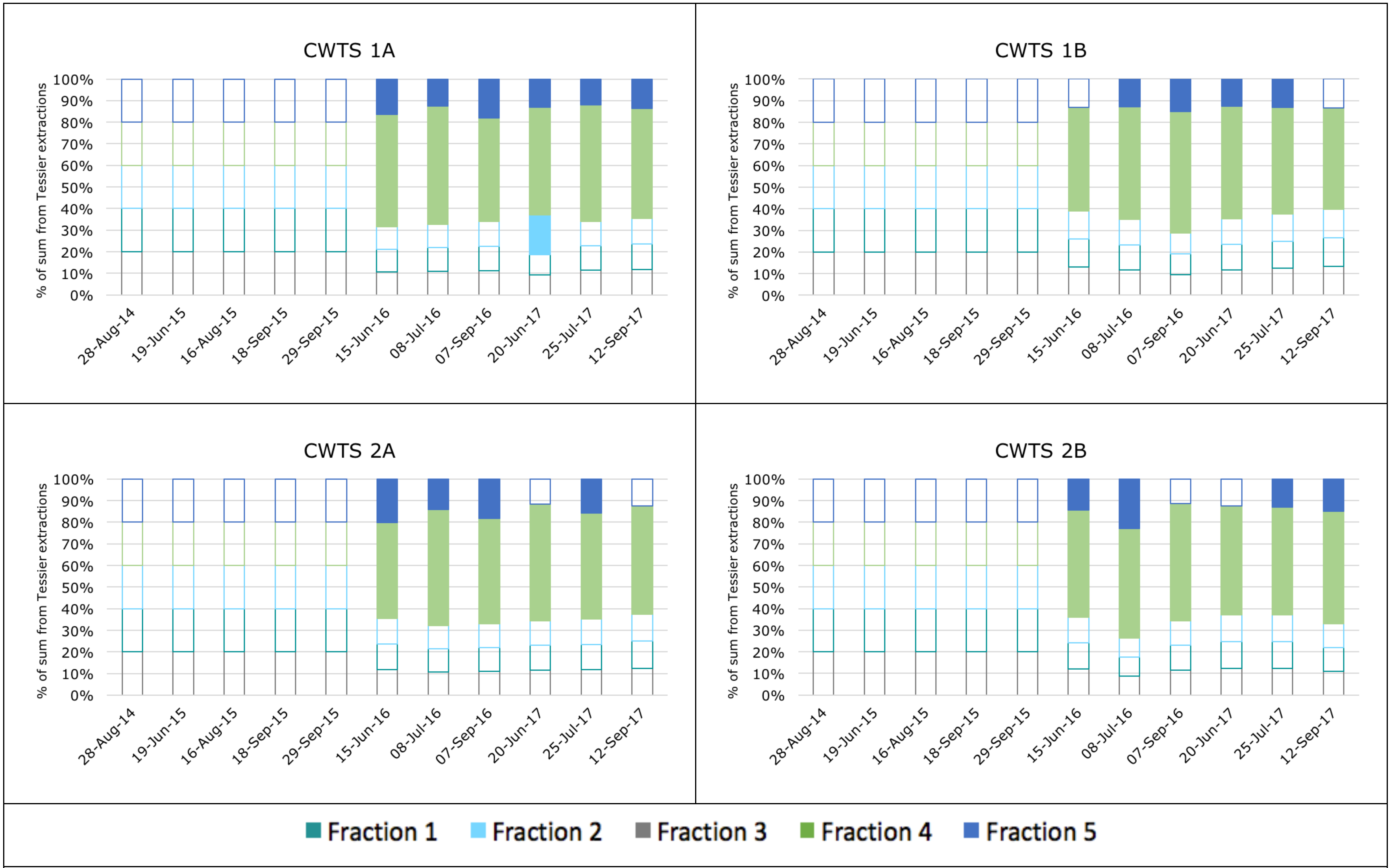


Figure B26 – Fraction distribution of selenium expressed as percent over time (2014 – 2017).
Unfilled areas are values at or below detection limits. Fractions are defined in Table B1.

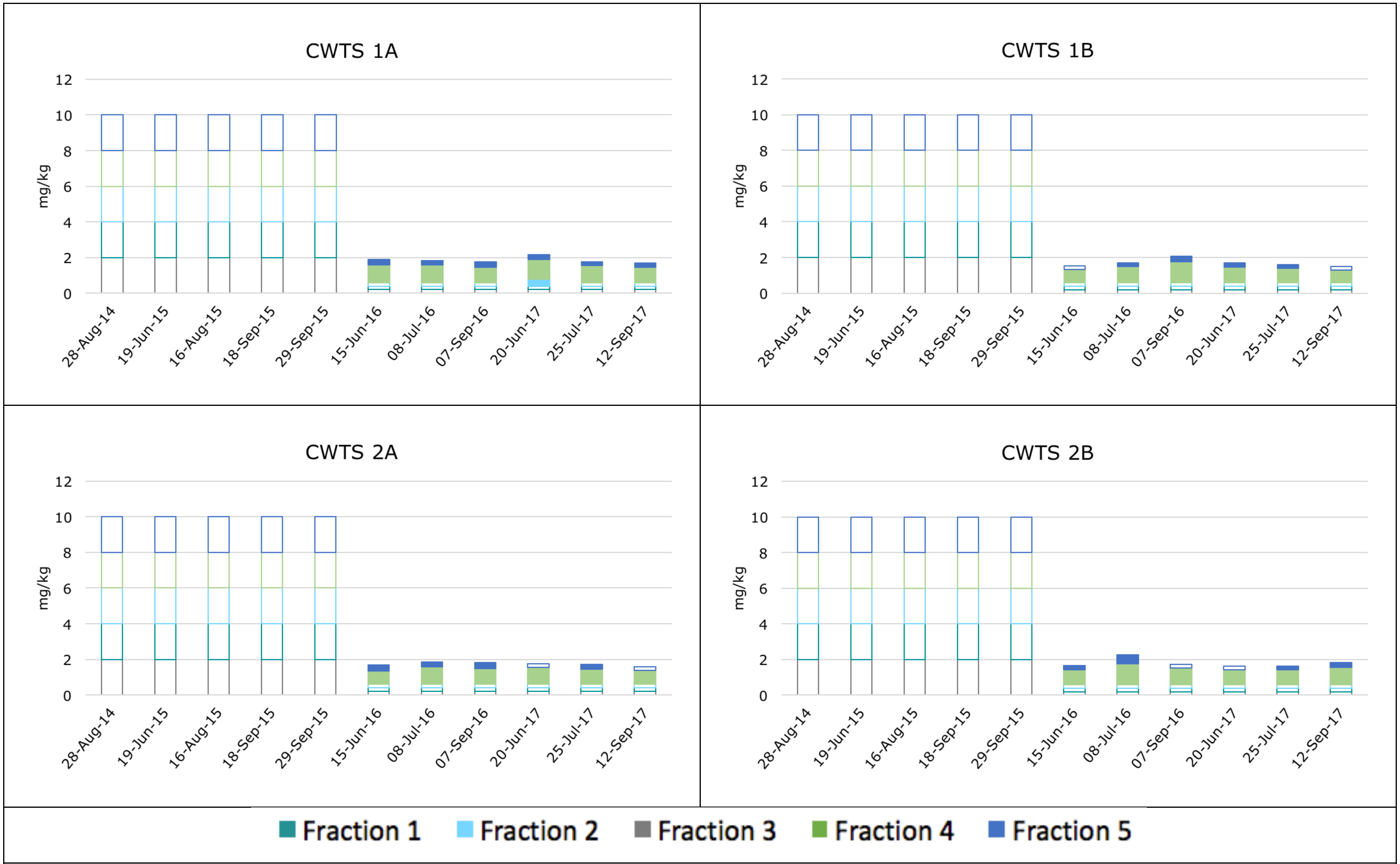


Figure B27 – Fraction distribution of selenium expressed as mg/kg over time (2014 – 2017).
Unfilled areas are values at or below detection limits. Detection limits changed in 2016 and 2017, which is indicated by the smaller bars after 2015. The detection limit for selenium in 2014 and 2015 was 2.0 mg/kg for all fractions. The detection limit for selenium in 2016 and 2017 is 0.20 mg/kg for all fractions. Fractions are defined in Table B1.

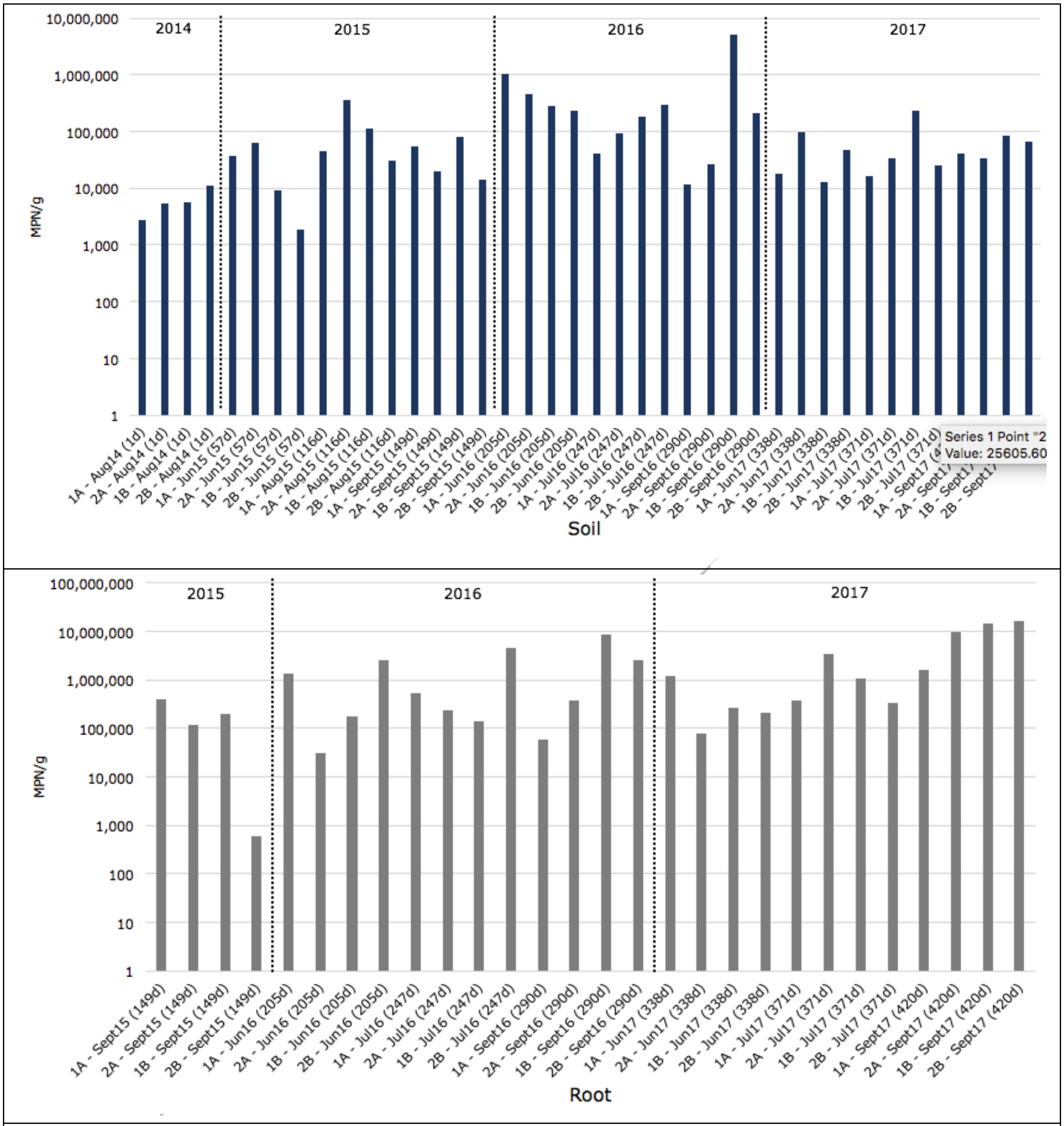


Figure B28 – Inferred abundance of sulphide-producing bacteria in soil (top) and roots (bottom) of the demonstration-scale CWTS.
Inferred abundance is calculated based on a combination of genetic and growth-based data. Shallow soil (0-5 cm); deep soil (10-20 cm); soil at 0d was that used for construction of CWTS. The root y-axis is different from the soil y-axis as the inferred abundance is much higher in root.

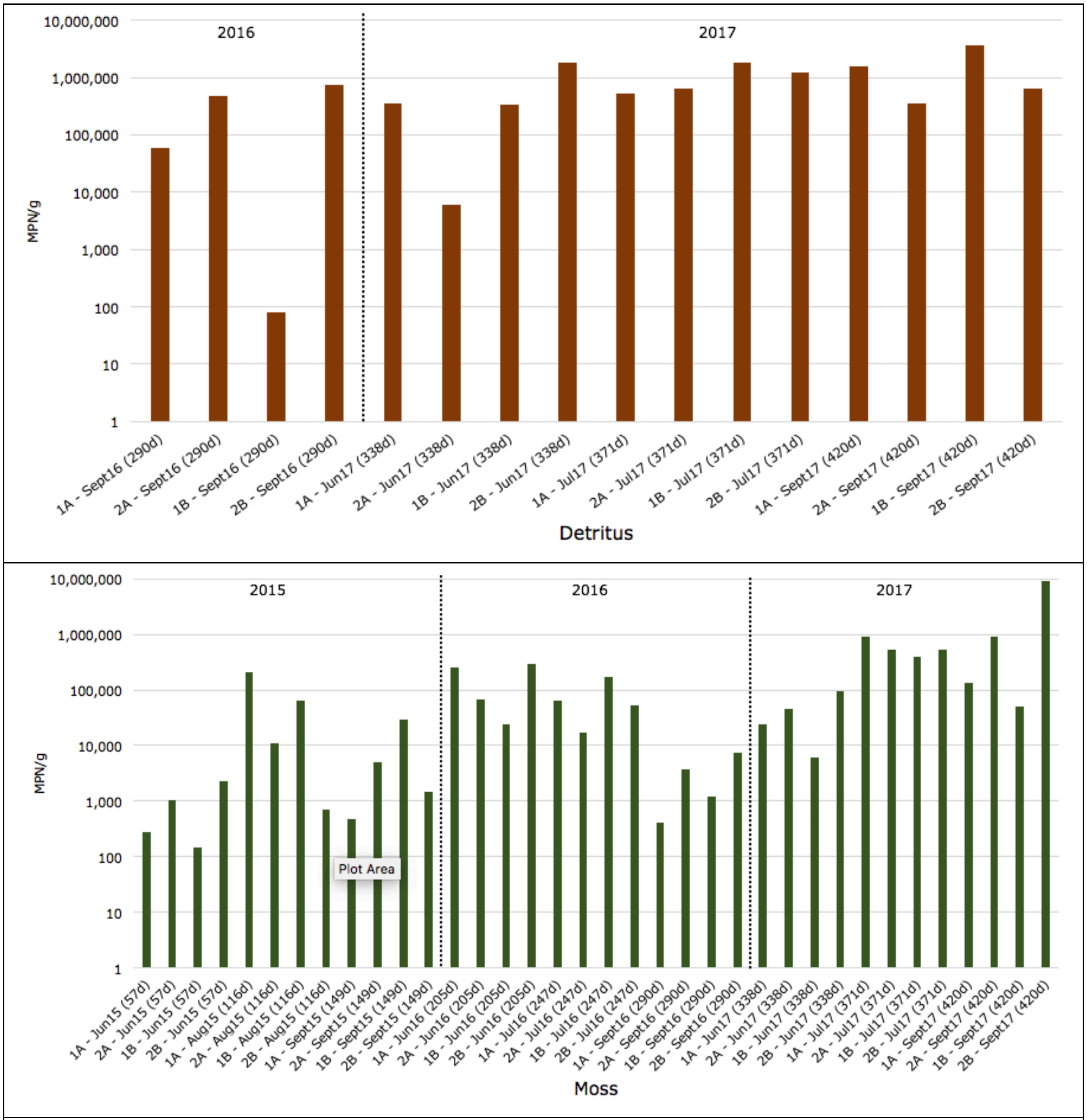


Figure B29 – Inferred abundance of sulphide-producing bacteria in detritus (top) and moss (bottom) of the demonstration-scale CWTS.
Inferred abundance is calculated based on a combination of genetic and growth-based data. Shallow soil (0-5 cm); deep soil (10-20 cm); soil at 0d was that used for construction of CWTS.

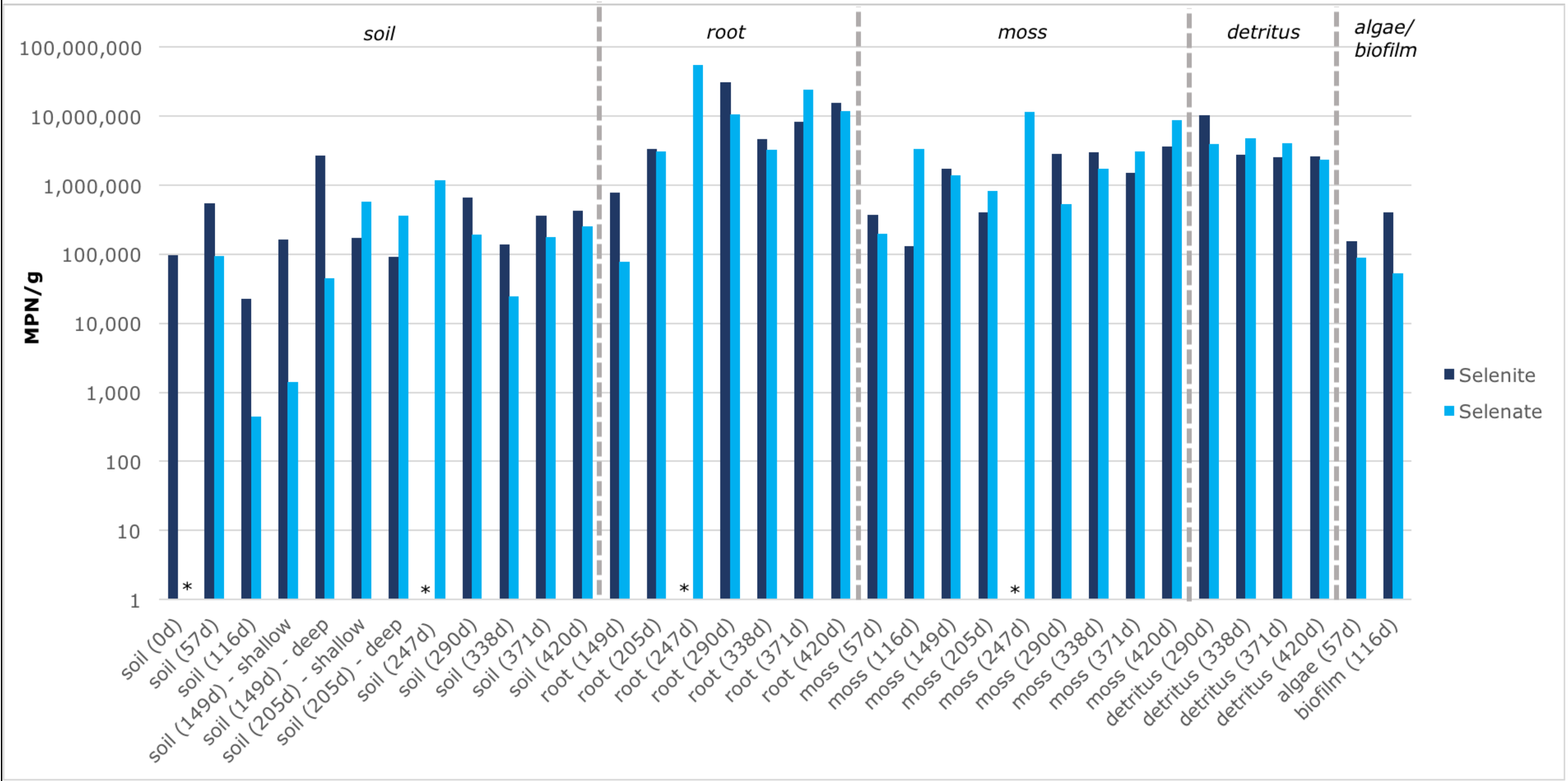


Figure B30 – Abundance of selenite- and selenate-reducing organisms in various CWTS sample types over time.

Shallow soil (0-5 cm); deep soil (10-20 cm); soil at 0d was that used for construction of CWTS. Organics material was added to the CWTS after day 236.

Appendix C

Table C1 - Schedule of work and activities for demonstration-scale CWTS

Item	Date	Activities	Actual
Construction	June 1-14 2014	Identify potential location for demonstration scale CWTS (Contango site visit – 1 scientist)	Completed
	June - July 2014	Engineering and geotechnical (Minto)	Completed
	July 2014	Construction (Minto)	Completed
	August 2014	Planting and bringing system online (Contango site visit – 1 scientist, 1 technologist), coordinate for local students to assist	Completed (no students available, brought 2 technologists)
Commissioning	2014	Acclimation and maturation at constant flow rate, ~20 hr HRT	Completed
		September - Contango site visit/checkup (1 technologist, 1 scientist)	Did not occur because construction was last week of August
	2015	Continued commissioning. Operation at constant flow rate, ~20 hr HRT	Completed (at shorter HRT)
		Spring – Contango site visit/checkup (1 technologist, 1 scientist), includes micro sampling	Completed
		Summer - Increase depth from 10 cm to 20 cm (1 technologist), includes micro sampling	Completed (scientist)
		Fall – Contango site visit/checkup (1 technologist), includes micro sampling	Completed (scientist)
	2016	Minto to add sandbags prior to first site visit and begin W15 creek monitoring	Completed May/June 2016
		Spring – Contango site visit (1 scientist, 1 technologist), includes microbial sampling and tasks outlined in Table 5 of report. HRT tracer study completed, outlined in section 7 of report.	Completed June 2016
		Summer - Contango site visit/checkup (1 scientist, 1 technologist), includes microbial sampling and tasks outlined in Table 5 of report. Evapotranspiration study completed as outlined in section 9 of report. Organics were added to the CWTS as outlined in section 5.1 of report.	Completed July 2016
		Fall - Contango site visit/checkup (1 technologist), includes microbial sampling and tasks outlined in Table 5 of report	Completed September 2016

	2017	Continued commissioning operations at constant flow rate.	Completed May 2017
		Two evapotranspiration studies were completed	May/June 2017
		Spring – Contango site visit (1 scientist, 1 technologist), includes microbial sampling and tasks outlined in Appendix A of report. Completed HRT tracer study. Sample for AVS to assess if the added organics are having the desired effect.	Completed June 2017
		Summer - Contango site visit/checkup (1 scientist), includes microbial sampling and tasks outlined in Appendix A of report.	Completed July 2017. Seasonal water sampling was not completed due to flow interruptions. Seasonal water sampling was completed by Minto in August.
Commissioning		Minto added sandbags to outflows of CWTS cells to increase water depth	August 2017
		Commissioning completed and beginning of operational period	Completed August 2017
Operations		Fall – Contango site visit/checkup (1 scientist), includes microbial sampling and tasks outlined in Table 5 of report.	Completed by Minto, after being taught microbial sampling by Contango. No site visit needed by Contango.
		Monitor soil redox. Determine when it consistently reaches targeted range.	Completed throughout 2017
Performance monitoring	2018	Fluctuate flow rates, based on expected amount of water for full-scale wetland (scaled to size). Evaluate performance of wetland at different key periods.	Throughout 2018,
Operations		Develop a flow rate schedule, sampling plan, and aphid control and monitoring plan for 2018	March, 2018
		Start water flow to CWTS; add sand bags on top of existing sandbags and to edges and end of CWTS to increase water depth to ~20 cm; aphid control using more powerful Insecticide on a routine schedule	April/May 2018

		Spring – Contango site visit; monitor for presence of aphids, collect one bag of *C. aquatilis* and one bag of polyester filter foam from each CWTS cell	May/June 2018
		Summer – Contango site visit; conduct a vegetation plot harvest and assessment of biomass produced	July/August 2018
		Conduct evapotranspiration study for warmer months	July/August 2018
		Fall – Contango site visit (if necessary), replanting if needed.	September 12, 2018
		2018 Update Report	December 2018
Reporting	2014-2018	Reporting will be performed annually, with verbal and/or emailed interim updates	On Schedule

[1] The commissioning-B period will continue in 2017 until the demonstration-scale CWTS performance is consistently achieving performance expectations.

Appendix A7

Minto Mine Constructed Wetland Treatment Research Program - Demonstration Scale 2018 Update

Appendix A – Methods

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A1. System Layout and Dimensions

The demonstration-scale CWTS includes two systems in parallel with two cells in each series and a final catchment basin that both systems flow into. Dimensions and construction details are available in the Minto Mine Constructed Wetland Treatment Research Program – Demonstration Scale (Contango, 2015). The two parallel systems serve as a replicate for data analysis, and as testing has progressed, the two systems have also allowed for comparison of different management techniques, such as the effect of iron addition on drought recovery in series 1.

A2. Soils Used in Construction

Soils used to construct the CWTS are described in the initial report that outlines construction (Contango, 2015). A brief summary is described in Appendix A of the Minto Constructed Wetland Treatment Research Program – Demonstration Scale 2017 Update (Contango, 2017b).

A3. Vegetation Used in Planting

The demonstration-scale CWTS was planted with *Carex aquatilis* (aquatic sedge) and aquatic mosses from the W10 area of the Minto Site. The plant selection and borrow source was previously determined through the site assessment (Contango, 2014). Five *C. aquatilis* plants were planted per square meter, with moss tied to stakes that outlined the 1 m x 1 m grid for planting (details provided in Contango, 2015).

A4. Water Source

The same water source was used for the demonstration-scale CWTS in 2018 as was used in 2017. A brief summary of the water source is described in Appendix A of the Minto Constructed Wetland Treatment Research Program – Demonstration Scale 2017 Update (Contango, 2017b).

A5. Flow Rates

Flow rates were consistent over the majority of the 2018 test period to evaluate the following conditions:

- A drought recovery period (May 15 – August 16, 2018); and
- An operational period (August 17-September 9, 2018).

Flow rates were increased near the end of the 2018 test period from September 10 – September 28, 2018, to evaluate the following operational period under faster flowing conditions, using a 5 day HRT.

The drought recovery period was stimulated by restricting flows to 0.37 gallons per minute (GPM) for series 1 and 0.31 GPM for series 2. Targeted flow rates were chosen based on the minimum range of the flow meter to simulate a drought recovery period and encourage reducing conditions. Flow rates, as well as the totalizer values, were periodically recorded throughout 2018 from the flow meters installed on the feed into the demonstration-scale CWTS, consistent with the 2017 flow rate measurement methodology (Contango, 2017b). The flow rates recorded by Minto Mine personnel represent the instantaneous flow rate at the flow meter while actual averaged flow rates were calculated based on the continuous totalizer values. The actual average flow rates calculated from continuous totalizer values from May 15, 2018 to September 10, 2018 were 0.34 GPM for series 1 and 0.29 GPM for series 2.

Once the drought recovery period was completed and the operations period was initiated on September 10, 2018, the targeted flow rates were increased to 0.52 GPM for series 1 and 0.36 GPM for series 2. Since the water levels were raised in each cell in spring 2018, the targeted flow rates were increased to achieve the same hydraulic retention time (HRT) as the 2017 target (5 days). However, the flow rates were unintentionally decreased back to 0.37 GPM for series 1 and 0.31 GPM for series 2 from September 14 to September 19, 2018. On September 19, 2018 the flow rate was returned to 0.52 GPM for series 1 and 0.36 GPM for series 2 and operated at that flow rate until the demonstration-scale CWTS was shut down for the year (September 28, 2018). Figure 1 in the main document of the Minto Constructed Wetland Treatment Research Program – Demonstration Scale 2018 Update illustrates the actual and targeted flow rates throughout 2018.

A6. Sampling and Analyses Methods

A6.1 Routine Monitoring of Explanatory Parameters

Explanatory parameters are quantifiable aspects of a CWTS environment that can be used to assess feasibility of treatment for a range of constituents, and therefore ‘explain’ the performance of a CWTS. These parameters and methods are described in Appendix A of the Minto Constructed Wetland Treatment Research Program – Demonstration Scale 2017 Update (Contango, 2017b).

A6.2 Water Sampling and Analyses

Water sampling occurred on a weekly basis from spring thaw in May 2018 to freeze up in September 2018, with additional parameters tested monthly. Frequencies and sampling parameters are outlined in Table A1. Grab samples were collected as described in Appendix A of the Minto Constructed Wetland Treatment Research Program – Demonstration Scale 2017 Update (Contango, 2017b).

Due to copper leaching from the CWTS substrates into the water in 2015, an additional sampling structure was designed to sample at the inflow, mid-point, and outflow of each cell. Details of this sampling method are described in Appendix A of the Minto Constructed Wetland Treatment Research Program – Demonstration Scale 2017 Update (Contango, 2017b). Water was sampled from the inflow, mid-point, and outflow of each cell at four timepoints in 2018 (June 22, July 8, August 2, and September 9, 2018).

Table A1 – Summary of 2018 water sampling analytical parameters, frequencies and locations.

Analytical Parameters	Frequency of Sampling	Sample Locations
Dissolved and total metals	Weekly	Outflow of each cell and feed
Ammonia		
Nitrate		
Nitrite		
Hardness ($CaCO_3$)		
Sulphate (SO_4)		
Flow rate	Weekly	Feed
pH, DO, ORP, Conductivity (in situ)	Weekly	All cells and feed
Anion Sum[1]	Monthly	Outflow of each cell and feed
Cation Sum[1]		
Ion Balance[1]		
Total Dissolved Solids (TDS)[1]		
Chloride (Cl)		
Nitrogen (Total)		
Alkalinity[1,2]		
pH[1,2]		
Conductivity[1,2]		
Chemical Oxygen Demand (COD)		
Total Organic Carbon (TOC)		
Total Kjeldahl Nitrogen (TKN)		
Total Suspended Solids (TSS)		
Dissolved Organic Carbon (DOC)		
Bicarbonate (HCO_3)[1,2]		
Carbonate (CO_3) [1,2]		
Hydroxide (OH) [1,2]		

[1] For samples collected on July 8, 2018, a log in error occurred by ALS; these parameters were initially not tested.
[2] For samples collected on July 8, 2018, a log in error occurred by ALS, these parameters were subsequently tested past the holding time.

A6.3 Soil Sampling and Analyses

Soil sampling was conducted four times in 2018 (May 27, July 8, September 9, and October 17 for acid volatile sulphides (AVS) and simultaneously extracted metals (SEM) only), while *in situ* relative soil redox was measured monthly. A sample of the top 0-10 cm of CWTS soil was collected into a 1 L glass jar for analyses. Analyses are outlined in Table A2. Each CWTS cell was sampled during each sampling event.

Table A2 – Summary of 2018 soil sampling analytical parameters, frequencies and locations.

Parameters	Frequency of Sampling	Sample Locations
Relative soil redox (in situ)	Monthly	All probes (6 per cell)
Analyses completed on soil sample		
SAR[1], pH, EC, %sat, Ca[1], Mg[1], Na[1], K[1], Cl, SO4	Seasonally (3x per year)	From a depth of 0-10 cm.
Available NPK and sulphur		
Bicarbonate (HCO_3)[1]		
Carbonate (CO_3)[1]		
Total Organic Carbon (TOC)		
Metals Analysis (Total)		
Sulfur by LECO		
Metals Leach		
Acid Volatile Sulphides (AVS) and Simultaneously Extracted Metals (SEM)		
Sequential Leaching (5 Acid Test)		
Analyses completed on special leach		
Bromide (Br)	Seasonally (3x per year)	From a depth of 0-10 cm.
Chloride (Cl)		
Sulphate (SO_4)		
Fluoride (F)		
Alkalinity		
Bicarbonate (HCO_3)		
Carbonate (CO_3)		
Hydroxide (OH)		
Dissolved Organic Carbon (DOC)		
Ammonia		
Nitrate		
Nitrite		
Total Dissolved Solids (TDS)		

[1] Parameters were not tested for the July 8, 2018 sample as the sample jar broke during shipment, resulting in low sampling volume for cell 1B.

The high initial leachable copper concentrations in the CWTS soils allowed for additional types of testing to be carried out on these systems. To assess the effect of the elevated metals (copper) in the soils used in construction on CWTS functionality, four soil analytical test methods were used as described in Appendix A of the Minto Constructed Wetland Treatment Research Program – Demonstration Scale 2017 Update (Contango, 2017b). Three of these analytical test methods were used in 2018:

1. Total concentration of elements in the soils by CRC ICPMS (EPA 200.2/6020A).
2. The concentration of metals that are being released from the soil into the overlying water column by leach method (EPA 6020A and EPA 300.1).

3. Stability and form of elements in soils by a sequential extraction procedure for the speciation of particulate trace metals (Tessier et al., 1979; EPA 6020A).

A6.4 Plant Sampling and Analyses

Both *C. aquatilis* and moss samples were collected for metals analysis at the final sampling period of the demonstration-scale CWTS. Above water vegetation for *C. aquatilis* samples were collected from each cell in the CWTS. Analyses are outlined in Table A3. Analyses of the tissue samples followed EPA 200.3/6020A and were reported in mg/kg dry weight. The tissue samples were homogenized and sub-sampled prior to digestion.

Table A3 - Summary of 2018 plant sampling analytical parameters, frequencies and locations.

Analytical Parameters	Plants Sampled	Location	Frequency of Sampling
Total Metals by ICPMS	*Carex aquatilis* and aquatic moss	Each cell	Year end

A6.5 Microbial Sampling and Analysis

Microbial sample collection was completed for four sample types: soil, roots, detritus, and moss. Soil, roots, detritus, and moss were collected from each cell in the CWTS for microbial analysis three times in 2018: June, July, and September. However, as moss, root, and detritus samples collected in June were received frozen, no further analyses were conducted. Quantification and DNA based analyses (genetic sequencing) were therefore conducted for all sample types collected in July and September, as well as for soil samples collected in June. Methods for sample collection for each sample type is described in Appendix A of the Minto Constructed Wetland Treatment Research Program – Demonstration Scale 2017 Update (Contango, 2017).

A6.5.1 Quantification Analyses

In 2018, Contango's microbial quantification analyses had evolved away from growth-based analyses (MPN) to a more efficient quantification analyses (quantitative polymerase chain reaction; qPCR). Consequently, the soil samples collected in June 2018, and all samples collected in July 2018 were analyzed for both growth-based microbial analysis, as well as qPCR to compare the two analyses. While not directly comparable, the results of the comparison indicated that quantification analyses were an appropriate technique to move forward with. Therefore, only results from 2018 qPCR analyses are shown in graphs and overall trends for all years are described.

Growth-based Analyses (MPN)

The most-probable number (MPN) of bacteria was determined for selected microbial samples as described in Appendix A of the Minto Constructed Wetland Treatment Research Program – Demonstration Scale 2017 Update (Contango, 2017b).

Quantification Polymerase Chain Reaction (qPCR) Analyses

Organisms of interest were quantified using quantitative polymerase-chain reaction (qPCR). All bacteria in a sample were quantified through qPCR for the 16S ribosomal RNA (rRNA) gene (normalized for gene copy number).

A6.5.2 Genetic Sequencing Analyses

DNA was extracted and sequenced as described in Appendix A of the Minto Constructed Wetland Treatment Research Program – Demonstration Scale 2017 Update (Contango, 2017b).

A6.6 Detritus Decomposition Trials

A detritus decomposition trial was developed and established in 2017 and will continue through 2019 to assess decomposition rates of *C. aquatilis* in the demonstration-scale CWTS over time, as well as evaluate the algae growth on CWTS organic materials within the water column (Chimney and Pietro, 2006; Hammerly et al.,1989). Methods are described in Appendix A of the Minto Constructed Wetland Treatment Research Program – Demonstration Scale 2017 Update (Contango, 2017b).

On July 9 and September 10, 2018 (after 383 and 446 days of submersion in the CWTS, respectively), one bag filled with polyester filter fiber and one bag filled with *C. aquatilis* was removed from each cell, dried, and weighed as described in Appendix A of the Minto Constructed Wetland Treatment Research Program – Demonstration Scale 2017 Update (Contango, 2017b).

A6.7 Vegetation Study

A vegetation plot harvest was completed in 2018 to assess the amount of above water biomass (*C. aquatilis)* that grows per year per m^2 in a mature CWTS. The results from the vegetation plot harvest were applied to the area of each cell in the CWTS to estimate the amount of *C. aquatilis* that would contribute organic matter into the CWTS each year. A 1 m^2 quadrant was delineated in cell 2B of the demonstration-scale CWTS and all the above water *C. aquatilis* was harvested within the quadrant (Figure A1). The *C. aquatilis* was weighed and placed in a drying oven (at 50^{o}C) until a constant mass was observed. The dry-weight of the *C. aquatilis* was then adjusted for the estimated size of the CWTS (estimated area of CWTS multiplied by 1 m^2 of *C. aquatilis*) to calculate the total biomass of *C. aquatilis* added to the CWTS in a year. Finally, the total biomass addition was compared to the decomposition rate and algal addition rates (Section A6.6) to establish a more accurate rate of organic matter addition to a CWTS of a given size.

Figure A1 – Vegetation plot harvest 2018.
Photo on the left shows vegetation plot harvest area delineated with wooden stakes. Photo on the right shows the area that was harvested. Photos were taken July 8, 2018.

A6.8 Water depth measurements

Depth sticks installed in the CWTS in June 2016 were used to measure the water depth over time (Contango, 2017a). One of the depth sticks in cell 1A had fallen over on June 15, 2018 and was subsequently re-installed by Minto staff. However, measurements after June 15, 2018 were higher than previously recorded. Therefore, the recorded depths for this depth stick have been corrected by subtracting 5 cm from the measured value. The corrected depths were used for further calculations regarding cell volume and HRT (Section A9). It is recommended that the depth sticks in cell 1A are corrected to the proper depth in 2019.

A6.9 Evapotranspiration Trials

In 2018, the evapotranspiration studies were performed on-site from June 27 to July 3 (trial 1) and August 3 to August 10 (trial 2). However, approximately 9.6 mm of rain occurred during trial 1 (although weather station data was unavailable on the first day of the trial) and 33 mm of rain occurred during trial 2. As it rained for the majority of trial 1 and trial 2, data obtained from this year's evapotranspiration trials were unreliable and, therefore, load removal calculations were adjusted using the 2017 evapotranspiration rate (5.4 L/m^2/day water loss).

A7. Performance Limit Calculations

The performance limit (previously referred to as thermodynamic minimum) is the lowest concentration consistently achievable for a given treatment design and water chemistry. These calculations were conducted as described in Appendix A of the Minto Constructed Wetland Treatment Research Program – Demonstration Scale 2017 Update (Contango, 2017b).

A8. Load Removal Calculations

Load removals are calculated both without adjustment for evapotranspiration and adjusting for evapotranspiration. The evapotranspiration adjustment converts the calculation of load removed during each flow period to the actual amount of load removed, taking into consideration the amount of water lost from the demonstrations-scale CWTS through evapotranspiration. Load removal was determined using equations to calculate the initial load removed without adjustment for evapotranspiration and with adjustment for evapotranspiration as described in Appendix A of the Minto Constructed Wetland Treatment Research Program – Demonstration Scale 2017 Update (Contango, 2017b).

A9. Removal rate coefficients and HRT calculations

An important factor for CWTS design is the rate of treatment, also known as the removal rate coefficient (*k*). The removal rate coefficient is based on the treatability of a specific compound and the HRT of the CWTS, both of which are site-specific based on water chemistry, CWTS designs, and characteristics of the CWTS. These calculations were conducted using removal rate coefficients (*k*)equations as described in Appendix A of the Minto Constructed Wetland Treatment Research Program – Demonstration Scale 2017 Update (Contango, 2017b).

A10. Iron Addition

Iron, in the form of ferrous sulphate, was added to the CWTS to promote AVS production, which in turn would serve as a redox buffer should the soils be exposed to oxygen (e.g., briefly drying out) and would also continue to treat metals and metalloids during periods of low microbial activity (e.g., cooler temperatures). Prior to adding iron to the CWTS a bench top test was conducted, and the methods for conducting the bench top test and the direct addition to the CWTS are detailed below.

A10.1 Bench Trial for Iron Addition

A bench trial was completed prior to adding the ferrous sulphate solution into cell 1A and 1B of the demonstration-scale CWTS to determine if there would be an associated drop in pH. The bench top test consisted of adding 0.050 g of ferrous sulphate heptahydrate to 1 L of water from cell 1A, for a final iron concentration of 10 mg/L. The pH of the water from cell 1A was measured using a YSI hand held meter prior to adding the ferrous sulphate and the pH was recorded at 7.59. The ferrous sulphate was then added to the 1 L container of water from cell 1A and the container was inverted three times. pH readings were recorded at 1 min, 3 min, 5 min, 10 min, 15 min, 20 min, 30 min, and 1 hour 30 mins to determine if there would be an effect on the pH. The pH remained circumneutral at 7.23 after 1 hour 30 minutes. Therefore, it was determined that a 10 mg/L concentration of iron was appropriate to add to the cells 1A and 1B.

A10.2 Iron Addition to the Demonstration-scale CWTS

On July 8, 2018, flow to series 1 was stopped and 303 g and 304 g of ferrous sulphate was added to cell 1A and 1B, respectively, to achieve a final iron concentration of 10 mg/L. Flow remained off until July 15, 2018 to promote reducing conditions and generation of AVS in the soil, which was monitored during the seasonal soil analyses on September 9, 2018 and on October 17, 2018 (Section A6.3).

A11. Aphid Monitoring and Pesticide Application

Application of pesticide (Trounce, End-All, and Bug-B-Gone) on *C. aquatilis* in each cell occurred bi-weekly, starting on May 14, 2018 as a preventative measure due to an aphid infestation identified during the 2017 test period (Contango, 2017b). Aphids were not observed in the CWTS until early August 2018 (exact date unknown), when small amounts of aphids were observed in cell 2A. Application of pesticide on *C. aquatilis* was subsequently conducted weekly starting August 24, 2018.

A12. Fertilizer addition calculations

Due to the impacts of the aphid infestation in 2017, fertilizer, in the form of monopotassium phosphate (MKP), was added bi-weekly to each cell in the CWTS to help with *C. aquatilis* growth, starting July 14, 2018. The quantity of MKP added to each cell is shown in Table A4 and was based on the volume of water in each cell to achieve a final concentration of 1 mg/L phosphorus. MKP application occurred bi-weekly by dissolving dry MKP into 1 L of water. The MKP solution was emptied along the inflow of each cell where the flow of water then spread the fertilizer throughout the cell.

Table A4 – Quantity of MKP added bi-weekly to each CWTS cell.

CWTS Cell	Dry MKP Quantity (g)
1A	26.74
1B	26.96
2A	20.44
2B	18.56

A13. Aphid Monitoring and Sedge Transplantation

Due to the impacts of the aphid infestation in 2017, areas of the demonstration-scale CWTS were devoid of dense *C. aquatilis* plants. Therefore, on July 8, 2018, Minto and Contango personnel transplanted approximately 25 *C. aquatilis* plants from water quality monitoring station W10 into cells 1A, 1B and at the outflow of 2A.

A14. References

All references provided in main report.

Appendix B – Additional Tables and Figures

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B1. Water Results

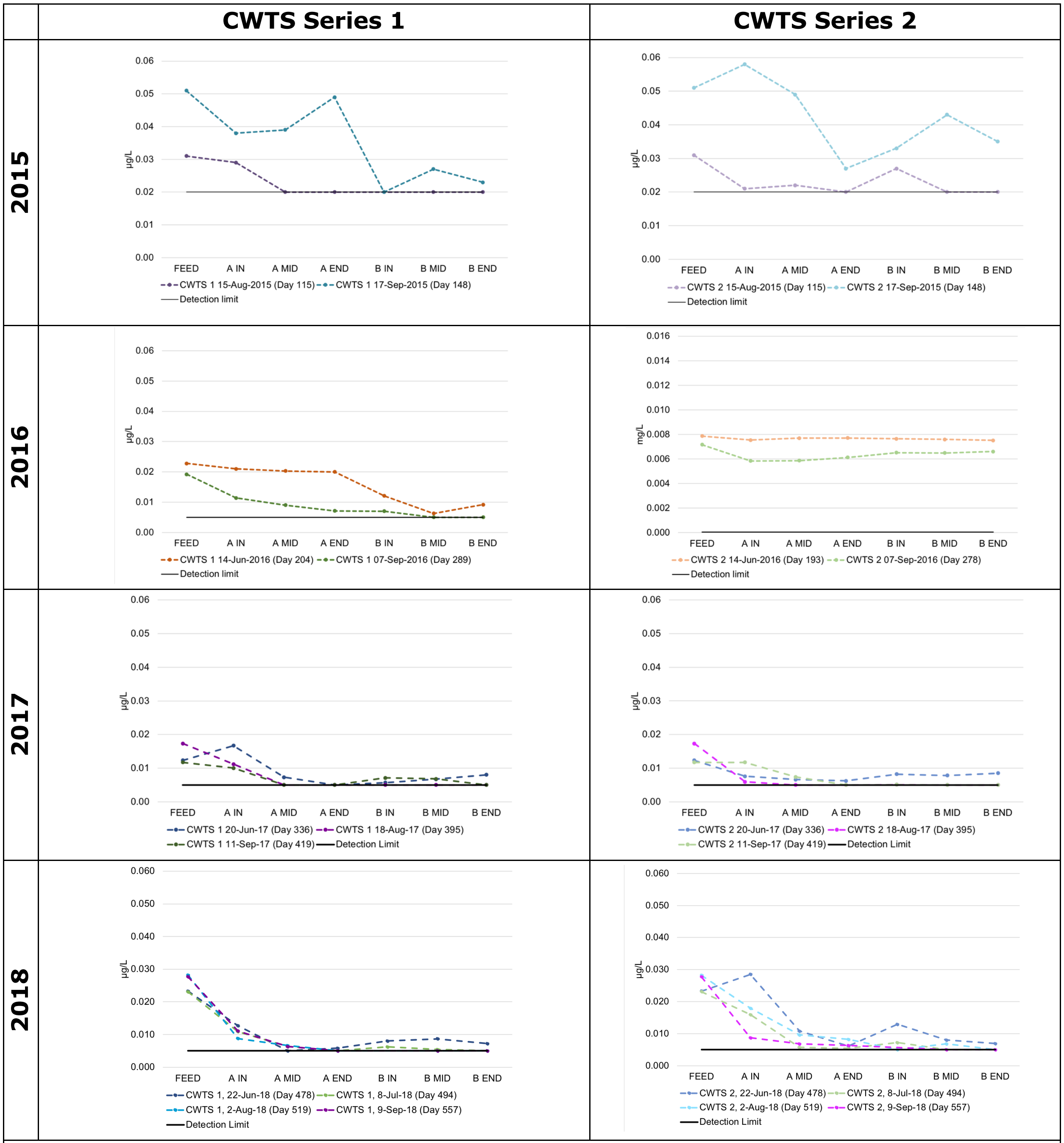


Figure B1 – Cadmium concentrations through the demonstration-scale CWTS. 2015 (top), 2016 (second down), 2017 (third down), and 2018 (bottom) dissolved cadmium concentrations. Data shown for 11 timepoints, where water was sampled at seven locations through the flow path of the CWTS to assess for treatment fronts within the CWTS, or possible leaching of constituents from the soils into the CWTS. The Maxxam (2015 results) detection limit (DL; black line) for cadmium is 0.020 µg/L. The ALS (2016 – 2018 results) DL for cadmium is 0.005 µg/L. The graphs indicate that leaching is not occurring as there are no spikes in cadmium concentrations throughout the CWTS. Data from August 2, 2018 for 1B IN and from September 9, 2018 for 1B IN and 2B IN were erroneous and therefore removed from the plot (dissolved concentration exceeded total concentration).

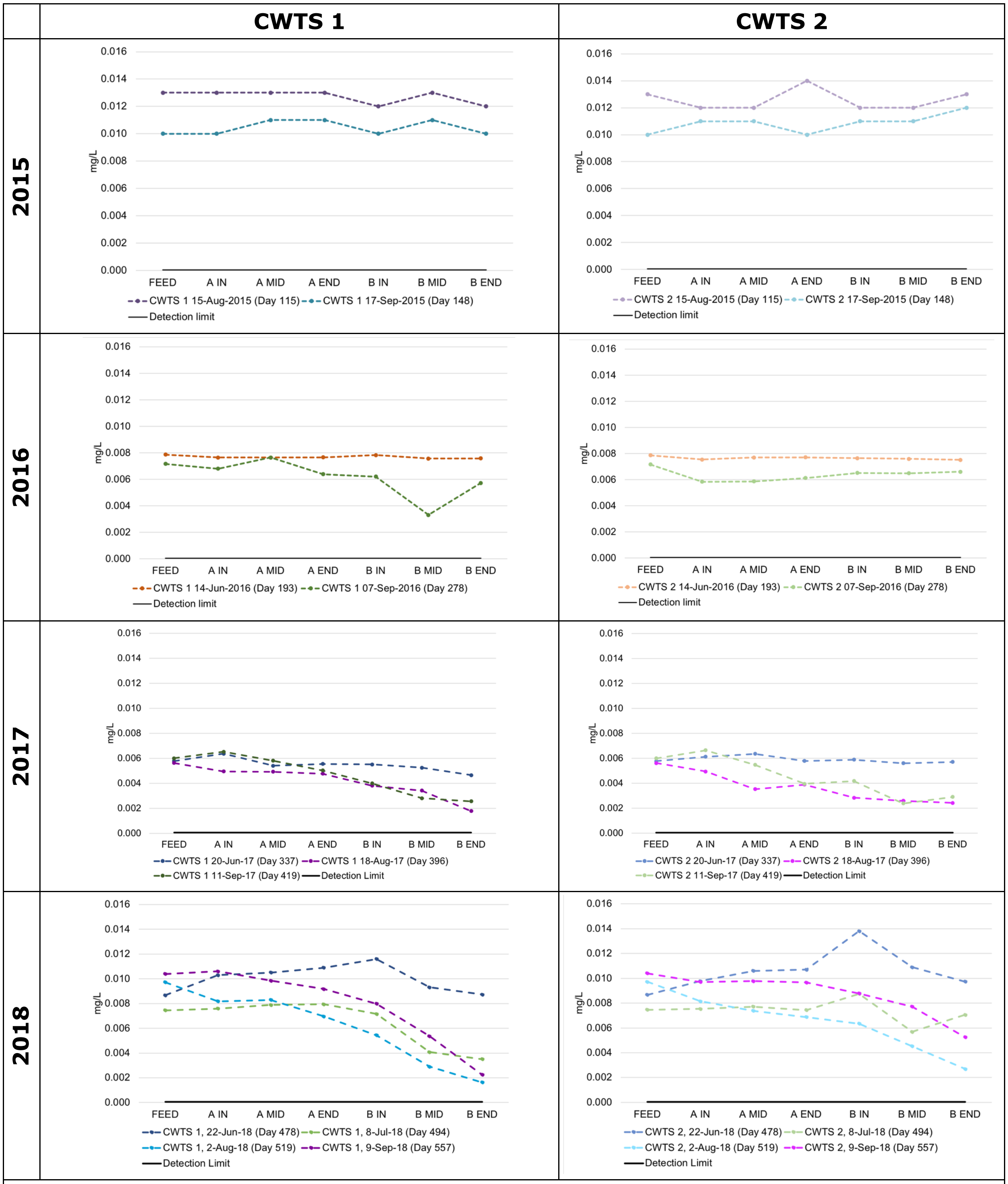


Figure B2 – Molybdenum concentrations through the demonstration-scale CWTS. 2015 (top), 2016 (second down), 2017 (third down), and 2018 (bottom) dissolved molybdenum concentrations. Data shown for 11 timepoints, where water was sampled at seven locations through the flow path of the CWTS to assess for treatment fronts within the CWTS, or possible leaching of constituents from the soils into the CWTS. The Maxxam (2015 results) detection limit (DL; black line) for molybdenum is 0.00020 mg/L. The ALS (2016 – 2018 results) DL for molybdenum is 0.000050 mg/L.

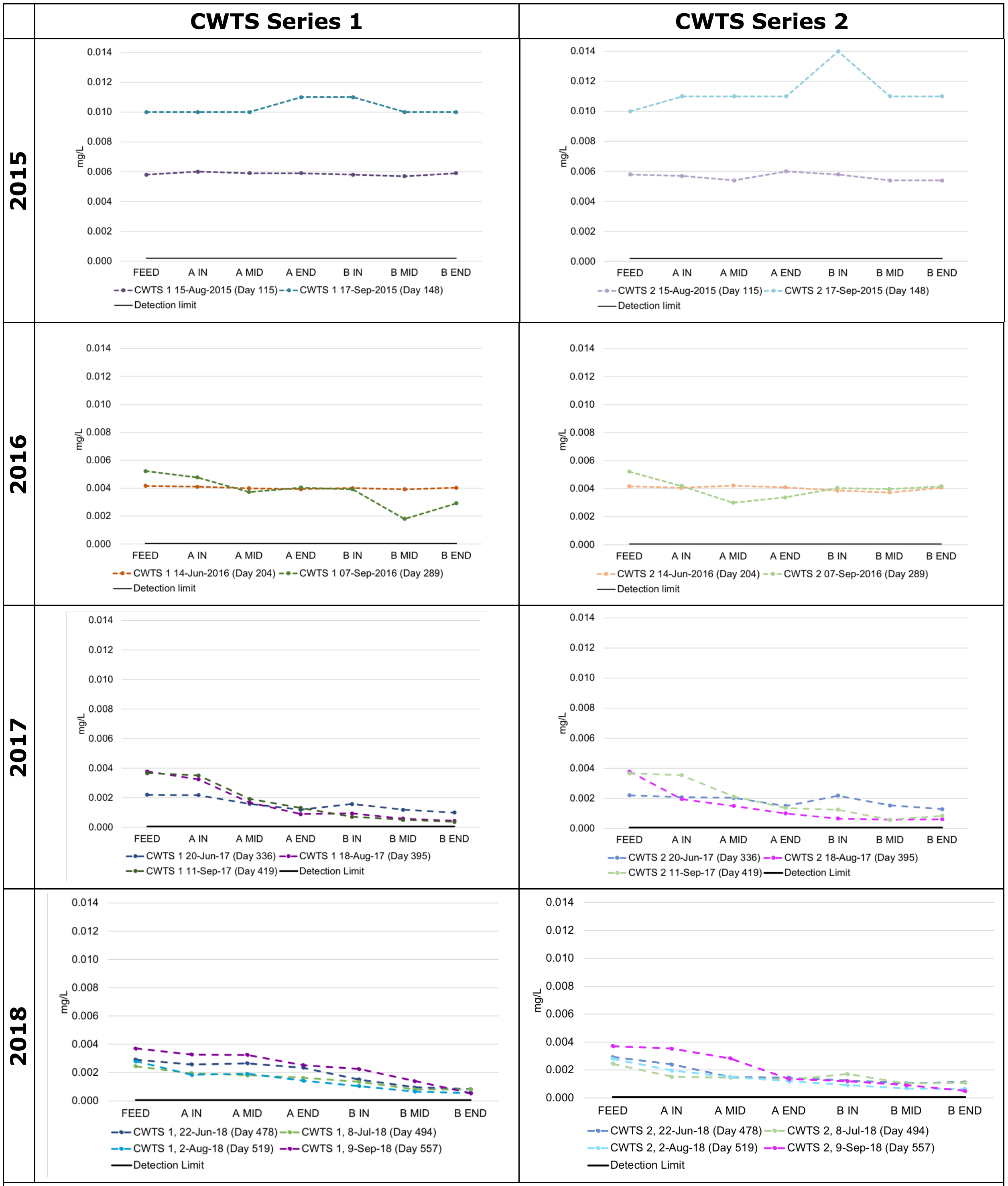


Figure B3 – Selenium concentrations through the demonstration-scale CWTS. 2015 (top), 2016 (second down), 2017 (third down), and 2018 (bottom) dissolved selenium concentrations. Data shown for 11 timepoints, where water was sampled at seven locations through the flow path of the CWTS to assess for treatment fronts within the CWTS, or possible leaching of constituents from the soils into the CWTS. The Maxxam (2015 results) detection limit (DL; black line) for selenium is 0.00020 mg/L. The ALS (2016 – 2018 results) DL for copper is 0.000050 mg/L. The graphs indicate that leaching is not occurring as there are no spikes in selenium concentrations throughout the CWTS. Data from June 22, 2018 for 2B IN was erroneous and therefore removed from the plot (dissolved concentration exceeded total concentration).

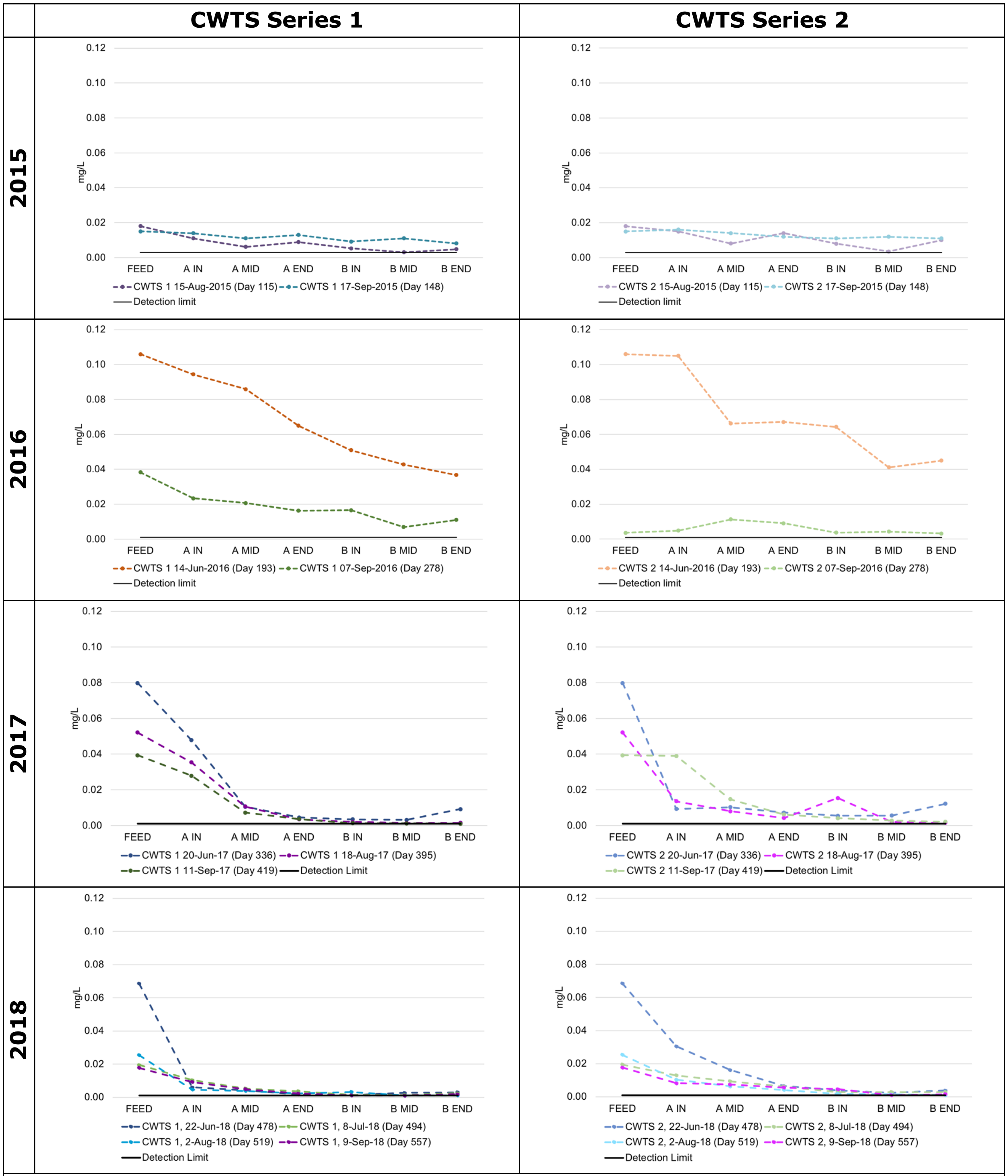


Figure B4 – Zinc concentrations through the demonstration-scale CWTS.
2015 (top), 2016 (second down), 2017 (third down), and 2018 (bottom) dissolved zinc concentrations. Data shown for 11 timepoints, where water was sampled at seven locations through the flow path of the CWTS to assess for treatment fronts within the CWTS, or possible leaching of constituents from the soils into the CWTS. The Maxxam (2015 results) detection limit (DL; black line) for zinc is 0.0030 mg/L. The ALS (2016 – 2018 results) DL for zinc is 0.0010 mg/L. The graphs indicate that leaching is not occurring as there are no spikes in zinc concentrations throughout the CWTS.

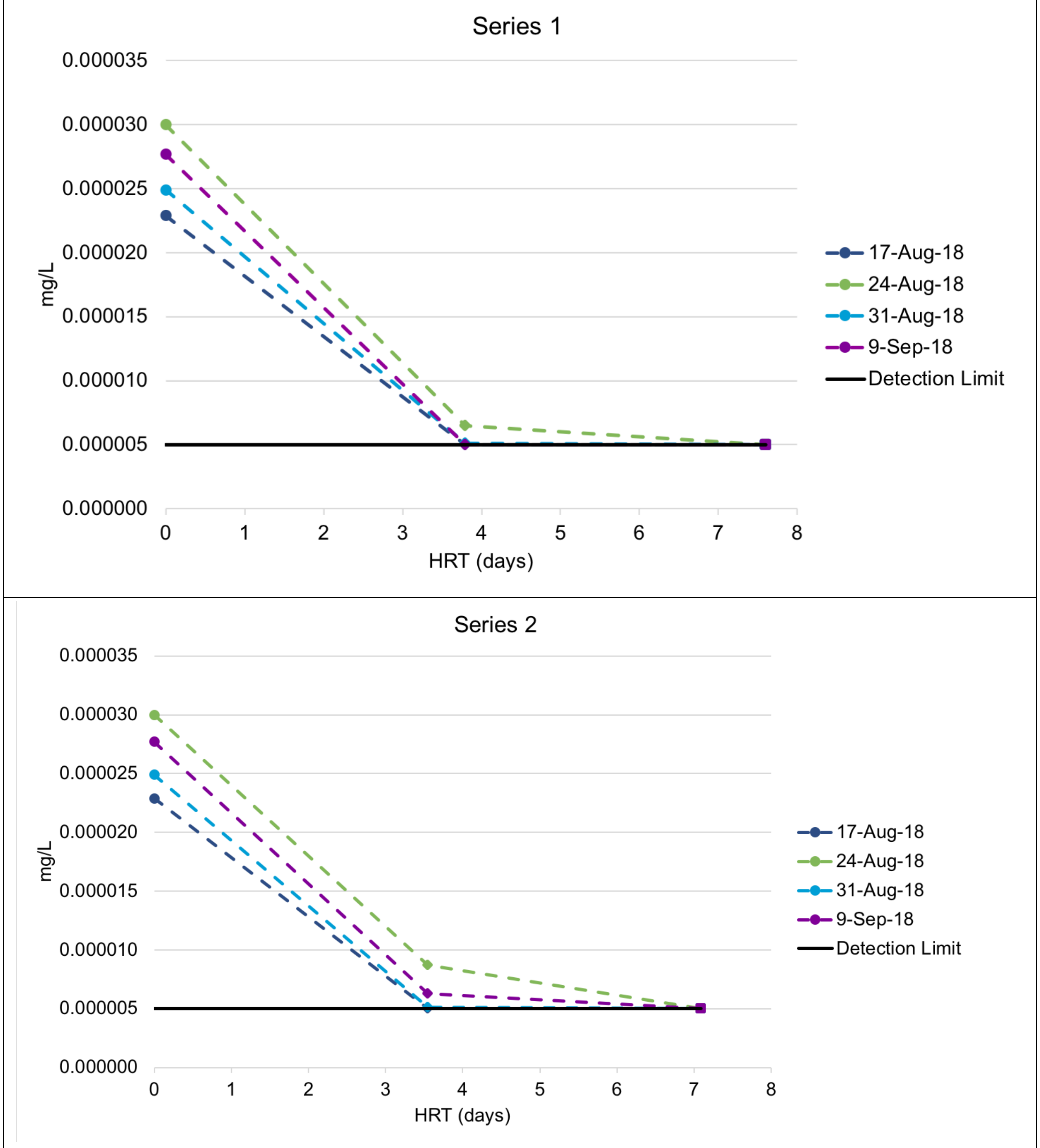
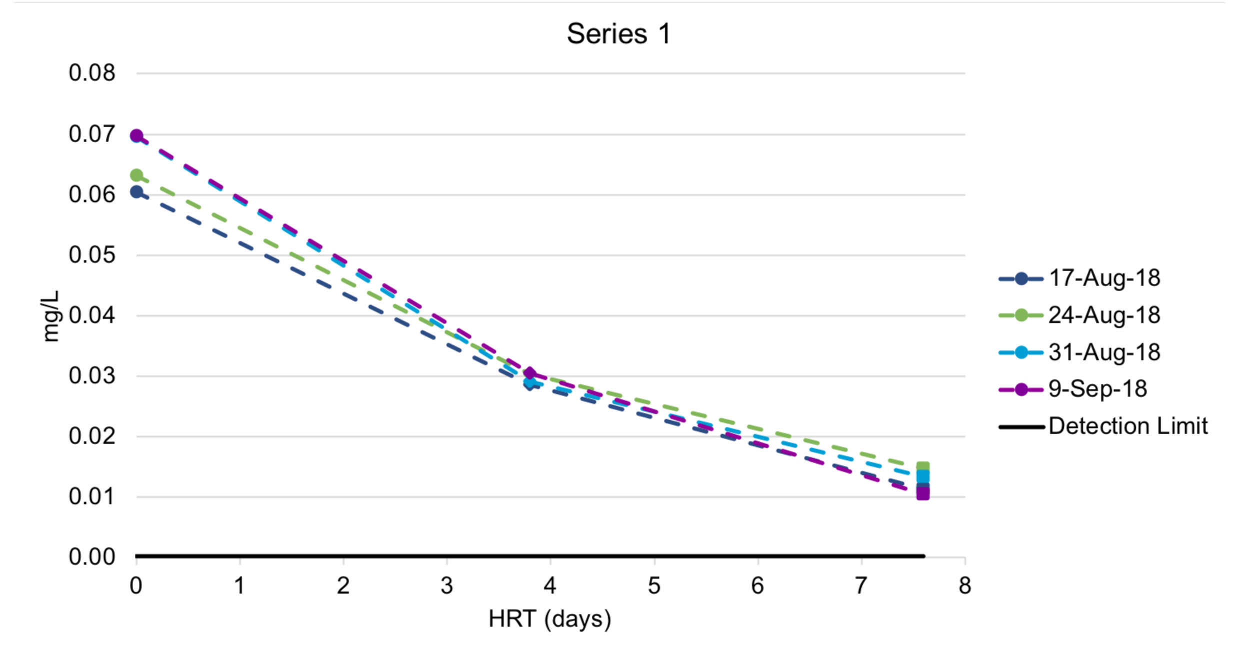


Figure B5 – Dissolved cadmium concentrations through Series 1 and Series 2. Circles represent the feed water entering the wetland, diamonds represent the outflow of cell A and squares represent the outflow of cell B. The ALS detection limit for cadmium is 0.000005 mg/L.



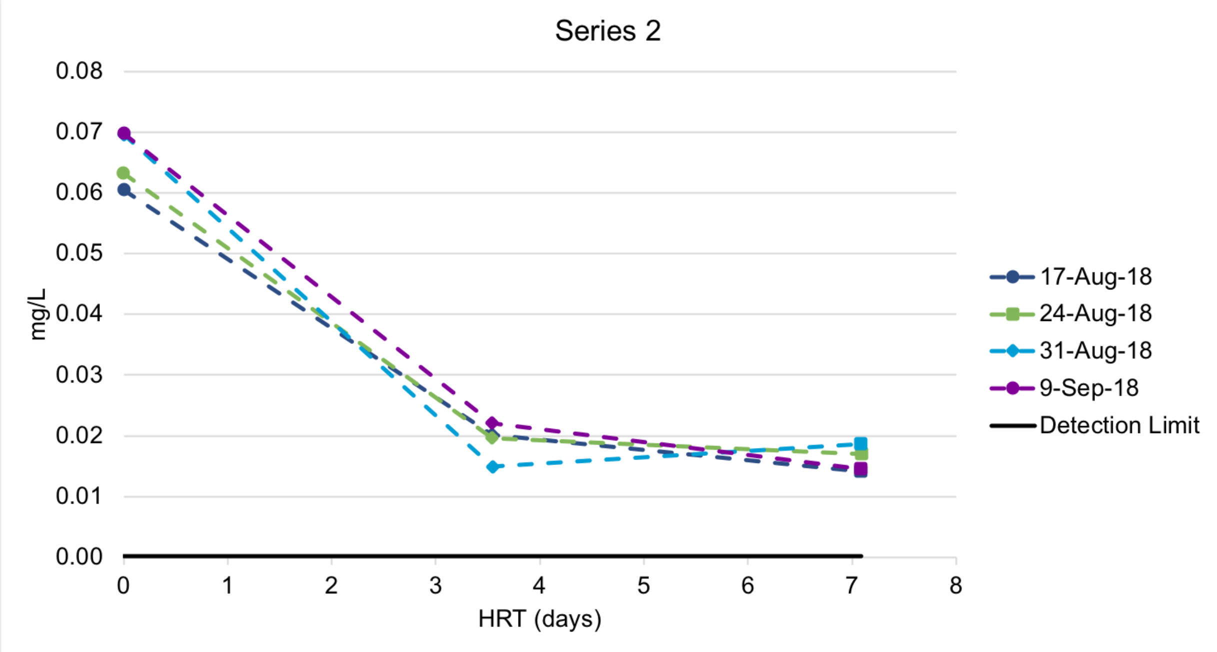
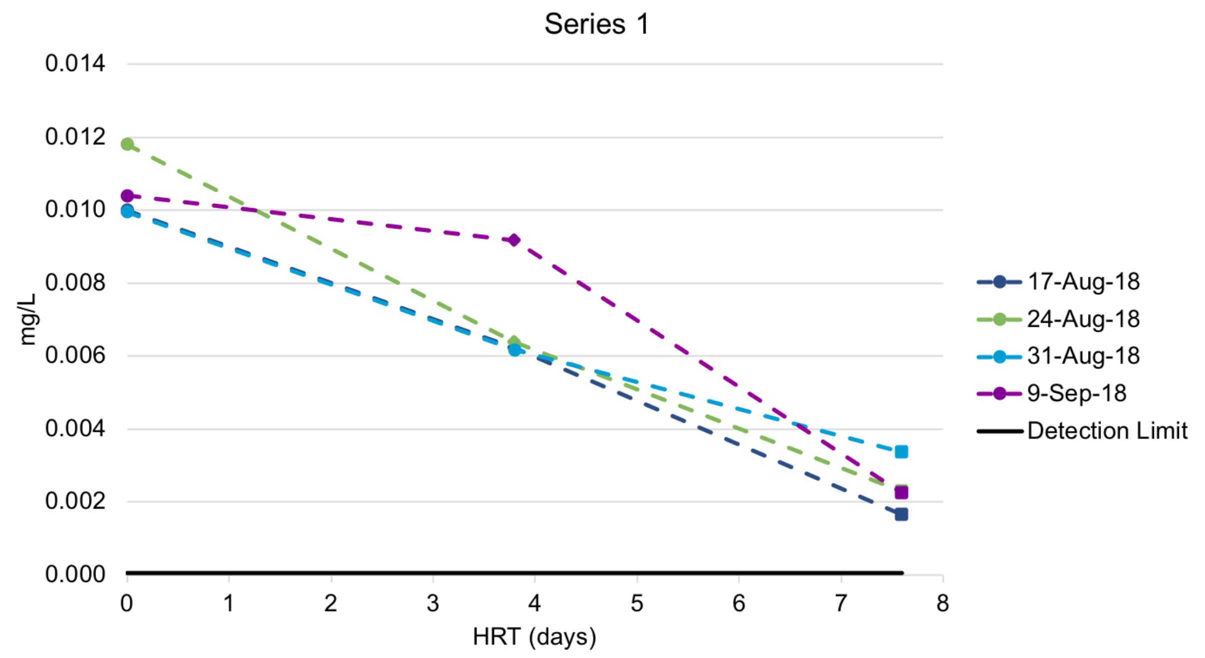


Figure B6 – Dissolved copper concentrations through Series 1 and Series 2.
Circles represent the feed water entering the wetland, diamonds represent the outflow of cell A and squares represent the outflow of cell B. The ALS detection limit for dissolved copper is 0.0002 mg/L.



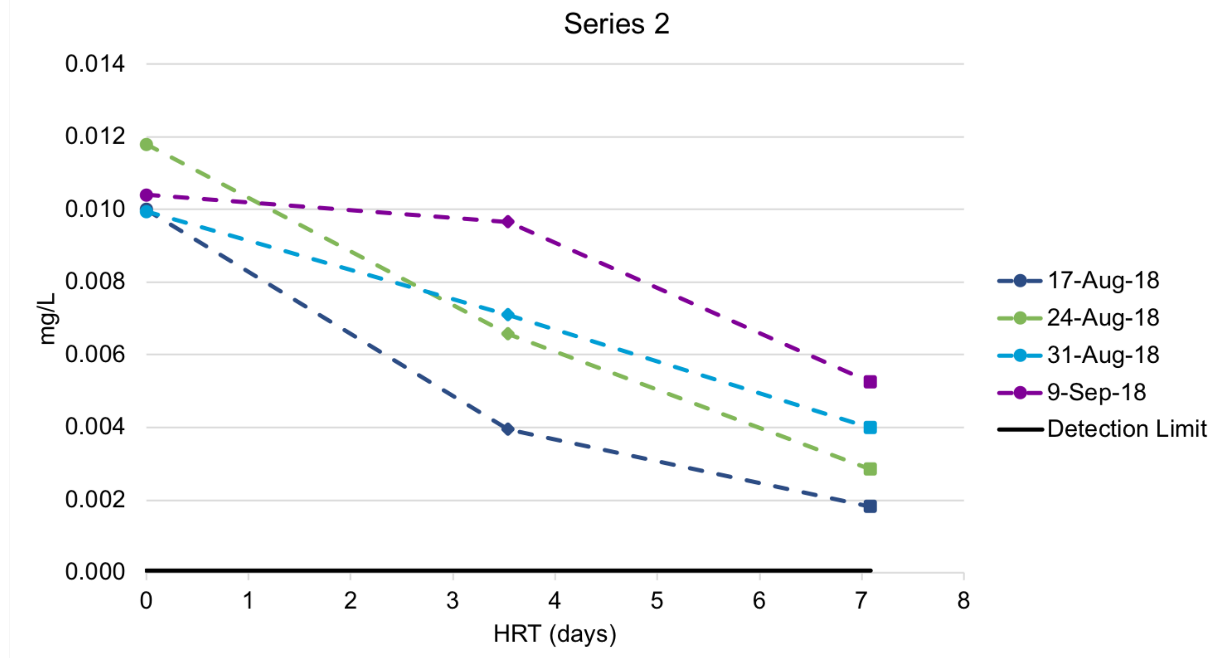


Figure B7 – Dissolved molybdenum concentrations through Series 1 and Series 2. Circles represent the feed water entering the wetland, diamonds represent the outflow of cell A and squares represent the outflow of cell B. The ALS detection limit for molybdenum is 0.00005 mg/L.

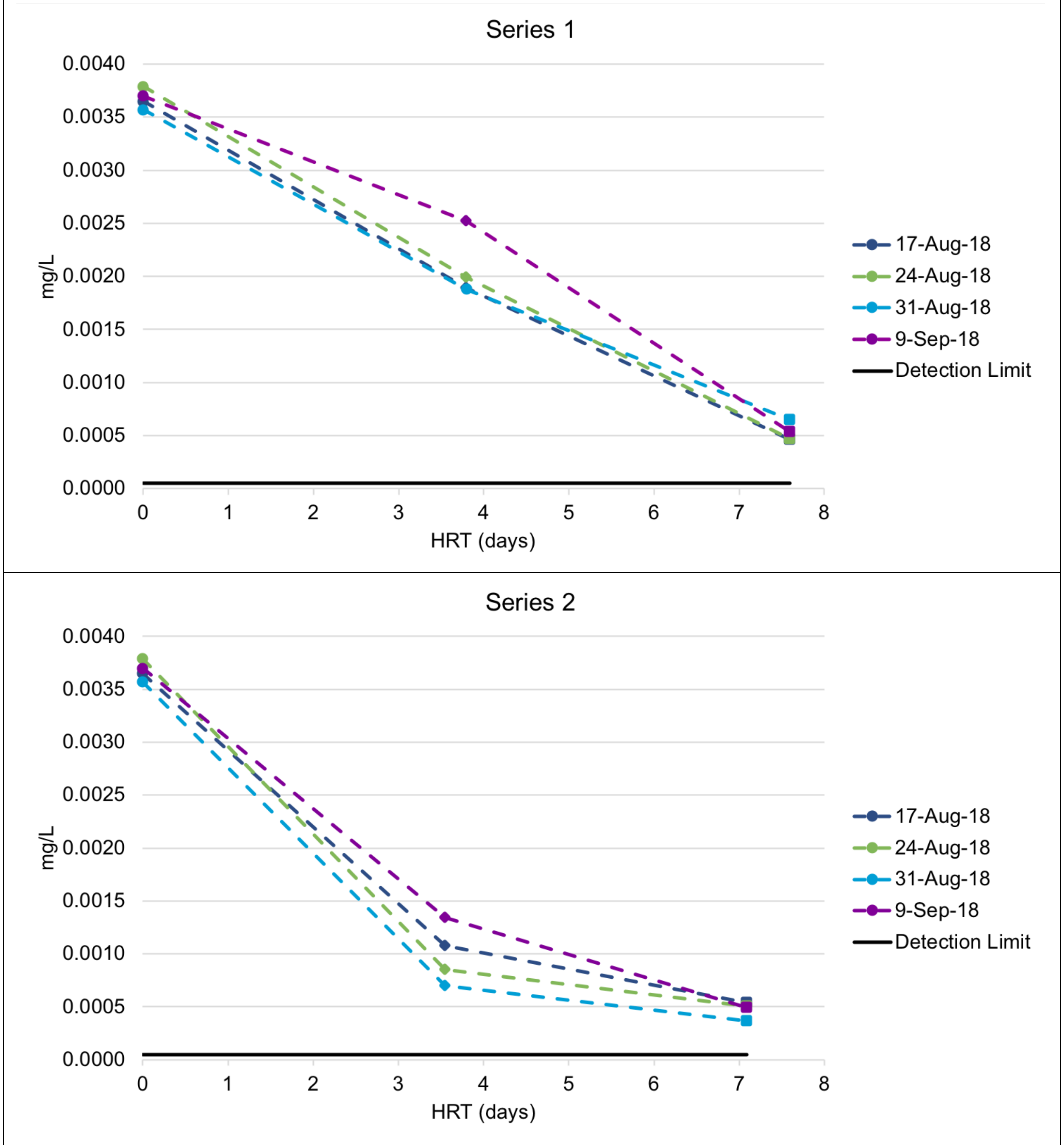


Figure B8 – Dissolved selenium concentrations through Series 1 and Series 2. Circles represent the feed water entering the wetland, diamonds represent the outflow of cell A and squares represent the outflow of cell B. The ALS detection limit for selenium is 0.00005 mg/L.

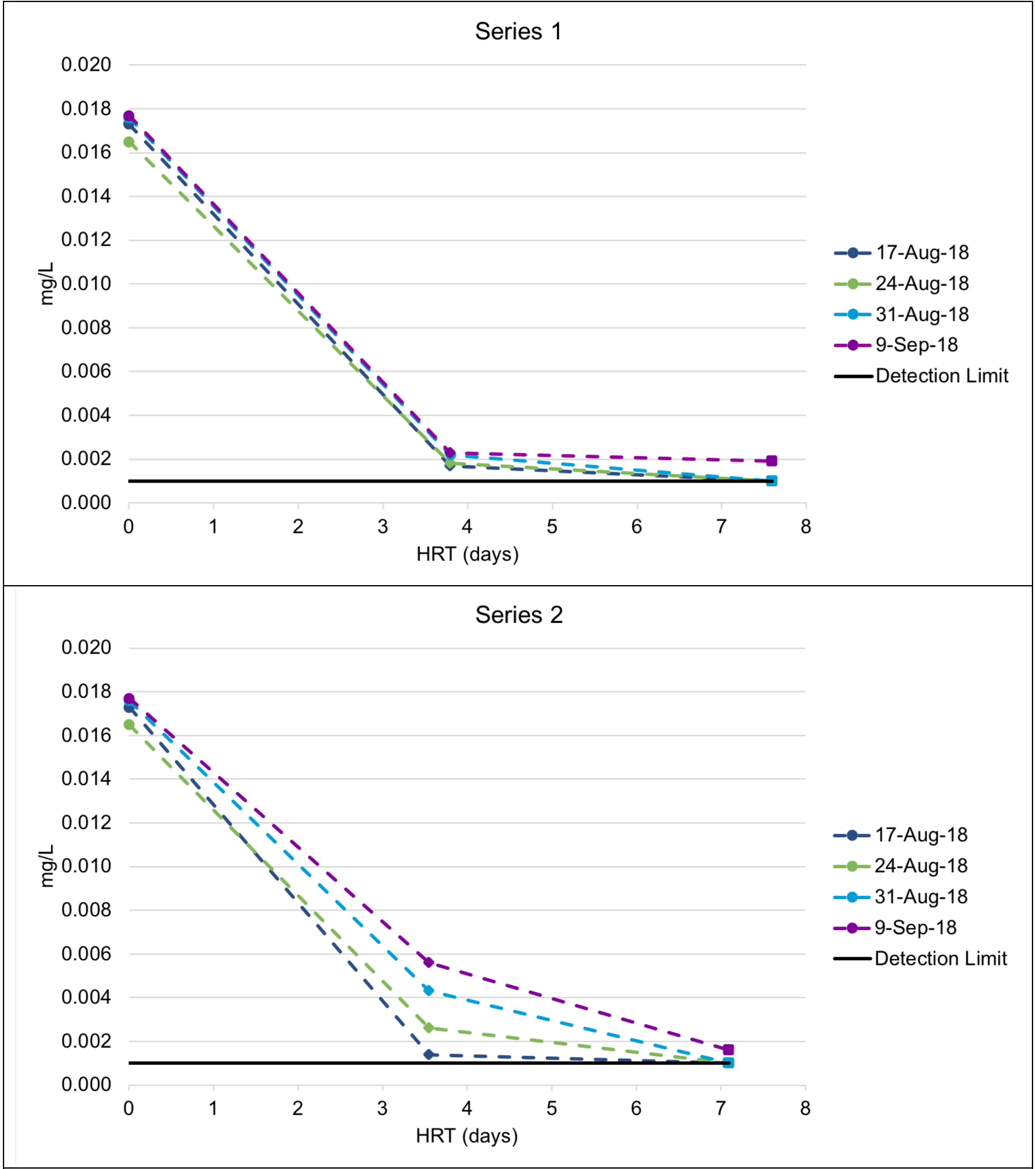


Figure B9 – Dissolved zinc concentrations through Series 1 and Series 2.
Circles represent the feed water entering the wetland, diamonds represent the outflow of cell A and squares represent the outflow of cell B. The ALS detection limit for dissolved zinc is 0.001 mg/L.

B2. Soil Results

Table B1 – Total and leachable soil copper concentrations in Series 1 since first year of operations.

CWTS Cell	Sampling Date	Days in Operation	Sample Depth (cm)	Total Cu (mg/kg)	SPLP Cu (mg/L)	Leachable Cu (mg/kg)
1A	28-Aug-14	1	Initial Composite	-	0.298 (0.148-0.608)	-
	19-Jun-15	58	0-5	960	0.055^1	-
	16-Aug-15	116	10-20	950	0.187	-
	18-Sep-15	149	10-20	1300	0.049	-
	29-Sep-15	160	10-20	910	0.069	-
	15-Jun-16	194	0-10	1440	-	0.953
	15-Jun-16	194	10-20	1210	-	0.66
	8-Jul-16	217	0-10	1430	-	0.603
	8-Jul-16	217	10-20	1730	-	0.832
	7-Sep-16	247	0-10	1290	-	0.449
	20-Jun-17	336	0-10	1470	0.315	0.308
	25-Jul-17	371	0-10	1630	0.529	0.463
	12-Sep-17	420	0-10	1490	0.590	0.481
	27-May-18	452	0-10	1510	-	0.616
	8-Jul-18	494	0-10	1420	-	0.628
	9-Sep-18	557	0-10	1160	-	0.038
1B	28-Aug-14	1	Initial Composite	-	0.298 (0.148-0.608)	-
	19-Jun-15	58	0-5	1400	0.033^1	-
	16-Aug-15	116	10-20	1400	0.209	-
	18-Sep-15	149	10-20	830	0.065	-
	29-Sep-15	160	10-20	880	0.059	-
	15-Jun-16	194	0-10	1130	-	1.01
	15-Jun-16	194	10-20	1240	-	0.822
	8-Jul-16	217	0-10	1250	-	1.11
	8-Jul-16	217	10-20	1620	-	1.21
	7-Sep-16	247	0-10	1190	-	0.197
	20-Jun-17	336	0-10	1290	0.450	0.338
	25-Jul-17	371	0-10	1100	0.290	0.165
	12-Sep-17	420	0-10	1100	0.716	0.492
	27-May-18	452	0-10	1930	-	0.784
	8-Jul-18	494	0-10	1430	-	0.232
	9-Sep-18	557	0-10	1580	-	0.238

[1] Samples collected in June 2015 were at a shallow depth (0-5 cm) and copper content had therefore likely already been removed by washing from the faster flows of the CWTS system. The blue shading indicated samples that were taken from a shallower depth (0-5 cm and 0-10 cm).

Table B2 – Total and leachable soil copper concentrations in Series 2 since first year of operations.

CWTS Cell	Sampling Date	Days in Operation	Sample Depth (cm)	Total Cu (mg/kg)	SPLP Cu (mg/L)	Leachable Cu (mg/kg)
2A	28-Aug-14	1	Initial Composite	-	0.298 (0.148-0.608)	-
	19-Jun-15	58	0-5	1175	0.037[1]	-
	16-Aug-15	116	10-20	660	0.139	-
	18-Sep-15	149	10-20	880	0.081	-
	29-Sep-15	160	10-20	1000	0.073	-
	15-Jun-16	194	0-10	1100	-	0.823
	15-Jun-16	194	10-20	1280	-	0.900
	8-Jul-16	217	0-10	1450	-	0.963
	8-Jul-16	217	10-20	1150	-	1.68
	7-Sep-16	247	0-10	1290	-	0.838
	20-Jun-17	336	0-10	1820	0.381	1.24
	25-Jul-17	371	0-10	1290	0.419	0.927
	12-Sep-17	420	0-10	1440	0.389	0.381
	27-May-18	452	0-10	1100	-	0.600
	8-Jul-18	494	0-10	1480	-	0.252
	9-Sep-18	557	0-10	1630	-	0.048
2B	28-Aug-14	1	Initial Composite	-	0.298 (0.148-0.608)	-
	19-Jun-15	58	0-5	1100	0.039[1]	-
	16-Aug-15	116	10-20	1000	0.201	-
	18-Sep-15	149	10-20	830	0.078	-
	29-Sep-15	160	10-20	540	0.059	-
	15-Jun-16	194	0-10	1040	-	0.771
	15-Jun-16	194	10-20	1310	-	1.16
	8-Jul-16	217	0-10	1070	-	1.38
	8-Jul-16	217	10-20	1180	-	1.25
	7-Sep-16	247	0-10	1520	-	0.123
	20-Jun-17	336	0-10	1110	0.283	0.523
	25-Jul-17	371	0-10	1240	0.477	0.540
	12-Sep-17	420	0-10	1140	0.596	0.809
	27-May-18	452	0-10	1430	-	1.01
	8-Jul-18	494	0-10	1260	-	0.637
	9-Sep-18	557	0-10	1670	-	0.046

[1] Samples collected in June 2015 were at a shallow depth (0-5 cm) and copper content had therefore likely already been removed by washing from the faster flows of the CWTS system. The blue shading indicated samples that were taken from a shallower depth (0-5 cm and 0-10 cm).

Table B3 – Summary of extractable fractions from sequential extraction procedure for the speciation of metals[1].

Fraction	Description	COCs unstable when
1	Exchangeable fraction for adsorbed minerals	Readily released (i.e., soluble and exchangeable)
2	Mineral fraction bound to carbonates or solubilized at pH 5	Decreased pH
3	Oxidized mineral fraction bound to Fe-Mn oxides	Reducing conditions
4	Reduced mineral fraction and sulphides	Oxidizing conditions
5	Residual mineral fraction (primary and secondary minerals)	Not expected to be released in solution over time under conditions normally encountered in nature

[1] Method based on Tessier et al., 1979.

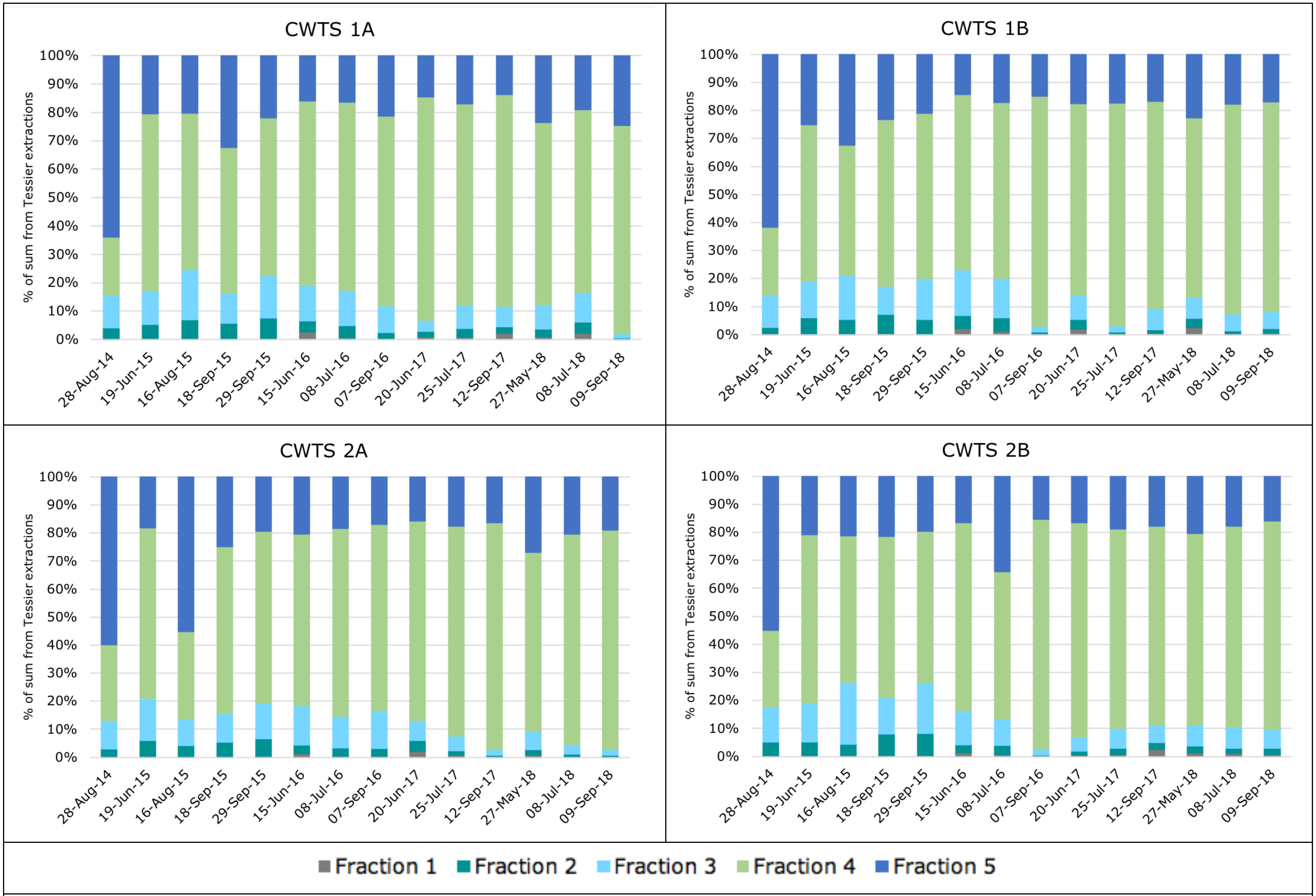


Figure B10 – Fraction distribution of copper expressed as percent over time (2014 – 2018).
Fractions are defined in Table B3.

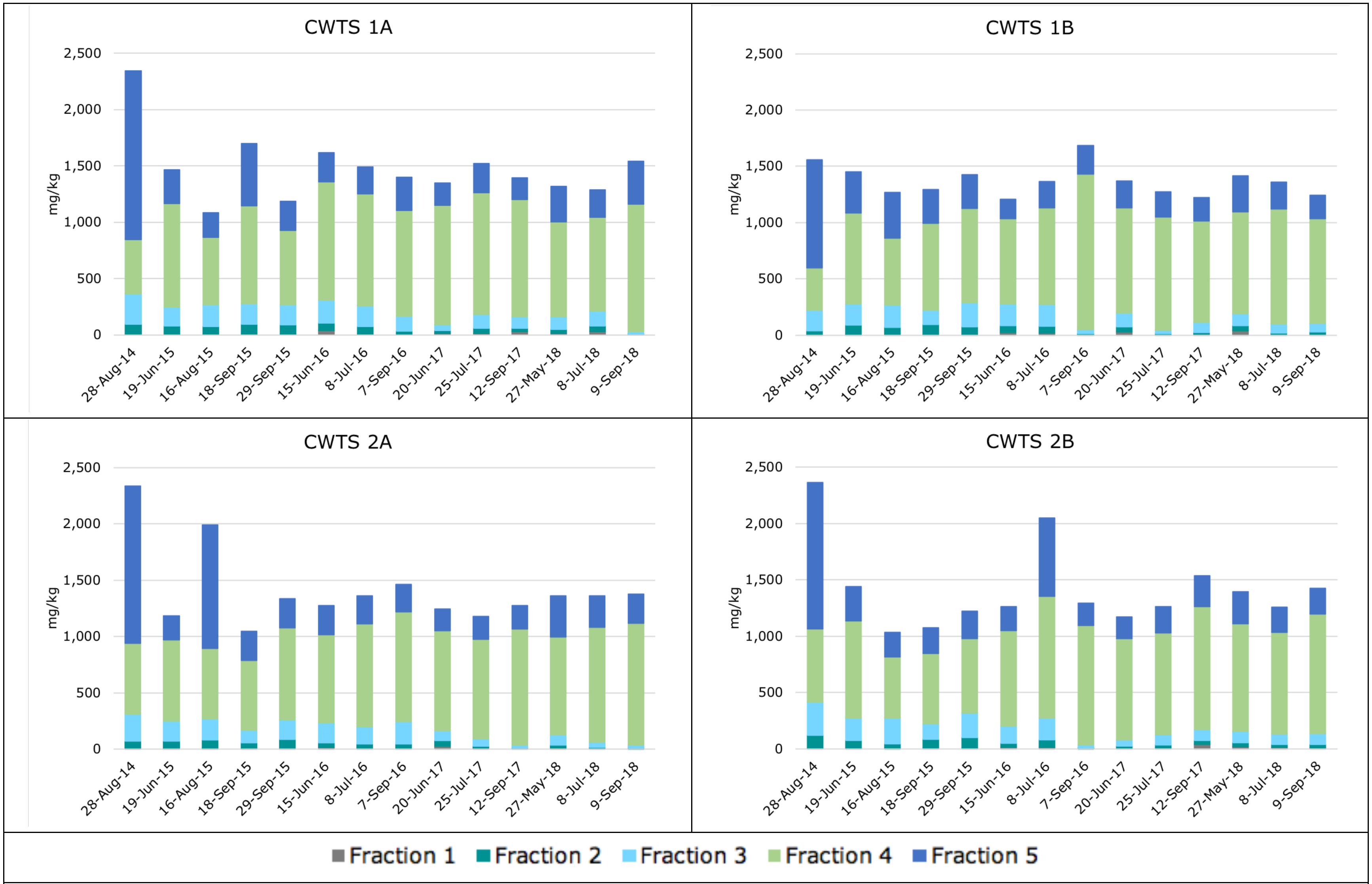


Figure B11 – Fraction distribution of copper expressed as mg/kg over time (2014 – 2018).
Fractions are defined in Table B3. The detection limit for copper is 0.50 mg/kg for all fractions.

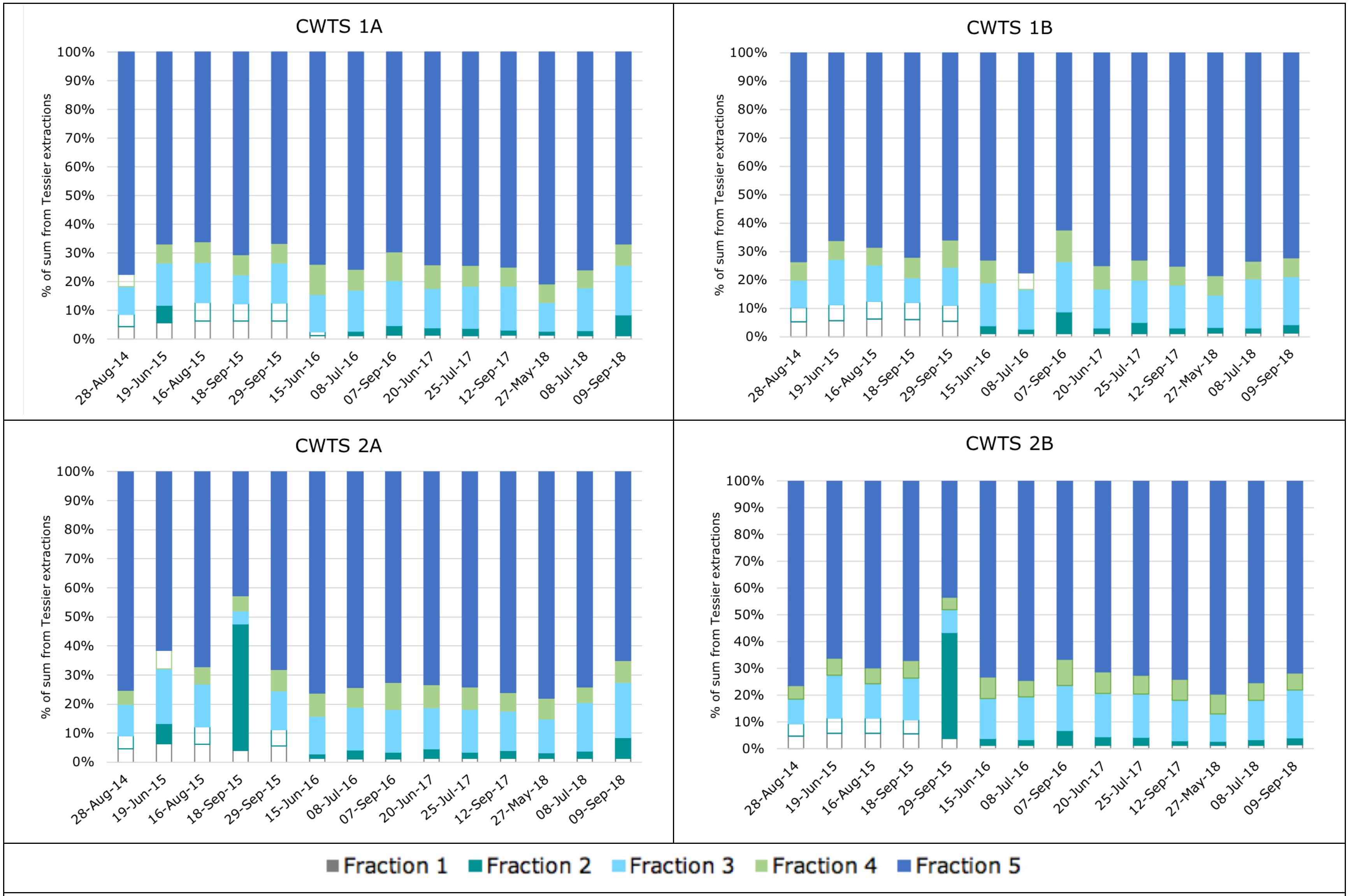


Figure B12 – Fraction distribution of zinc expressed as percent over time (2014 – 2018).
Unfilled areas are values at or below detection limit. Fractions are defined in Table B3.

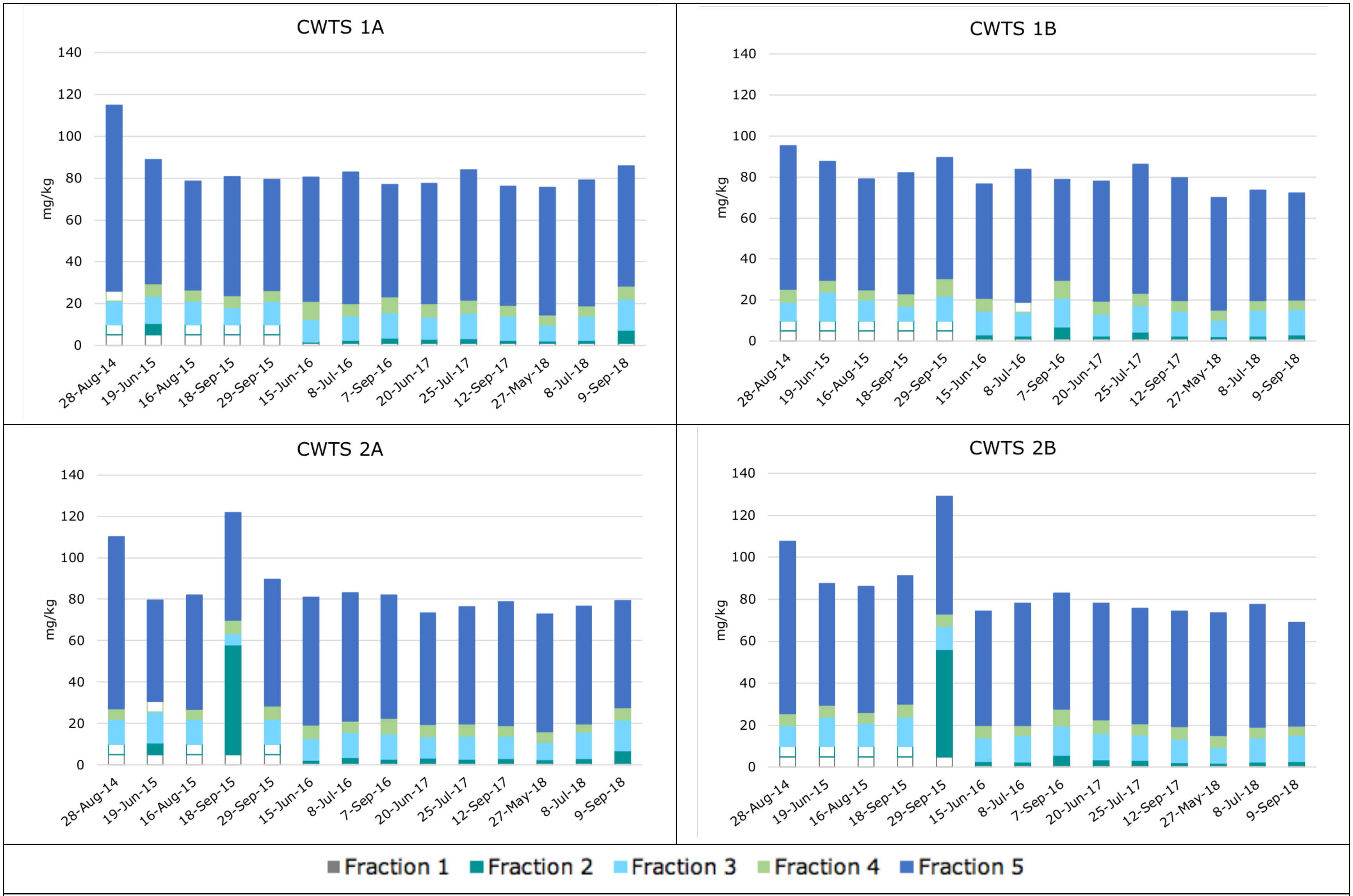


Figure B13 – Fraction distribution of zinc expressed as mg/kg over time (2014 – 2018).
Unfilled areas are values at or below detection limit. The detection limit for zinc is 1.0 mg/kg. Fractions are defined in Table B3.

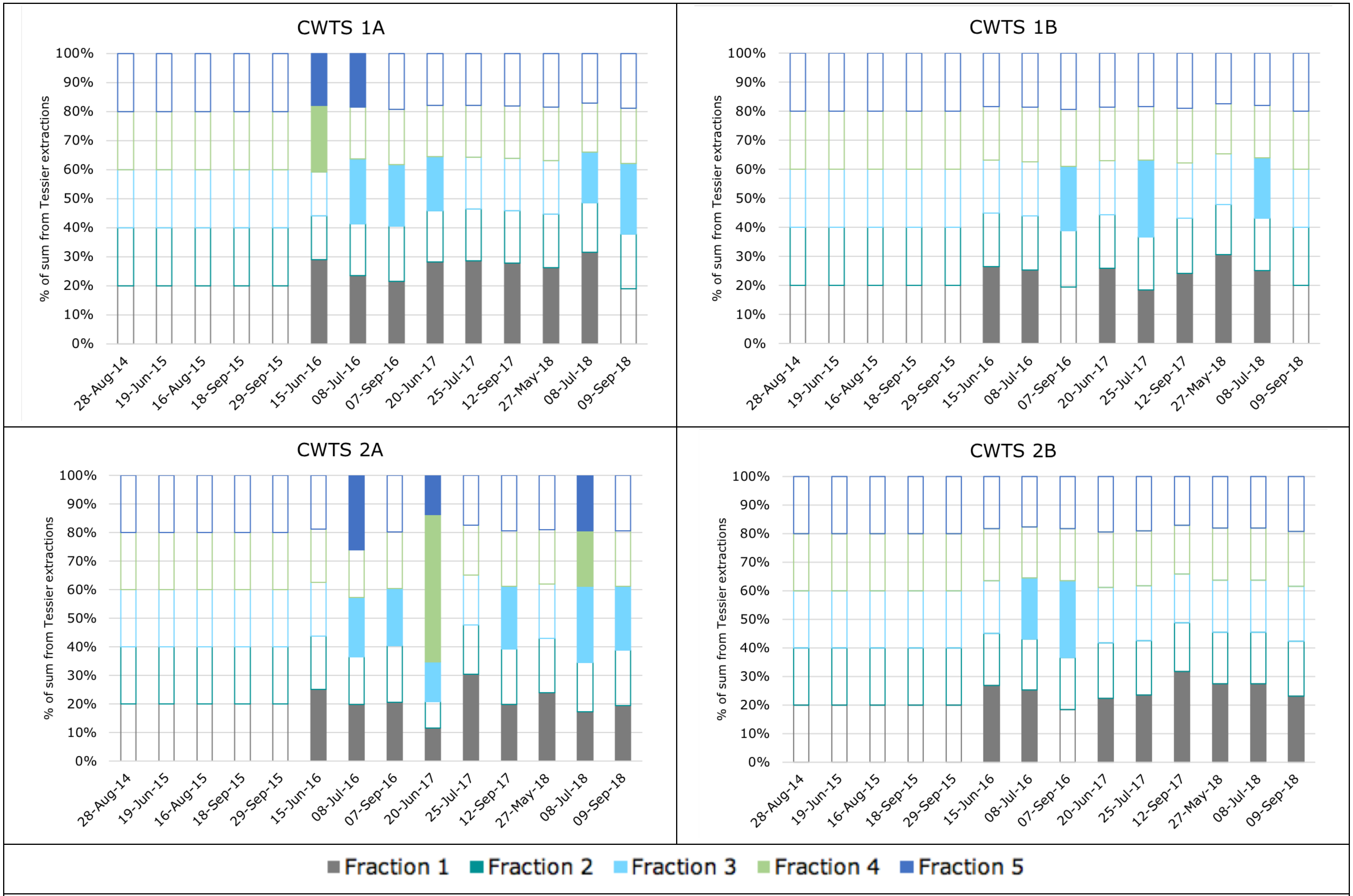


Figure B14 – Fraction distribution of cadmium expressed as percent over time (2014 – 2018).
Unfilled areas are values at or below detection limit. Fractions are defined in Table B3.

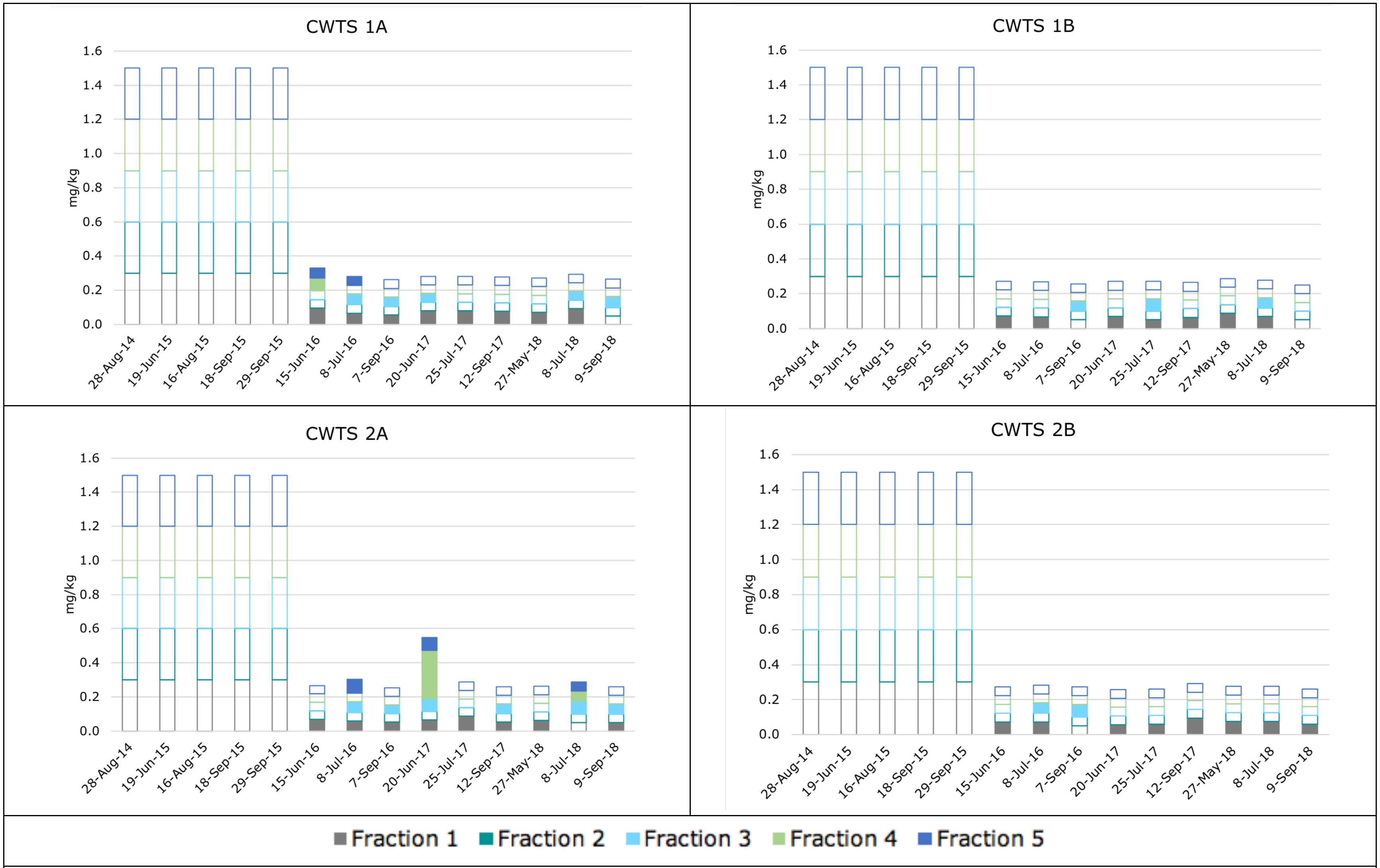


Figure B15 – Fraction distribution of cadmium expressed as mg/kg over time (2014 – 2018).
Unfilled areas are values at or below detection limit. Detection limits changed in 2016 and 2017, which is indicated by the smaller bars after 2015. The detection limit (DL) for cadmium in 2014 and 2016 was 0.30 mg/kg for all fractions. The DL for cadmium in 2016-2018 was 0.050 mg/kg for all fractions. Fractions are defined in Table B3.

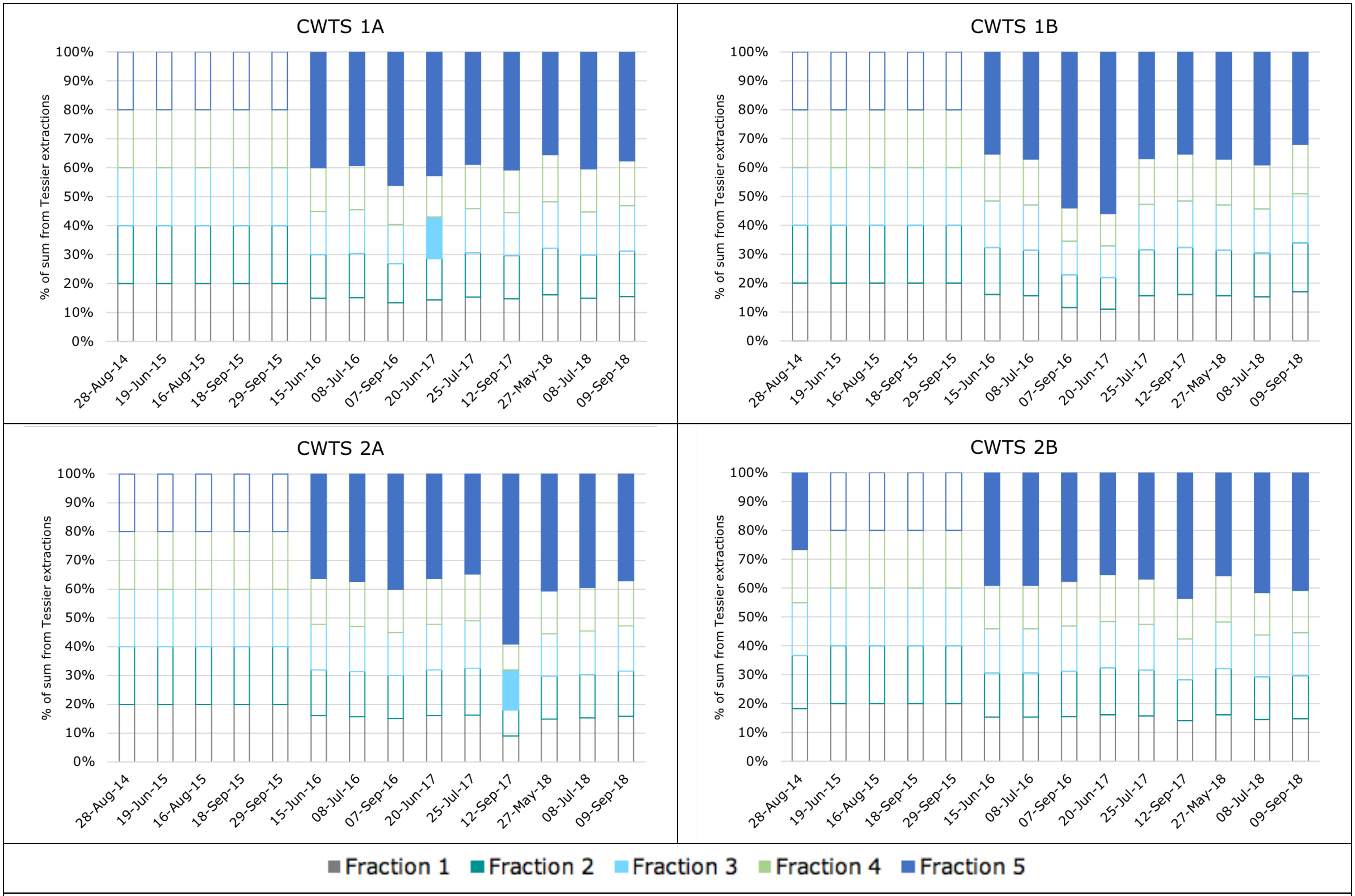


Figure B16 – Fraction distribution of molybdenum expressed as percent over time (2014 – 2018).
Unfilled areas are values at or below detection limit. Fractions are defined in Table B3.

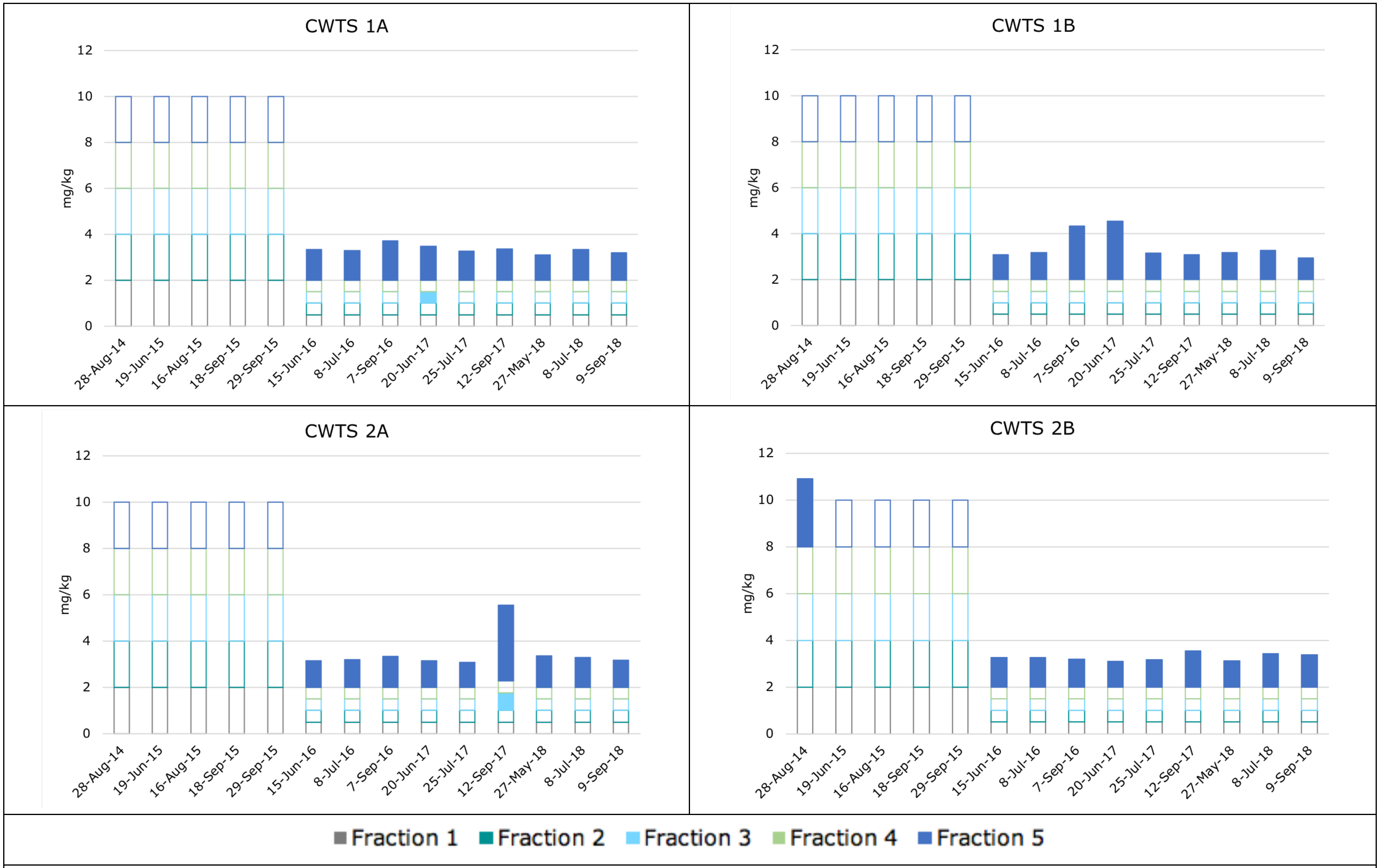


Figure B17 – Fraction distribution of molybdenum expressed as mg/kg over time (2014 – 2018).
Unfilled areas are values at or below detection limit. Detection limits changed in 2016 and 2017, which is indicated by the smaller bars after 2015. The detection limit (DL) for molybdenum in 2014 and 2016 was 2.0 mg/kg for all fractions. The DL for molybdenum in 2016-2018 was 0.50 mg/kg for all fractions. Fractions are defined in Table B3.

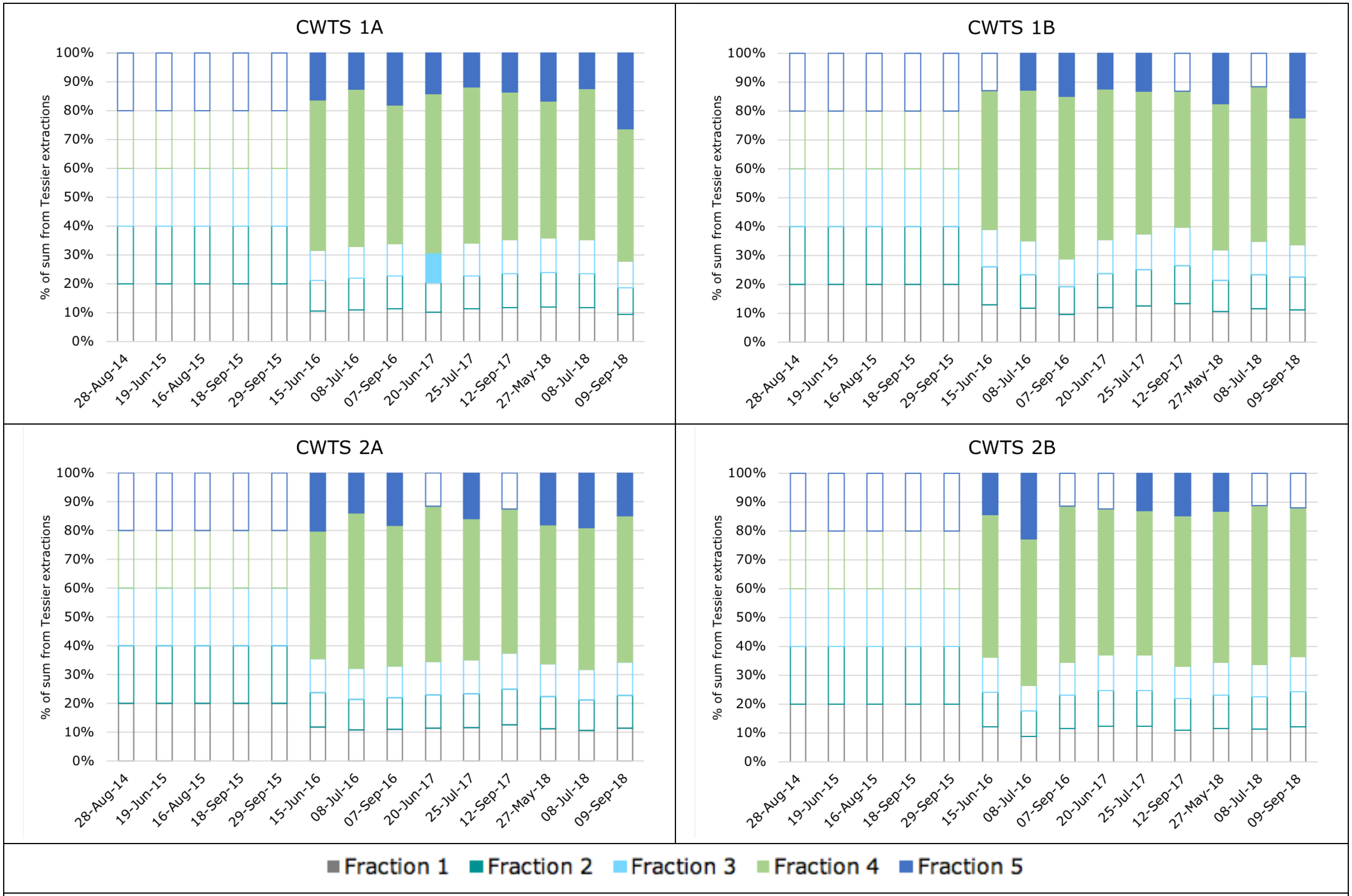


Figure B18 – Fraction distribution of selenium expressed as percent over time (2014 – 2018).
Unfilled areas are values at or below detection limit. Fractions are defined in Table B3.

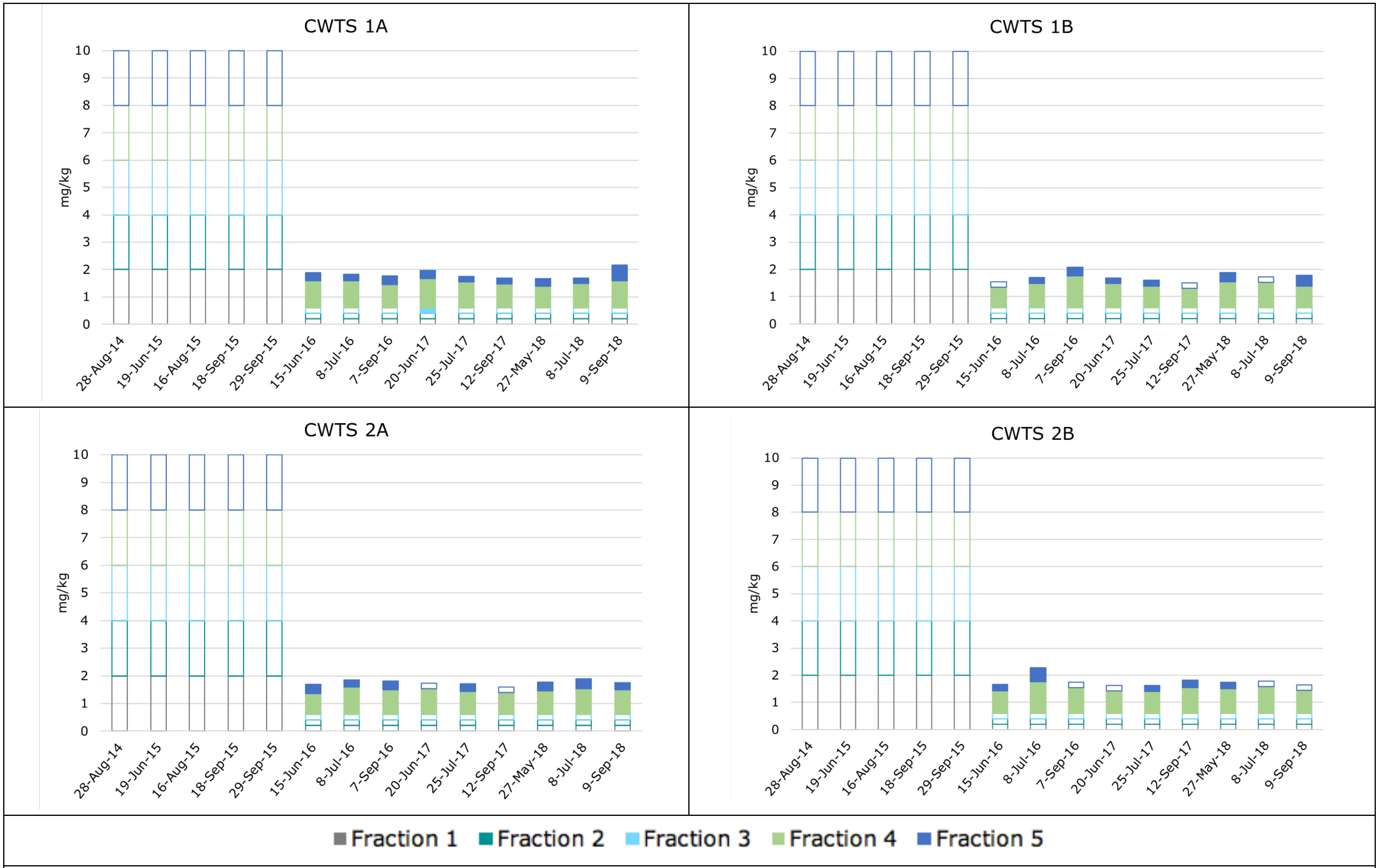


Figure B19 – Fraction distribution of selenium expressed as mg/kg over time (2014 – 2018). Unfilled areas are values at or below detection limit. Detection limits changed in 2016 and 2017, which is indicated by the smaller bars after 2015. The detection limit (DL) for selenium in 2014 and 2016 was 2.0 mg/kg for all fractions. The DL for selenium in 2016-2018 was 0.20 mg/kg for all fractions. Fractions are defined in Table B3.

B3. Plant Results

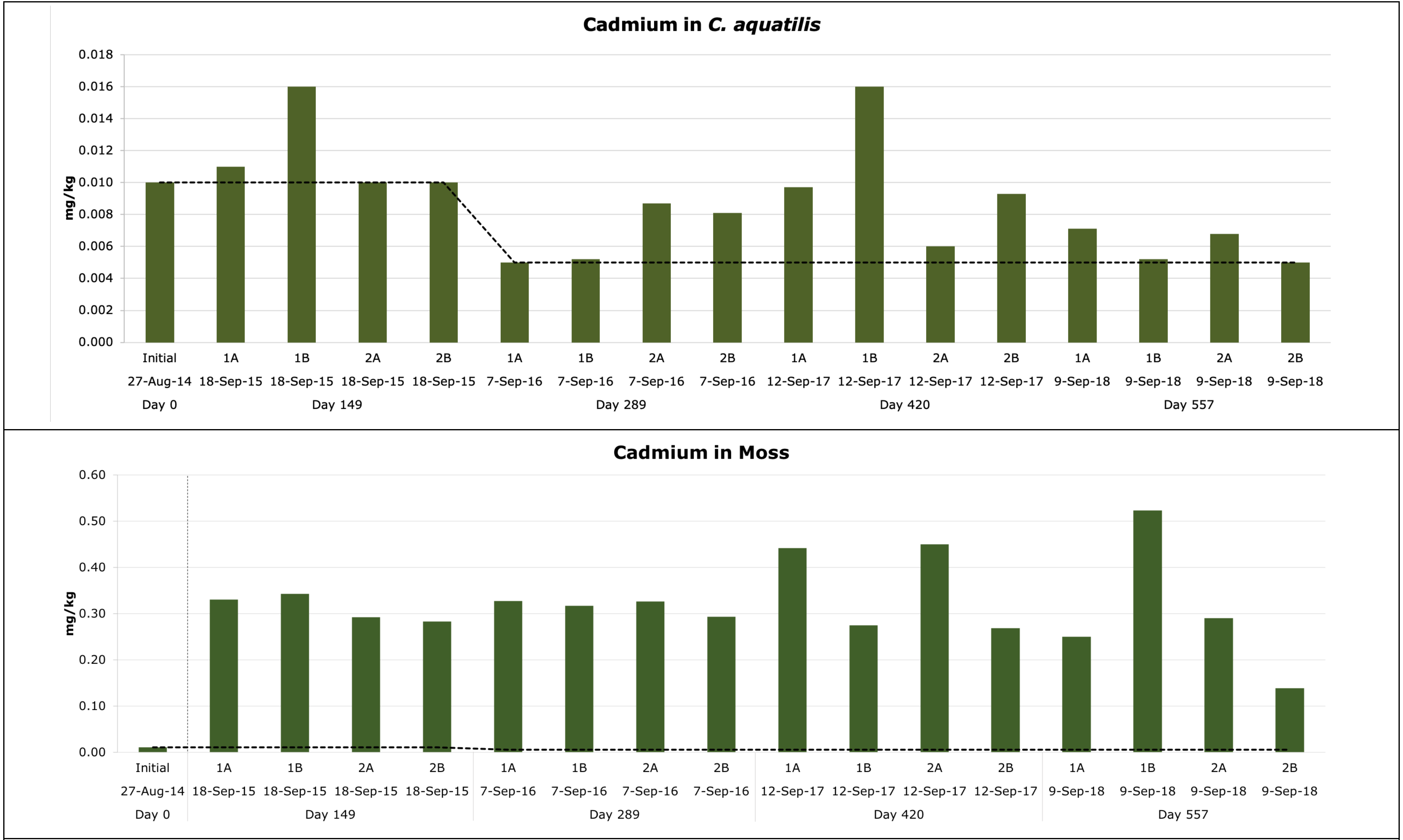


Figure B20 – Cadmium concentrations in plants.
The 2014 detection limit (DL; horizontal dotted line) for cadmium is 0.10 mg/kg, the 2015 DL is 0.010, and the 2016-2018 DL is 0.0050 mg/kg. The initial timepoint is the average of the three *C. aquatilis* or three moss replicates at construction. The vertical dashed line separates the initial timepoint (following CWTS construction) and remaining timepoints.

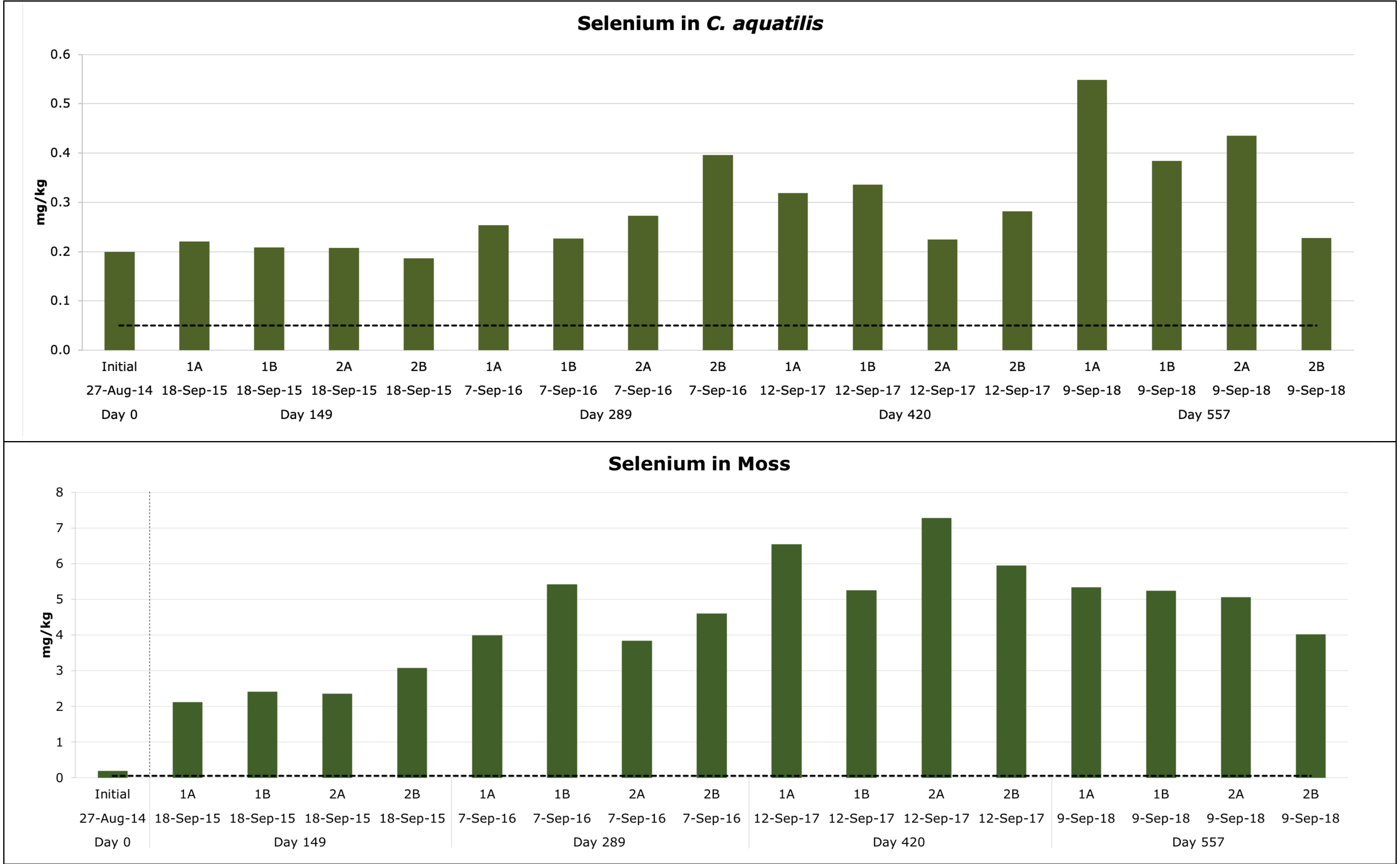
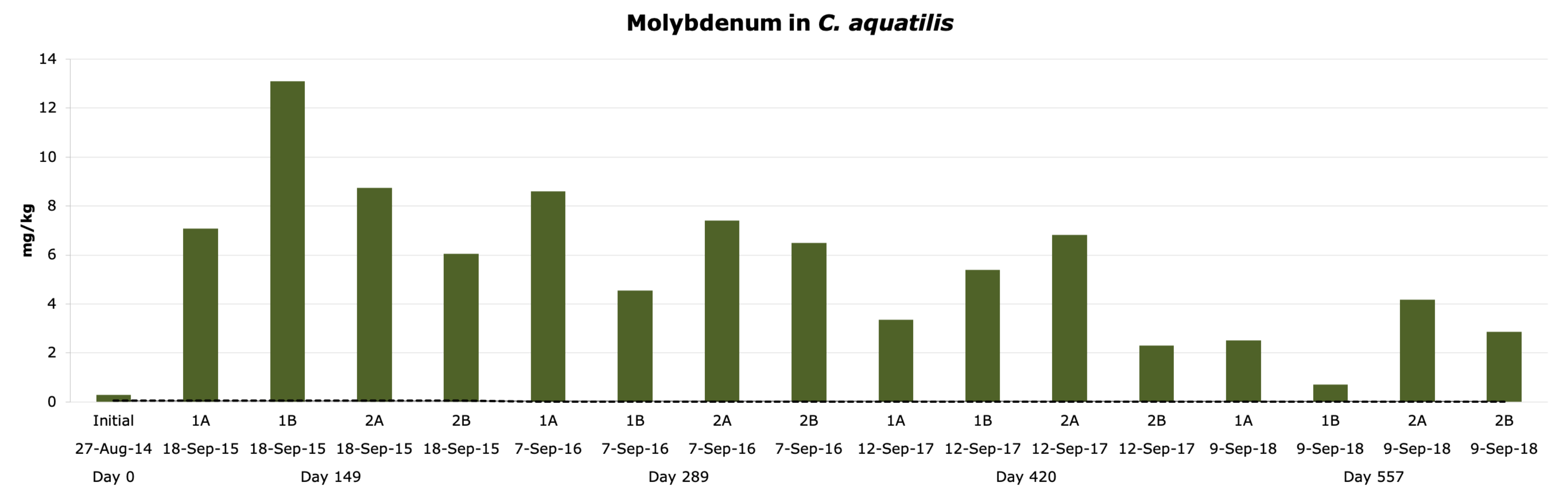


Figure B21 – Selenium concentrations in plants.
The detection limit (DL; horizontal dotted line) for all years for selenium is 0.050 mg/kg. The initial timepoint is the average of the three *C. aquatilis* or three moss replicates at construction. The vertical dashed line separates the initial timepoint (following CWTS construction) and remaining timepoints.



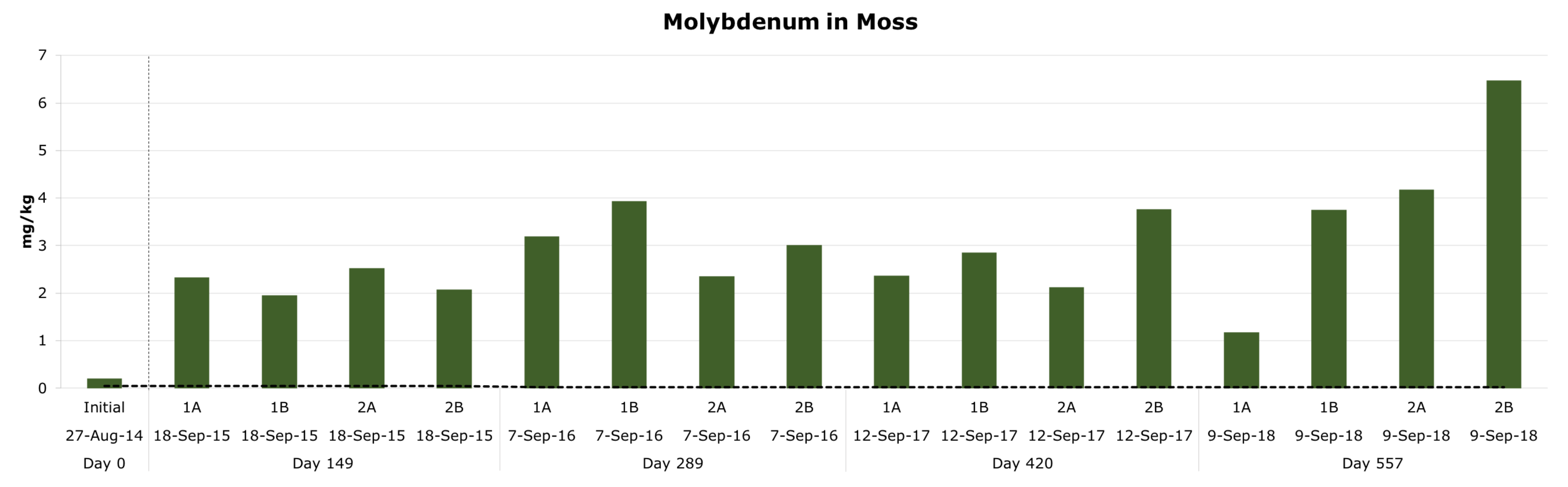
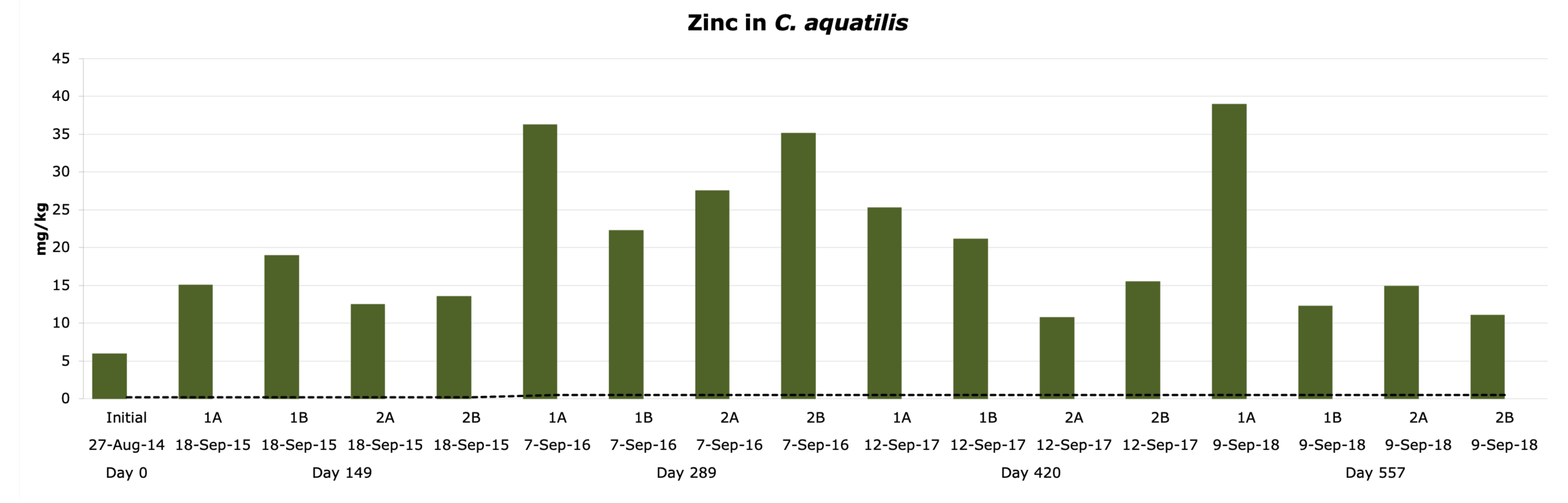


Figure B22 – Molybdenum concentrations in plants.
The 2014 and 2015 detection limit (DL; horizontal dotted line) for molybdenum is 0.05 mg/kg, and the 2016-2018 DL is 0.020 mg/kg. The initial timepoint is the average of the three *C. aquatilis* or three moss replicates at construction. The vertical dashed line separates the initial timepoint (following CWTS construction) and remaining timepoints.



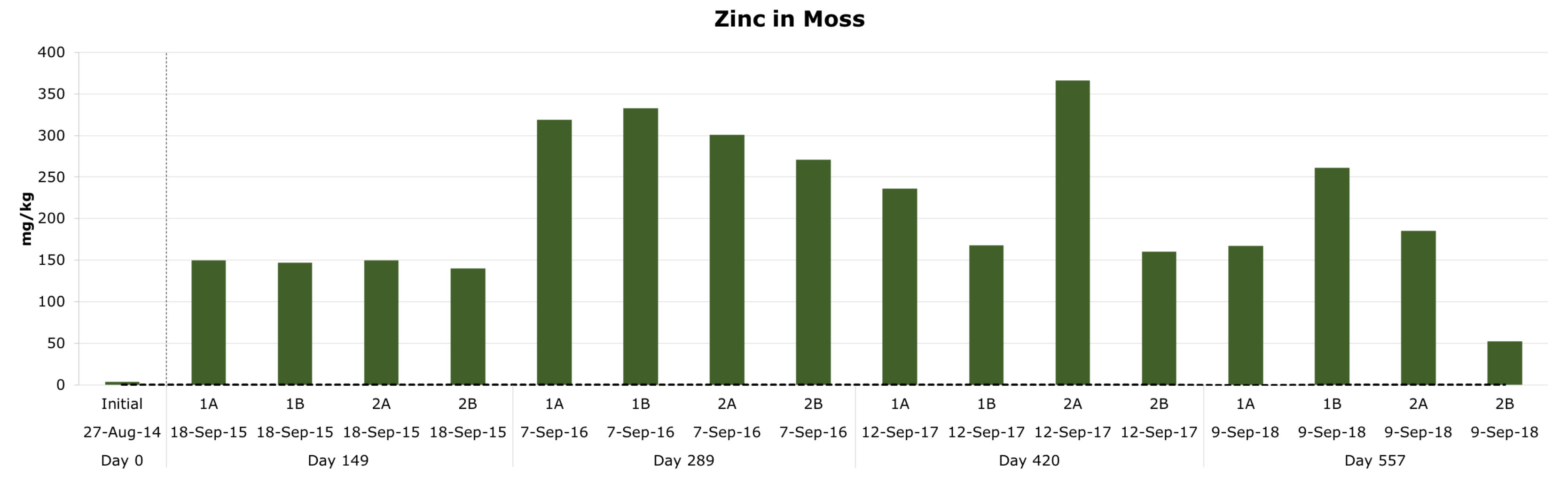


Figure B23 – Zinc concentrations in plants.
The 2014 detection limit (DL; horizontal dotted line) for zinc is 0.20 mg/kg, and the 2016-2018 DL is 0.50 mg/kg. The initial timepoint is the average of the three *C. aquatilis* or three moss replicates at construction. The vertical dashed line separates the initial timepoint (following CWTS construction) and remaining timepoints.

B4. Microbiology Results

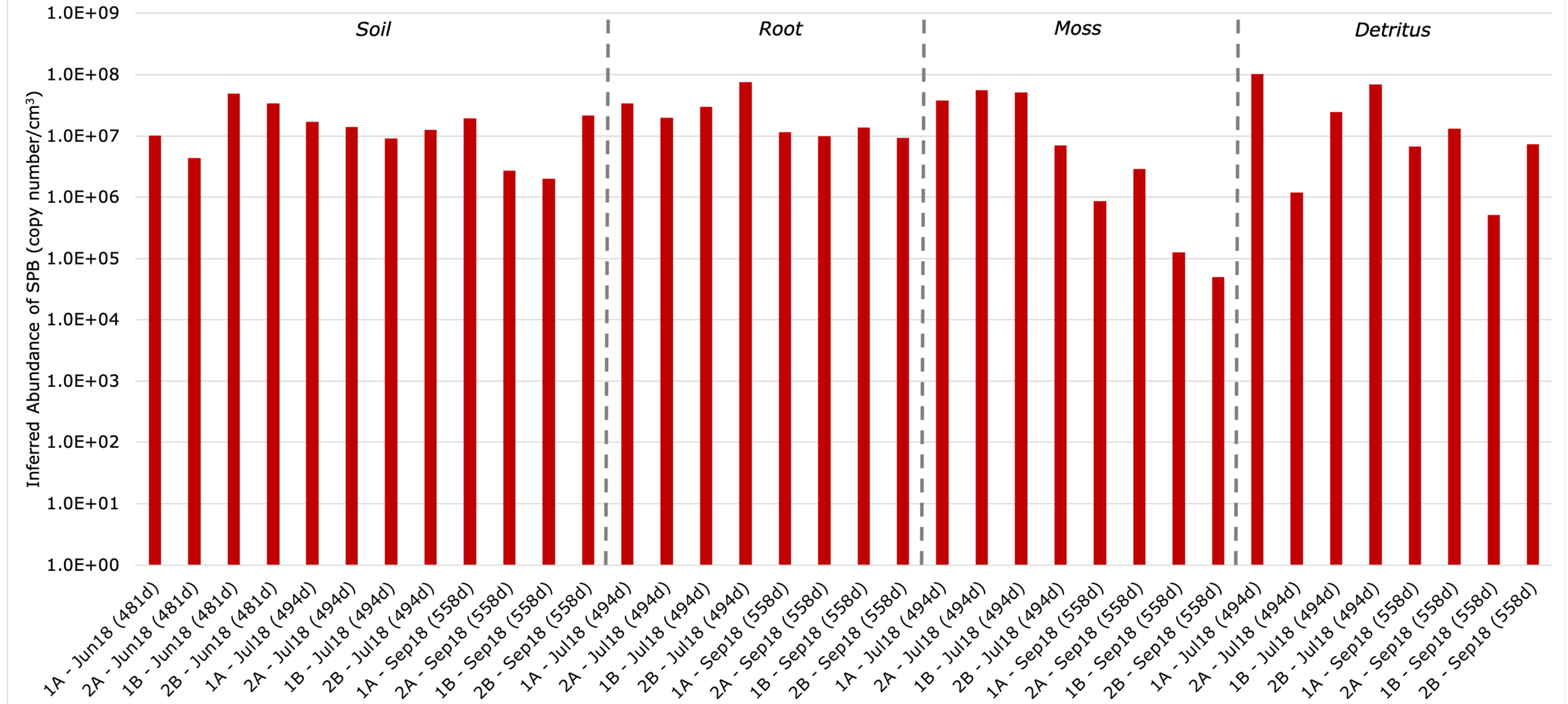


Figure B24 – Inferred abundance of sulphide-producing bacteria in soil, root, moss, and detritus in the demonstration-scale CWTS in 2018.

Inferred abundance is calculated based on a combination of genetic and quantification data. Methods for quantification changed from growth-based analyses (most probable number) from 2014 to 2017 to quantitative polymerase chain reaction (qPCR) analyses in 2018. As methods are not directly comparable (Appendix A, Section A6.5), only results from 2018 analyses are shown here and overall trends for all years are described in the main report.

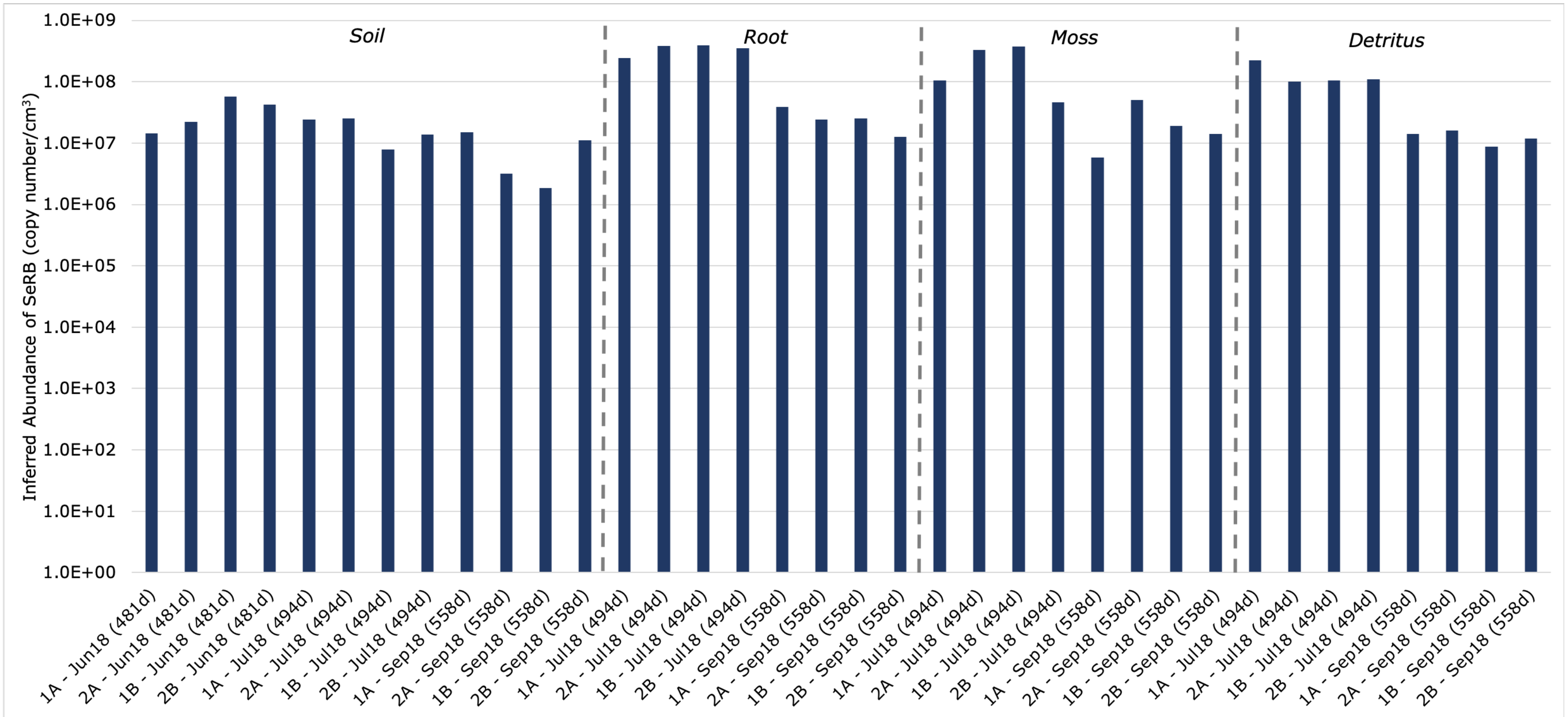


Figure B25 – Inferred abundance of selenium-reducing bacteria in soil, root, moss, and detritus in the demonstration-scale CWTS in 2018.

Inferred abundance is calculated based on a combination of genetic and quantification data. Methods for quantification changed from growth-based analyses (most probable number) from 2014 to 2017 to quantitative polymerase chain reaction (qPCR) analyses in 2018. As methods are not directly comparable (Appendix A, Section A6.5), only results from 2018 analyses are shown here and overall trends for all years are described in the main report.

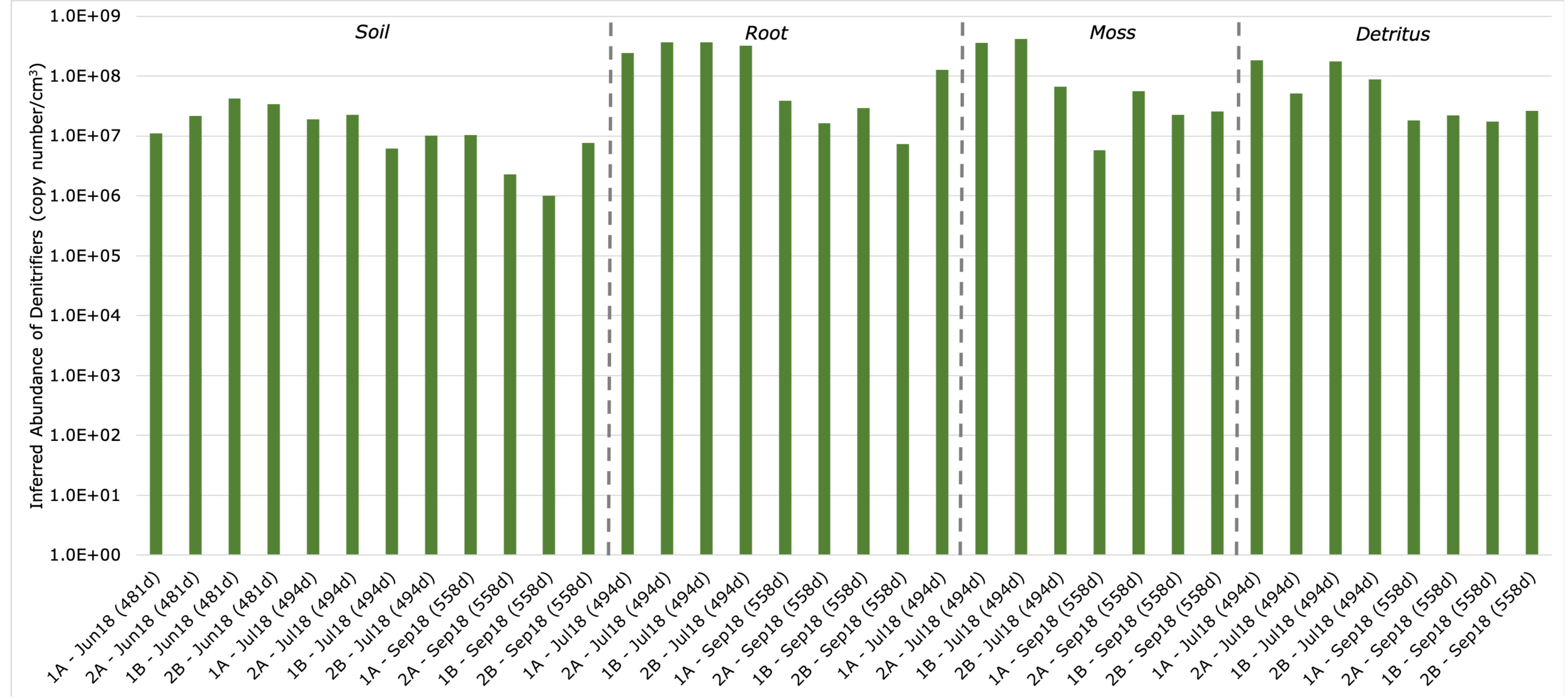


Figure B26 – Inferred abundance of denitrifying bacteria in soil, root, moss, and detritus in the demonstration-scale CWTS in 2018.

Inferred abundance is calculated based on a combination of genetic and quantification data. Methods for quantification changed from growth-based analyses (most probable number) from 2014 to 2017 to quantitative polymerase chain reaction (qPCR) analyses in 2018. As methods are not directly comparable (Appendix A, Section A6.5), only results from 2018 analyses are shown here and overall trends for all years are described in the main report.

Appendix C – Multi-year Workplan

Table C1 – Schedule of work and activities for demonstration-scale CWTS.

Item	Date	Activities	Actual
Construction	2014	Identify potential location for demonstration scale CWTS (Contango site visit – 1 scientist)	Completed June 2014
		Engineering and geotechnical (Minto)	Completed July 2014
		Construction (Minto)	Completed July 2014
		Planting and bringing system online (Contango site visit – 1 scientist, 1 technologist), coordinate for local students to assist	Completed August 2014 (no students available, brought 2 technologists)
Commissioning	2014	Acclimation and maturation at constant flow rate, ~20 hr HRT	Completed
		September - Contango site visit/checkup (1 technologist, 1 scientist)	Did not occur because construction was last week of August
	2015	Continued commissioning. Operation at constant flow rate, ~20 hr HRT	Completed (at shorter HRT)
		Spring – Contango site visit/checkup (1 technologist, 1 scientist), includes micro sampling	Completed
		Summer - Increase depth from 10 cm to 20 cm (1 technologist), includes micro sampling	Completed (scientist)
		Fall – Contango site visit/checkup (1 technologist), includes micro sampling	Completed (scientist)
	2016	Minto to add sandbags prior to first site visit and begin W15 creek monitoring	Completed May/June 2016
		Spring – Contango site visit (1 scientist, 1 technologist), includes microbial sampling and tasks outlined in Table 5 of report. HRT tracer study completed, outlined in section 7 of report.	Completed June 2016
		Summer - Contango site visit/checkup (1 scientist, 1 technologist), includes microbial sampling and tasks outlined in Table 5 of report. Evapotranspiration study completed as outlined in section 9 of report. Organics were added to the CWTS as outlined in section 5.1 of report.	Completed July 2016

Item	Date	Activities	Actual
		Fall - Contango site visit/checkup (1 technologist), includes microbial sampling and tasks outlined in Table 5 of report	Completed September 2016
	2017	Continued commissioning operations at constant flow rate.	Completed May 2017
		Two evapotranspiration studies were completed	Completed May/June 2017
		Spring – Contango site visit (1 scientist, 1 technologist), includes microbial sampling and tasks outlined in Appendix A of report. Completed HRT tracer study. Sample for AVS to assess if the added organics are having the desired effect.	Completed June 2017
		Summer - Contango site visit/checkup (1 scientist), includes microbial sampling and tasks outlined in Appendix A of report.	Completed July 2017. Seasonal water sampling was not completed due to flow interruptions. Seasonal water sampling was completed by Minto in August.
Commissioning		Minto added sandbags to outflows of CWTS cells to increase water depth	Completed August 2017
		Commissioning completed and beginning of operational period	Completed August 2017
Operations		Fall – Contango site visit/checkup (1 scientist), includes microbial sampling and tasks outlined in Table 5 of report.	Completed by Minto, after being taught microbial sampling by Contango. No site visit needed by Contango.
		Monitor soil redox. Determine when it consistently reaches targeted range.	Completed throughout 2017
Performance monitoring	2018	Develop a sampling plan, and aphid control and monitoring plan for 2018	Completed March, 2018
Drought recovery		Start water flow to CWTS; add sandbags to end and along perimeter of each CWTS cell to increase water depth by 1 to 5 cm; aphid control using more powerful insecticide on a routine schedule	Completed May 2018
		Assess recovery of CWTS from drought	Completed throughout 2018
		Summer – Contango site visit (1 scientist); conduct a vegetation plot harvest and assessment of biomass produced; collect one bag of *C. aquatilis* and one bag of polyester filter	Completed July 2018

Item	Date	Activities	Actual
		foam from each CWTS cell; replant *C. aquatitilis* in areas with sparse vegetation	
		Iron added to Series 1	Completed July 2018
		Two evapotranspiration studies were attempted (were not informative due to precipitation during trials)	Completed July/August 2018
Performance monitoring	2019	Fluctuate flow rates, based on expected amount of water for full-scale wetland (scaled to size). Evaluate performance of CWTS at different key periods. Fertilize plants (if necessary).	Throughout 2019
Operations		Develop a flow rate schedule and sampling plan for 2019	April 2019
		Provision of updated standard operating procedures for new staff responsible for monitoring and sampling CWTS	
		Start water flow to CWTS; continue aphid control using insecticide on a routine schedule	April/May 2019
		Spring – Contango site visit; training of new staff responsible for monitoring and sampling CWTS, monitor for presence of aphids, add iron to Series 1, collect one bag of *C. aquatilis* and one bag of polyester filter foam from each CWTS cell	May/June 2019
		Summer – Contango site visit; conduct a vegetation plot harvest and assessment of biomass produced; conduct evapotranspiration trial for warmer months	July/August 2019
		Fall – Contango site visit (if necessary), replanting if needed, soil harvesting for additional off-site stress tests, final sampling event.	September, 2019
Reporting	2014-2020	Reporting will be performed annually, with verbal and/or emailed interim updates	On Schedule

Minto Mine Constructed Wetland Treatment Research Program – Demonstration-Scale 2018 Update Report

Document #011_0119_13B

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Executive Summary

The Minto Mine is an open pit and underground copper mine located 240 km northwest of Whitehorse in the Yukon Territory. As a result of mining activities, cadmium, copper, molybdenum, selenium, and zinc are slightly elevated beyond background concentrations and have been identified as constituents of concern in the Reclamation and Closure Plan for the Minto Mine. As part of the Reclamation and Closure Plan, a constructed wetland treatment system (CWTS) was designed by Contango with the objective of attaining suitable passive treatment of water quality at mine closure. In October 2018, Capstone announced that due to unfavourable equity market conditions, the Minto Mine would be placed into temporary care and maintenance (Capstone, 2018), and that condition is currently in effect.

A phased approach is being followed to guide the site-specific design and implementation of a CWTS at closure. The phased approach for Minto Mine was initiated with a site assessment in 2013 followed by pilot-scale testing to confirm and provide proof-of-concept before constructing the on-site demonstration-scale wetland.

The demonstration-scale constructed wetland treatment system was constructed at Minto in 2014, commissioned from 2015 through mid-2017 and transitioned into the operational period in August 2017. In 2018 it was planned that the demonstration-scale CWTS would continue in the operational period with the primary objective being to assess performance under conditions that would be similar to the full-scale CWTS. However, this objective shifted to assessing the CWTS ability to recover and preform under the unintentionally imposed stresses of a winter/freshet drought and elevated nitrate concentrations (on average 3 times higher than 2017 concentrations in early spring) in the inflow water (feed). This double stress test provided an opportunity to evaluate mitigation strategies for returning the CWTS to an operational status. Recovery period from the double stress test in 2018 was variable for each COC. Additional recovery strategies were attempted on the systems, including stagnation (both series), and addition of iron (Series 1). These recovery strategies are applicable to full-scale operation and are detailed in this report. Recovery periods ranged from 0 days (treatment likely unaffected) to 93 days for different constituents and recovery strategies.

Additional aspects of the performance and operation of the system were measured in 2018 and are detailed in this report including: treatment performance, fate and distribution of treated metals, evapotranspiration, detritus decomposition, microbial community characterization (catalyzing treatment reactions), and pest control.

During the operational period Series 1, (which received an additional recovery intervention strategy of iron addition) achieved an average decrease of 0.0214 µg/L for cadmium, 53.3 µg/L for copper, 8.16 µg/L for molybdenum, 3.15 µg/L for selenium, and 16.1 µg/L for zinc. Series 2, an average decrease of 0.0214 µg/L for cadmium, 49.7 µg/L for copper, 7.06 µg/L for molybdenum, 3.20 µg/L for selenium, and 16.1 µg/L for zinc. Additional positive results were also documented; plant uptake of constituents remained minimal throughout operation, maintenance of high abundance of beneficial sulphide-producing bacteria for metals treatment, and nitrate- and selenium-treating bacteria associated with plant roots.

The operational period of the demonstration CWTS confirmed that the predicted water quality for the Minto Mine at closure is amenable to treatment by these methods. Results from ongoing monitoring of the system in 2019 will be used to inform the designs for the full-scale constructed wetland treatment system.

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Abbreviations and Definitions

Accretion – The process of growth or increase of sediments through deposition and accumulation of organic material deposited solids (such as minerals) within a wetland.

Acid volatile sulphide (AVS) – Sulphide complexed with Fe (FeS) where the sulphide can preferentially exchange Fe for heavy metals (Ni, Zn, Cd, Pb, Cu, Hg) which are then more stably bound.

Amendment – A chemical or organic material added to encourage specific conditions (e.g., aerobic/anaerobic, pH, ORP) or as a source of something that is needed for passive treatment (e.g., nutrients, alkalinity, binding sites, etc).

Bio-Banked – Samples received were stored frozen for potential future DNA extraction and MCP analysis.

Biofilm(s) – A visible and often slimy-looking film (community) of bacteria (may contain other microbes).

Biochemical oxygen demand (BOD) – The amount of dissolved oxygen needed by aerobic microorganisms to break down organic material in water.

Carbon source – A source of carbon (energy/electrons) for microbes (see **electron donors**). Examples include ethanol, methanol, acetate, sugar (glucose), molasses, wood chips, detritus (dead plant matter).

***Carex aquatilis* (*C. aquatilis*)** – A plant (emergent macrophyte) commonly known as water sedge.

Chemical oxygen demand (COD) – A measurement of all organic and inorganic material in the water than can be oxidized.

Contango – Contango Strategies Ltd.

Constituent of Concern (COC) – Specific elements that have been identified for evaluation, including cadmium, copper, molybdenum, selenium, and zinc.

Constructed wetland treatment system (CWTS) – Wetlands that are designed and constructed to remove compounds from water, using natural processes to sequester them into the soils rendering them less bioavailable. They are different from wetlands that provide habitat for wildlife.

Denitrification – Where nitrate (NO_3^-) is reduced by microorganisms to form nitrite (NO_2^-), nitric oxide (NO), or nitrous oxide (N_2O), or nitrogen gas (N_2) (see **nitrate reduction**).

Dissolved organic carbon (DOC) – Organic (carbon based) molecules in water, that have passed through a filter of 0.45 µm.

Dissolved oxygen (DO) – Diatomic oxygen (O_2) dissolved in water; oxygen can dissolve in water by diffusion from surrounding air, as a product of photosynthesis, or through forced aeration.

Explanatory parameters – Quantifiable parameters that describe how water treatment reactions take place.

Evapotranspiration – The process by which water is transferred to the atmosphere by evaporation from the surface of water and by transpiration from plants.

Forebay – A Forebay is an artificial pool of water in front of a larger body of water. The larger body of water may be natural or man-made. In the context of a CWTS a forebay can allow for the addition of supplementary amendments (e.g. organics, iron) as needed.

Genetic analysis/sequencing – Analysis to assess the presence, identity, and diversity of different microbes in a sample.

Hydraulic retention time (HRT) – The residence time of the inflow water to outflow.

ICP-MS – Inductively coupled plasma mass spectrometry.

Microbes – Microscopic organisms that cab be uni- or multi-cellular. This includes algae, bacteria, fungi, viruses, and yeast.

Most probable number (MPN) – A statistical value representing the viable population of microbes in a sample through use of dilution and multiple inoculations.

Nitrate reduction – Where microbes reduce nitrate (NO_3^-) to form nitrite (NO_2^-); the first step in denitrification (see **denitrification**).

Nominal HRT – The targeted HRT calculated based on the targeted flow rate for a given size of wetland.

Oxidation – The loss of electrons, or increase in valence state, by a molecule, atom, or ion. Can be driven by microbes. Process is complementary to chemical reduction.

Oxidation-reduction potential (ORP) – A measure of the tendency of a chemical species to acquire or donate electrons, thus becoming reduced or oxidized, respectively, measured in millivolts.

Redox – Oxidation-reduction potential (in sediment), a measure of the tendency of a chemical species acquire or donate electrons, thus becoming reduced or oxidized, measured in millivolts. This measurement is relative to the water ORP.

Reduction (chemical) – The gain of electrons, or a decrease in valence state, by a molecule, atom, or ion. Can be catalyzed by microbes. Process is complementary to chemical oxidation.

Selenium reduction – Microbially mediated reduction of soluble Se(VI) and Se(IV) to insoluble elemental selenium.

Simultaneously extracted metals (SEM) – amounts of heavy metals such as Ni, Zn, Cd, Pb, Cu, Hg in sediment, assessed in the context of AVS for excess sulphide. (also see **acid volatile sulphide**)

Sorption – The physical and/or chemical process by which one substance becomes attached to another substance.

Specific conductivity (SPC) – A measurement of electrical conductivity in water that is typically expressed in μs/cm, which has been adjusted for temperature (25°C).

Species (sp.) – One of the basic units of biological classification and a taxonomic rank. Rank in the classification of organisms below genus and above strain. Also can be used to refer to the oxidation state of a mineral (e.g., selenate and selenite are species of selenium).

SPLP – Synthetic precipitation leachate procedure.

Sulphide – An inorganic anion of sulphur that can form stable complexes with metals and make them insoluble in water (remove them from the water).

Sulphide producing bacteria (SPB) – Microbial reduction of sulphur compounds, such as sulphate, sulphite, thiosulphate, and sulphur, which produces sulphides and alkalinity. (see also **SRB**).

Sulphate reducing bacteria (SRB) – a form of sulphide producing bacteria that specifically uses sulphate for reduction (see **sulphide producing bacteria**).

Sulphide production – Microbial reduction of sulphur compounds, such as sulphate, sulphite, thiosulphate, and sulphur, which produces sulphides and alkalinity.

Total dissolved solids (TDS) – A measure of the combined organic and inorganic salts dissolved in water.

Total kjeldahl nitrogen (TKN) – The sum of organic nitrogen, ammonia (NH_3), and ammonium (NH_4^+) in water (or soil). To calculate the total nitrogen, the concentrations of nitrate as N (NO_3^-N) and nitrite (NO_2^-N) are added to TKN.

Total organic carbon (TOC) – A measurement of the total organic carbons present in water.

Total suspended solids (TSS) – A measurement of all particles in water that are larger than 2 µm (anything smaller than 2 µm considered a dissolved solid).

Transfer – Processes that treat water by transferring a constituent to another location without changing its form. For example: absorption, adsorption, dilution, dispersion, filtration, precipitation (aqueous to solid), and volatilization.

Transform – Processes that change the chemical form or state of a constituent. For example: biodegradation, biotransformation, hydrolysis, ionization, oxidation, photolysis, and reduction.

1. Introduction

The Minto Mine, owned and operated by Capstone Mining Corp. (Capstone), is located 240 km northwest of Whitehorse on the west side of the Yukon River. The Minto Mine is a combination open pit/underground copper mine that has been mining since October 2007. In October 2018, Capstone announced that due to unfavourable equity market conditions, the Minto Mine would be placed into temporary care and maintenance (Capstone, 2018), and that condition is currently in effect.

The Minto Mine has been in commercial operation since October 2007 and the deposits being mined are copper sulphide mineralized zones. Surface and groundwater water quality is a key consideration in the evaluation of potential effects of mining and mineral development projects and changes to water quality parameters have the potential to affect aquatic and human use of water resources. A Reclamation and Closure Plan (RCP) is required under both the Water Use License and the Quartz Mining License. The RCP is intended to address the long-term physical and chemical stability of the site and closure of the proposed features and disturbances associated with the mine. As a part of the RCP, a Constructed Wetland Treatment System (CWTS) is being designed, evaluated, and optimized for water treatment at closure through a phased program approved during the Minto Phase V/VI Expansion Project (Yukon Online Registry Project Number 2013-0100).

The CWTS is currently undergoing a phased design approach, including design, evaluation, and optimization for post-closure water treatment. Constituents of concern that are being evaluated through the CWTS program include cadmium, copper, molybdenum, selenium, and zinc. Nitrate is also being evaluated as it impacts treatment rates by consuming electrons (Contango, 2014b).

The phased design used at the Minto Mine include:

1) Site assessment and information gathering (complete);
2) Technology selection and conceptual design (complete);
3) Pilot-scale testing and optimization (controlled environment, off-site; complete);
4) Demonstration-scale confirmation and optimization (on-site; current scope); and
5) Full-scale implementation (future scope).

Phases 1 to 3 have been completed, and this work is summarized in the Site Assessment, and Pilot-Scale reports (Contango, 2014a and 2014b). Phase 4 of the project is currently underway, with the on-site demonstration-scale CWTS constructed at the Minto Mine during fall 2014. Commissioning was conducted from 2015-2017 and operations beginning in late 2017 with update reports provided annually (Contango, 2015, 2016; 2017a; 2017b).

The primary objective of the demonstration-scale program in 2018 was to assess performance under conditions that would be similar to the full-scale CWTS. However, this objective shifted to assess the CWTS ability to recover and preform under the unintentionally imposed stresses of a drought and elevated nitrate concentrations in the inflow water (feed). These imposed stresses will be herein referred to as the double stress test period.

Due to delays in running water to the system, the cells had dried out significantly by May 2018 and soils were exposed to air. This was problematic as the demonstration-scale CWTS was designed to operate under reducing conditions requiring constant water cover. This spring drought scenario is highly unlikely to occur in full-scale operation as that system would have water entering from gravity flow from freshet, rather than the pumped scenario of the demonstration-scale CWTS. Even though the freshet drought scenario is unlikely to occur at full-scale, the information gathered could generally inform about recovery from drought scenarios for other times of year. Furthermore, upon analysis of data, it was determined that nitrate concentrations in the influent (feed) from May to mid-June 2018 were on average 14.5 mg/L, which is about three times higher than nitrate concentrations in the same timeframe in 2017. While elevated nitrate concentrations are a potential stress that could occur on the full-scale CWTS in early closure, it is not expected to be a concern in long term closure as the residues from blasting will deplete over time.

The recovery from the double stress test period and subsequent calculation of operational removal rate coefficients (RRC; *k*) were the focus of the 2018 program documented in this report. Other ongoing activities that have been reported on in previous years and continued in 2018 included:

- Evaluating CWTS performance, and determining achievable concentrations of contaminants of concern (COCs; performance limits);
- Updating site-specific RRCs with data from the operational period;
- Determining the amount of water loss due to evapotranspiration and the effect on outflow concentrations;
- Monitoring metals leaching from the mineralized soils used in construction;
- Monitoring for the presence of aphids in the CWTS, and implementing a routine insect pest control plan (for aphids);
- Determining the rate and extent of detritus decomposition (*Carex aquatilis* leaves) in the CWTS over time;
- Assessing treatment mechanisms (including microbes).

Other activities completed in 2018 included:

- Adding sandbags to the end and along the perimeter of each CWTS cell to increase the water depth (to enhance reducing conditions) and minimize short circuiting (would be achieved by rip rap armouring in full-scale system);
- Replanting areas in the CWTS that had been impacted by aphid infestation in 2017;
- Monitoring of explanatory parameters and performance to determine when the double stress test recovery was complete, and full operational capacity had returned;
- Assessing the stability of COCs in soils and production of acid volatile sulphides (AVS) with the addition of iron to Series 1; and
- Harvesting of a vegetation plot to determine amount of growth of above water biomass of *C. aquatilis* in a 1 m^2 plot.

Results and recommendations are presented within this main document, while background information and methods are provided in Appendix A, data in Appendix B, and summary of past and future recommended activities in Appendix C. Operations of the CWTS are detailed in Section 2, timeline and sampling schedule in Section 3, and results in Section 4. Summary of results and next steps for 2019 are summarized in Sections 5 and 6, respectively.

2. Demonstration-Scale CWTS Operations 2018

2.1 Overview of operations

The demonstration-scale CWTS was constructed in 2014 and commissioned throughout 2015 - 2017 (Table 1). The completion of commissioning and the start of operations was marked by the achievement of the expected treatment performance objectives on August 18, 2017 (Table 1). Details on the construction and commissioning can be found in past Contango reports (Contango, 2015; 2016; 2017a; 2017b). In 2018, it was anticipated that the CWTS would continue with the operational period; however, due to the unintentionally imposed stresses of drying out of the CWTS and the elevated nitrate concentrations in the spring (May to mid-June), an opportunity arose to determine the effects these stresses on CWTS performance and assess the amount of time needed for the CWTS to recover. Beginning of the operational period (and, therefore recovery from the double stress test) was marked by meeting the same criteria used to determine the end of commissioning period in 2017 and by achieving consistent extent of removal of COCs, comparable or better removal than what was observed during the operational period in 2017 (Contango, 2017b). The following criteria were used to evaluate stress test recovery and are further discussed in the sections as listed:

- Plant establishment and maturation such that the plants have grown in to densities visually similar to natural wetlands in the area, but in monoculture (Section 2.6),
- Establishment of reducing conditions within the CWTS soils (i.e., average soil redox was below -100 mV consistently in 2018; Section 4.1),
- No increase in aqueous copper concentrations through the CWTS (due to leaching from copper containing soils used in construction; Sections 4.2.1 and 4.6),
- Achieving consistent extent of removal of COCs, comparable or better than removal observed during the operational period in 2017 (Section 4.2.3), and
- Microbial population establishment and maturation to levels similar or better to 2017 operational period (Section 0).

Once the above criteria were met, the CWTS was deemed to be returned to operational status. The same criteria, other than the copper leaching (which would be avoided by proper substrate selection), could be used for the full-scale CWTS.

2.2 Recovery period and definition of operational period

Recovery period from the double stress test in 2018 was variable for each series and COC and is further discussed in Section 4.2.2. Additional recovery strategies were attempted on the systems, including stagnation (both series), and addition of iron (Series 1). Recovery periods ranged from 0 days (treatment likely unaffected) to 54 days for Series 1 and 0 days (treatment likely unaffected) to 93 days for Series 2. For consistency of data analysis and comparison of performance between series, only data from when recovery criteria were met for all COCs in both series, and flows were at target levels was used (August 17 to September 9, 2018). This 24 day period will be referred to as the 2018 operational period (
Table 1). Flow to the CWTS continued until September 28, 2018; however, intermittent flow occurred after September 9, 2018 due to pumps and waterlines freezing. Although treatment

continued to occur, it was not possible to calculate accurate retention times therefore removal rate coefficients were not calculated for this time period. Discussions in this document are focused on the defined operational period of August 17 to September 9, 2018.

Table 1 – Days of operation of demonstration-scale CWTS.

Scale	Year	Period (days)	Date	
			Start	End
Commissioning-A[2]	**2014[1]**	23	Aug 27	Sep 19
	2015	135	May 16	Sep 29
	2016	87	May 2	Jul 28
Commissioning-B[3]	**2016**	63	Jul 29	Sep 30
	2017	82	May 27	Aug 17
Operational Period[3]	**2017**	35	Aug 18	Sep 22
Double Stress Test Period - Series 1[4]	**2018**	0-54	May15	Jul 8
Double Stress Test Period - Series 2[4]	**2018**	0-93	May15	Aug 16
Operational Period[4]	**2018**	24	Aug 17	Sep 9

[1] The CWTS was constructed in 2014, but no water testing occurred during this first month of commissioning-A.

[2] The end of the commissioning-A period and beginning of the commissioning-B period was marked by the addition of organics on July 28, 2016.

[3] The end of the commissioning-B period and beginning of the operational period in 2017 was marked by stabilization of flow rates and resolution of feed water delivery complications.

[4] The end of the double stress test period and beginning of the operational period in 2018 was marked by re-establishment of commissioning criteria. Series 1 recovered sooner than Series 2.

2.3 Start-up

The Minto Mine typically experiences fully frozen conditions from October to March, with overnight freezing temperatures beginning in September and persisting until May (Access, 2013). To start-up the demonstration-scale CWTS at the Minto Mine, temperatures must be sufficiently above freezing to operate the water supply pumps from monitoring station W62. In 2018, the criteria for the pumps was met on May 11, 2018 and water was pumped from station W62 to the header tank and subsequently into the CWTS on May 14, 2018 (Figure 2).

Once the ice and snow as melted from the CWTS, it was also observed on May 11, 2018 that the standing water in the CWTS had receded from all four cells (Figure 1), exposing the soils to oxygen for a period of time, and potentially releasing metals from the soils once the flow of water was re-introduced to the system. Ideally, a reducing CWTS such as that at Minto should operate under a constant water cover to maintain reducing conditions. This scenario of spring freshet drought is not expected to occur during full-scale operations as water will be flowing into the wetland by gravity as spring melt occurs and will not rely on pumps with seasonal constraints to supply water to the CWTS.

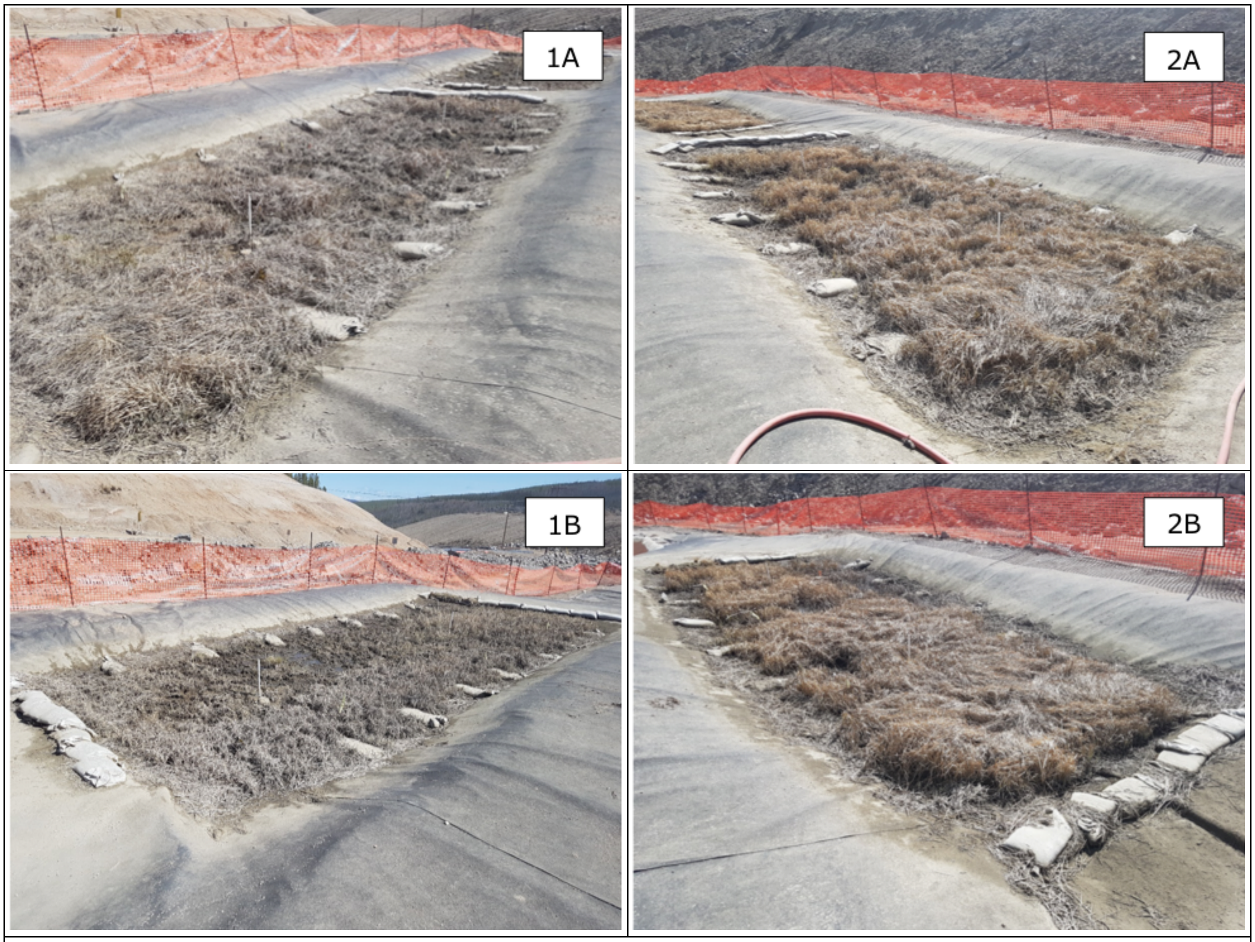


Figure 1 – Demonstration-Scale CWTS prior to start-up on May 11, 2018.

No standing water in cells as water dried out in early spring/freshet. Although vegetation is brown, other vegetation around the area is also brown at this time of year. Therefore, actual effects of drought on vegetation could not be evaluated at this time.

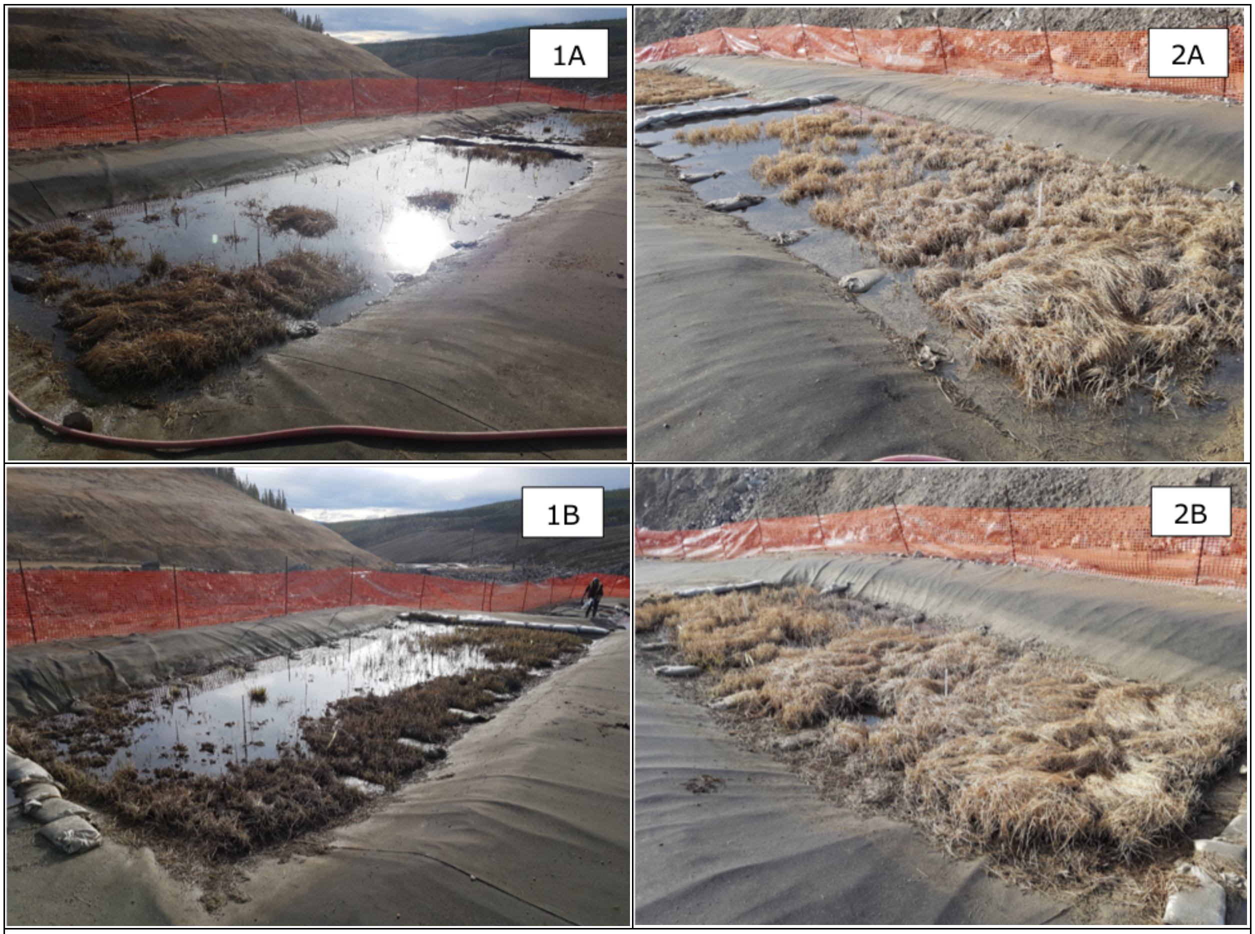


Figure 2 – Demonstration-Scale CWTS after water was pumped into the system on May 14, 2018.

2.4 Water Depth

Sandbags were added to the end and along the perimeter of each CWTS cell on May 18, 2018 to increase the water depth and minimize short circuiting, respectively. At full-scale short circuiting would be achieved by rip rap armouring around the edges of the wetland. The increase in water depth was conducted to promote reducing conditions and speed recovery of the cells from the drought. The depths were increased by 1 to 5 cm in each of the four cells (Table 2).

Table 2 – Demonstration-scale CWTS water depths.

CWTS Cell	Water Depth 2017 (cm)	Water depth 2018 (cm)
1A	15.2	20.2
1B	16.0	20.3
2A	15.9	18.6
2B	14.4	15.6

2.5 Flow Rates

To facilitate recovery of the CWTS cells from the double stress test, a long hydraulic retention time (HRT) was required to reintroduce reducing conditions. The targeted nominal HRT was calculated using the actual depth in each series (after adding sandbags on May 18, 2018; Section 2.4), plus the correction factor obtained from the 2017 tracer study. The targeted HRT was 7.25 days. Actual flow rates varied from the targeted flow rates and are presented with their corresponding HRTs in Table 3.

Once the CWTS had recovered from the double stress test, the targeted flow rates were continued into the operational period (August 17 to September 9, 2018) to continue monitoring the extent of treatment of COCs at a low flow. Due to flow meter fluctuations, the actual flow rates varied from targeted flow rates as outline in Table 3 below.

The flow rates were increased on September 10 to obtain a nominal HRT of 5 days to mimic the nominal HRT in 2017. However, due to unintentional changes in flow rates and shutdown of the demonstration-scale CWTS on September 28, 2018, there was limited data provided at the increased flow rate and the data collected from September 10 – 28, 2018 was omitted from further interpretation.

Table 3 – 2018 targeted and actual flow rates and corresponding HRTs.

Testing Period	Series 1				Series 2			
	Flow		HRT		Flow		HRT	
	GPM (m^3/day)		days		GPM (m^3/day)		days	
	Target	Actual	Target[3]	Actual[4]	Target	Actual	Target[1]	Actual[2]
Double Stress Test Period[3]	0.37 (2.02)	0.32 (1.76)	7.25	8.42	0.31 (1.69)	0.25 (1.39)	7.25	7.61
Operational Period[4]	0.37 (2.02)	0.36 (1.95)	7.25	7.60	0.31 (1.69)	0.27 (1.49)	7.25	7.09

[1] Targeted HRTs were calculated with the targeted depth of 0.2 m corrected with the 0.01 m depth correction factor from the tracer study of 2017 (Contango, 2017b).

[2] Actual HRTs were calculated with the actual measured depth corrected with the 0.01 m depth correction factor from the tracer study of 2017 (Contango, 2017b).

[3] Actual HRT and flow rate are an average from May 15 to August 16, 2018.

[4] Actual HRT and flow rate are an average from August 17 to September 9, 2018.

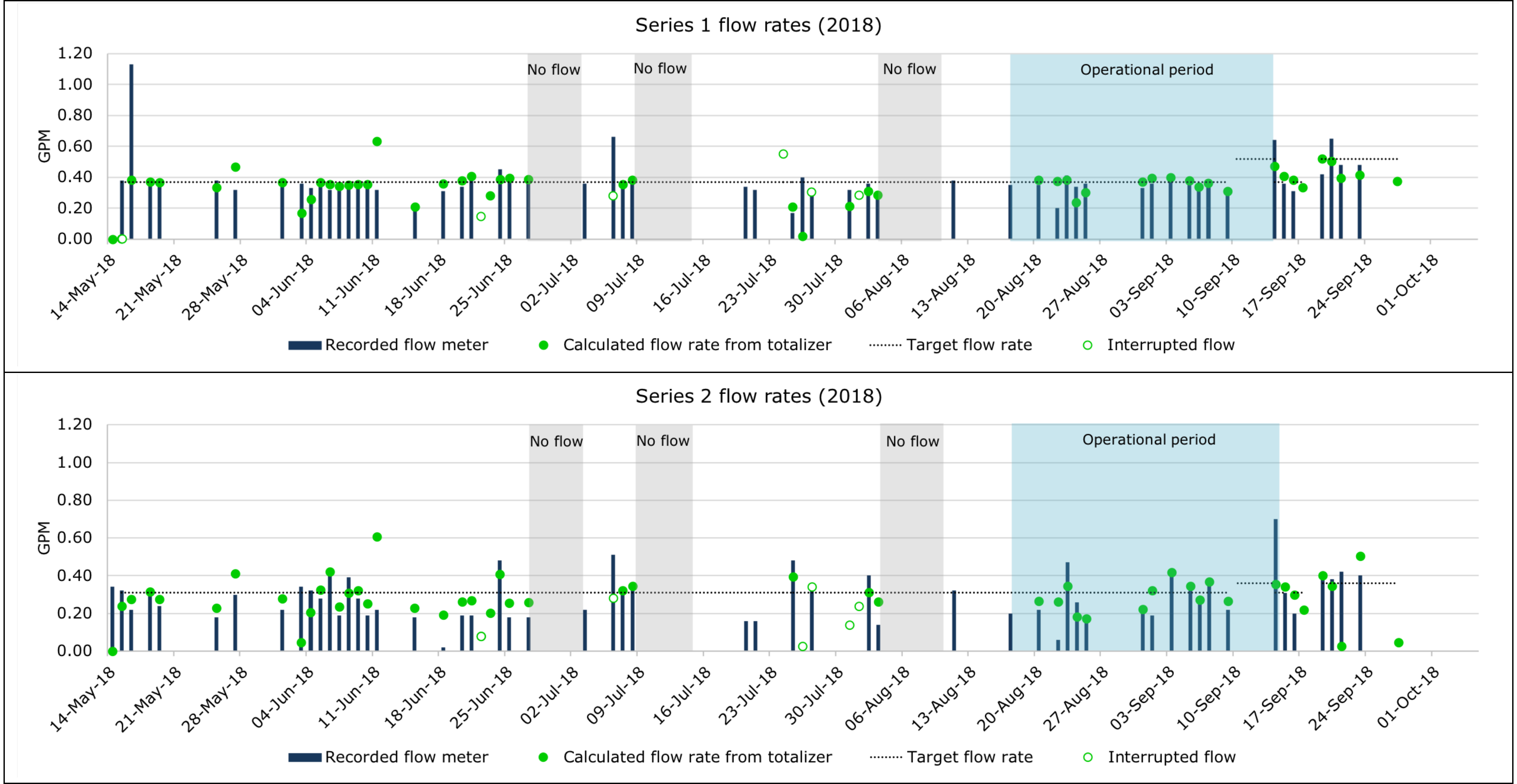


Figure 3 – Flow rates during CWTS operations in 2018.

Blue bars indicate flow rates displayed on flow meter, while green dots are flow rates calculated from the totalizer values (values from meter were recorded by Minto personnel). Specific flow rates of 0.37 and 0.31 gallons per minutes (GPM) for Series 1 and Series 2, respectively, were targeted where the lower flow rates in Series 2 are due to the smaller size of Series 2 cells. Due to flow meter fluctuations, the actual flow rates during the drought recovery period averaged 0.32 and 0.25 GPM for Series 1 and Series 2, respectively. The totalizer value is the cumulative volume of water passing through the flow meter between two measurement dates. Areas with no blue bars or green dots are time periods where flow rates and totalizer values were not recorded. Areas shaded grey indicate dates of interrupted flow due to evapotranspiration trials. Areas shaded blue indicate the 2018 operational period. Further details are outlined in Table 3.

2.6 Health and Establishment of CWTS Vegetation

2.6.1 Carex aquatilis

During the commissioning period, plants establish and mature, with density expected to increase over time. From planting in 2014 to the last site visit in July 2017, *Carex aquatilis* thrived in the CWTS creating a dense emergent macrophyte monoculture, supplemented with aquatic mosses (Figure 4). Due to the location of the CWTS on the waste rock dump being in a relatively isolated area, away from other vegetation and potential sources of predatory insects, in July 2017, an aphid infestation occurred in the CWTS which affected the growth of *C. aquatilis* (September 2017 and May 2018 photos in Figure 4, Contango, 2017b). The biomass above water partially died off, however, the plants continued to send out new shoots suggesting the *C. aquatilis* were resilient to the infestation. To assist with plant recovery in 2018, the CWTS was sprayed with pesticide biweekly starting on May 14, 2018 (Section 4.8), and on July 8, 2018, *C. aquatilis* was replanted where vegetation was sparse. Plant re-establishment and maturation such that the plants had grown in to densities visually similar to natural wetlands in the area, but in monoculture, was reached after replanting *C. aquatilis* (Figure 4), with the exception of cell 1A which was still recovering. Weekly pesticide application was conducted starting on August 24, 2018 to control a small aphid population in cell 2A (Section 4.8). It is recommended that pictures of the CWTS cells are taken from all four corners to better monitor plant growth and development in the cells in 2019.

Generally, the *C. aquatilis* has been successful in creating the desired conditions for water treatment, and the results of the 2018 operations confirm that *C. aquatilis* is a good candidate for use in the full-scale CWTS at Minto.

2.6.2 Moss

Aquatic mosses have also continued to mature and expand in size from 2014 through 2018 (Figure 5). The mature mosses show signs of successful transfer (sorption, filtration) and transformation (mineralization, reduction) processes such as new green biomass at the top of moss and black decomposition at the bottom of the moss.

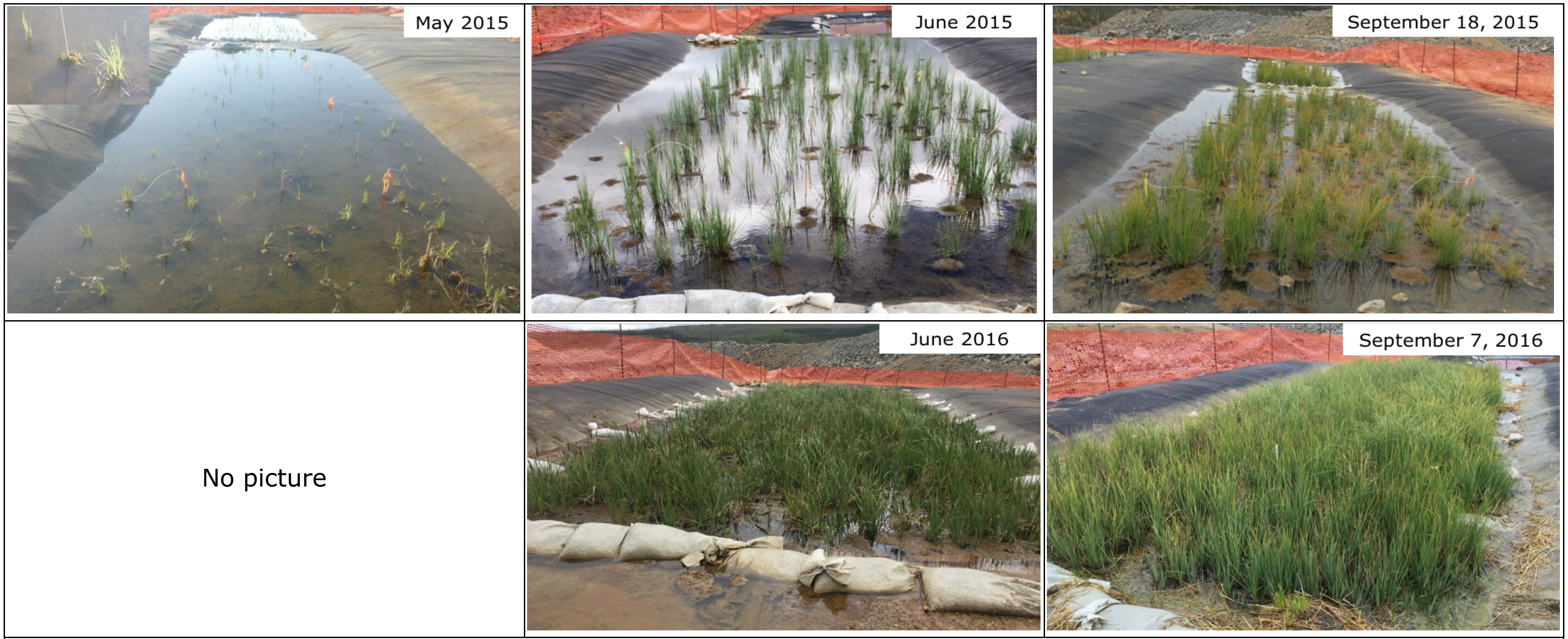


Figure 4 – Maturation of the CWTS from construction through operations.
2015 pictures show cell 2A. 2016 pictures show cell 1B.

Figure 4 continued – Maturation of the CWTS from construction through operations.
2017 and 2018 pictures show cell 1B. September 12, 2017 shows increased yellowing and die off in cell 1B due to aphid infestation.

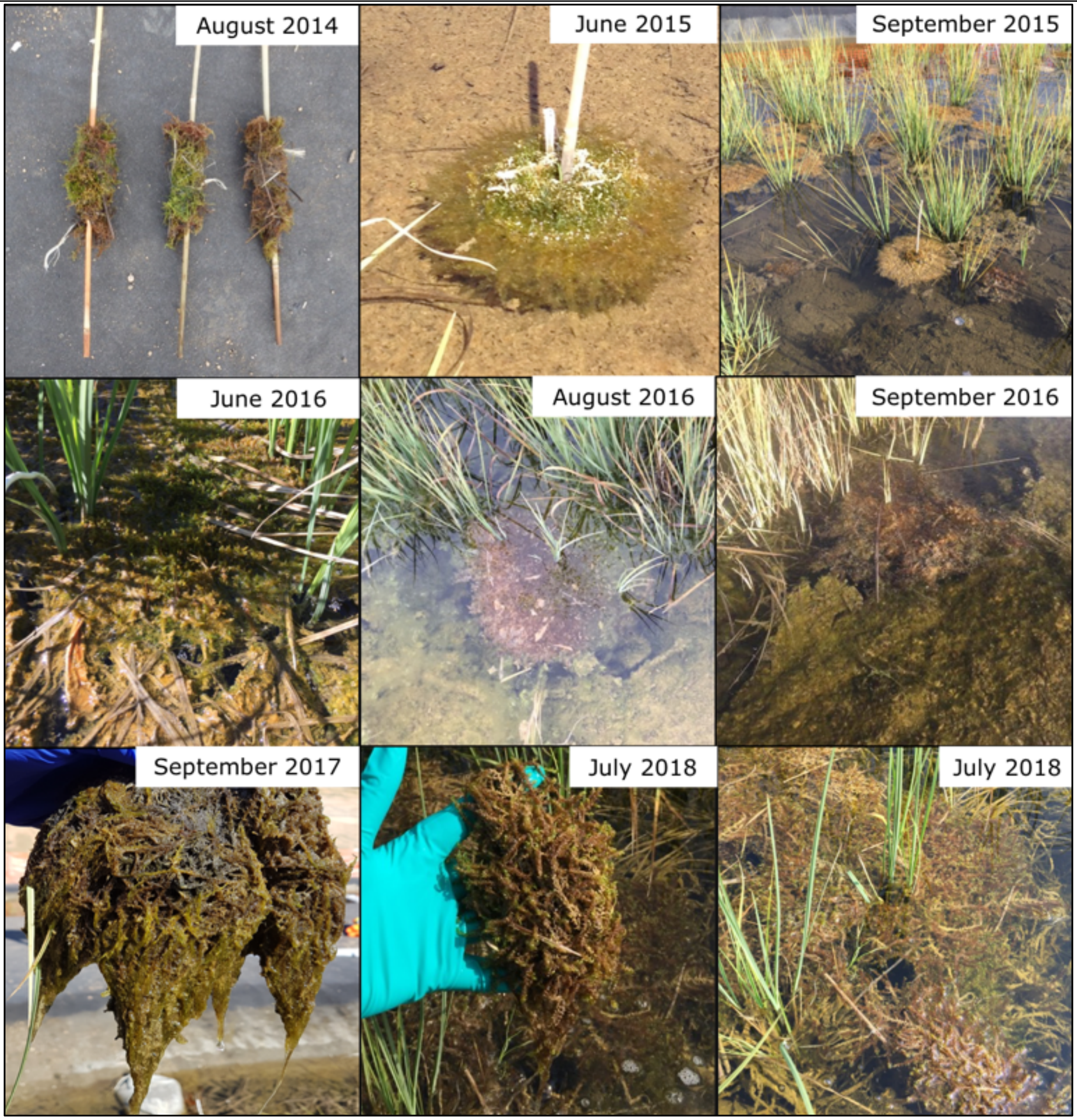


Figure 5 – Moss maturation in CWTS from construction through operations.

3. Timeline and Sampling Schedule

Major events and operational adjustments or amendments for 2018 are listed in Table 4. Details for events up to 2018 can be found in the Minto Demonstration-scale 2017 Update Report (Contango, 2018). The actual dates as well as effective days of operation are provided, which adjusts for time that the CWTS was not receiving water when it was frozen. The effective days of operation allows for comparison to expected timelines from the pilot-scale testing, and for planning and scheduling to be done for full-scale construction and commissioning. The sampling schedule for 2018 was conceptually developed prior to beginning construction of the demonstration-scale CWTS (Appendix A). Actual dates of sampling were adjusted for timing of spring thaw and winter freeze-up, and the associated ability to have the pumps operating at the W62 sump to supply water to the demonstration-scale CWTS.

Table 4 – Events and sampling activities in 2018.

Event	Key Activity	Flow Rate Recorded m^3/day (GPM)		Dates	Effective Days of Operation (start date = August 27, 2014)
		Series 1	Series 2		
Aphid spraying started	Applied insecticide biweekly	n/a	n/a	May 14, 2018	439
CWTS refilled	Re-established water level post drought	No flow	No flow	May 14, 2018	439
Drought recovery period started	Flow started	2.07 (0.38)	1.74 (0.32)	May 15, 2018	440
Water level raised	Added sandbags	2.02 (0.37)	1.64 (0.30)	May 18, 2018	443
Spring seasonal sampling	Tested soils, water & sampled microbiology[1]	1.74 (0.32)	1.64 (0.30)	May 27, 2018	452
Spring microbiology re-sampling	Tested microbiology[1]	2.13 (0.39)	0.98 (0.18)	June 25, 2018	481
Evaporation Study #1	Flow stopped	No flow	No flow	June 27, 2018	483
	Flow re-started	1.96 (0.36)	1.20 (0.22)	July 3, 2018	489
Contango Site Visit #9 & summer seasonal sampling	Tested microbiology, soils, water, detritus bags, and vegetation plot	1.96 (0.36)	1.74 (0.32)	July 7 – 9, 2018	493 – 495
Sedge transplanted	Replenished aphid devastated areas	No flow	No flow	July 8, 2018	494
Iron addition	Flow stopped	No flow	No flow	July 8, 2018	494
	Flow re-started	*	*	July 15, 2018	501
Fertilizer additions started	Applied biweekly to *C. aquatilis*	n/a	n/a	July 14, 2018	500
Unknown flow and HRT	Missed totalizer record	*	*	July 20, 2018	506
Evaporation Study #2	Flow stopped	No flow	No flow	Aug 3, 2018	520
	Flow re-started	*	*	Aug 10, 2018	527
Operational period for all COCs began				August 17, 2018	534
Aphids observed and spraying regiment changed	Applied insecticide weekly	n/a	n/a	August 24, 2018	541
Target flow rates increased	Adjusted flow to target a 5 day HRT	2.83 (0.52)	1.96 (0.36)	September 10, 2018 – September 14, 2018	558 – 562
Flow rate unintentionally reduced[2]	Adjusted flow to drought recovery targets	2.29 (0.42)	2.07 (0.38)	September 14, 2018 – September 19, 2018	562 – 567
Winter freeze up	Flow stopped & wetland closed	0.00 (0.00)	0.00 (0.00)	September 28, 2018	576

'*' – indicates that no flow rate was given or that flow rate was unmeasurable or variable; however, cells remained flooded throughout. n/a – flow rate not applicable.

[1] Contango received microbiology samples that exceeded hold times for testing. Microbiology re-sampled on June 25, 2018 was bio-banked until analyzed.

[2] Due to miscommunication on site, new target flow rates were returned to original target flow rates.

4. Results

4.1 Monitoring Explanatory Parameters

Key findings (detailed below):

- Dissolved oxygen (DO) increased during the double stress test period and operations in 2018. Elevated DO is likely the result of photosynthesis of algae, which had increased growth due to fertilizer addition. Despite the DO levels being in aerobic ranges, stable reducing conditions were achieved in CWTS soils within the targeted range.
- Other than the day that the CWTS was refilled (May 14, 2018), soil redox was unaffected by the drought. Average soil redox values were more reducing (and stable in the targeted range) in 2018 than 2017.

Average water temperature of the demonstration-scale CWTS in 2018 were similar to those in 2015 (12.9°C), 2016 (10.2°C), and 2017 (9.7°C). The average water temperature during the operational period in 2018 was 9.8°C, ranging from 6.4°C to 12.6°C. Conductivity decreased slightly since 2017, and as expected, pH remained circumneutral. Water oxidation-reduction potential (ORP) was similar to 2017 (Table 5).

During operations, DO concentrations in the CWTS cells in 2018 were on average 7.9 mg/L, which is higher than the operational period in 2017 (Table 5). DO measurements at Minto were taken mainly during the day, between 8 am and 4 pm, when DO concentrations have been shown to be higher (SRCSD, 1998). Furthermore, DO fluctuations are generally more extreme in open (such as the demonstration-scale CWTS in this phase where vegetation is still growing in) versus densely vegetated waters and may vary based on distance through the wetland (SRCSD, 1998). Algae can also cause DO levels to fluctuate through their photosynthetic cycles, which peak during the afternoon and are at a minimum in the early morning (SRCSD, 1998). Algae growth increased compared to 2017, particularly in cell 1A, due to the addition of fertilizer, and average DO was notably higher than other cells (10.0 mg/L in 1A, compared to 8.1, 5.1, and 8.5 mg/L in 1B, 2A, and 2B, respectively). The elevated DO in cell 1A is associated with decreased performance in that cell, specifically for selenium and copper (Section 4.2.3). Despite the elevated DO concentrations, treatment in Series 1 still occurred by the end of the B cells. Due to the fluctuations in DO, it is recommended that DO is measured at various locations and water depths through the CWTS in 2019 for a more thorough understanding of aerobic zones within the CWTS.

Table 5 – Average *in situ* measurements from the demonstration-scale CWTS.

Testing Period		DO (mg/L)	Conductivity (µS/cm)	pH	ORP (mV)	Soil redox (mV)
Demonstration-scale 2015		10.0	817.9	8.11	147.9	-52
Demonstration-scale 2016	Commissioning-A[1]	15.9	890.9	7.79	143.7	-85
	Commissioning-B[2]	8.4	1020	7.59	157.6	-89
Demonstration-scale 2017	Commissioning-B[3]	4.3	795.9	7.43	18.7	-162
	Operational period[4]	5.3	879.7	7.36	124.9	-152
Demonstration-scale 2018	Double stress test period[5]	6.1	753.0	7.55	143.3	-176
	Operational period[6]	7.9	703.4	7.45	143.1	-178

DO – dissolved oxygen; ORP – oxidation-reduction potential.

[1] Data for commissioning-A period is from May 2-July 28, 2016.

[2] Data for commissioning-B period is from July 29-September 30, 2016.

[3] Data for commissioning-B period is from May 27-August 17, 2017.

[4] Data for operational period is from August 18-September 22, 2017.

[5] Data for double stress test is from May 15-August 16, 2018.

[6] Data for operational period is from August 17-September 9, 2018.

As expected from the pilot-scale testing, the soil redox in all the demonstration-scale CWTS cells has decreased and stabilized to within the targeted range (-100 and -250 mV; Contango, 2014b), indicating maturation of the CWTS (Figure 6). At the end of 2016, the demonstration-scale CWTS had begun achieving soil redox values that are conducive to sulphide production due to the decomposition of the organics that were added on July 28, 2016 (Contango, 2017). By the end of 2017, the CWTS had matured and became self-sufficient in producing enough organic matter to maintain reducing soil redox conditions between -100 and -250 mV. In 2018, the average soil redox in Series 1 was unaffected by the CWTS drying out in early spring/freshet, while Series 2 was above -100 mV on May 14, 2018. However, the average soil redox in Series 2 decreased to ideal reducing conditions by May 27, 2018 without additional carbon amendments. The average soil redox for Series 1 and 2 was -176 mV during the double stress test period and remained in the targeted range (-178 mV) throughout the operational period in 2018, indicating a matured CWTS. Soil redox will continue to be monitored throughout operation in 2019.

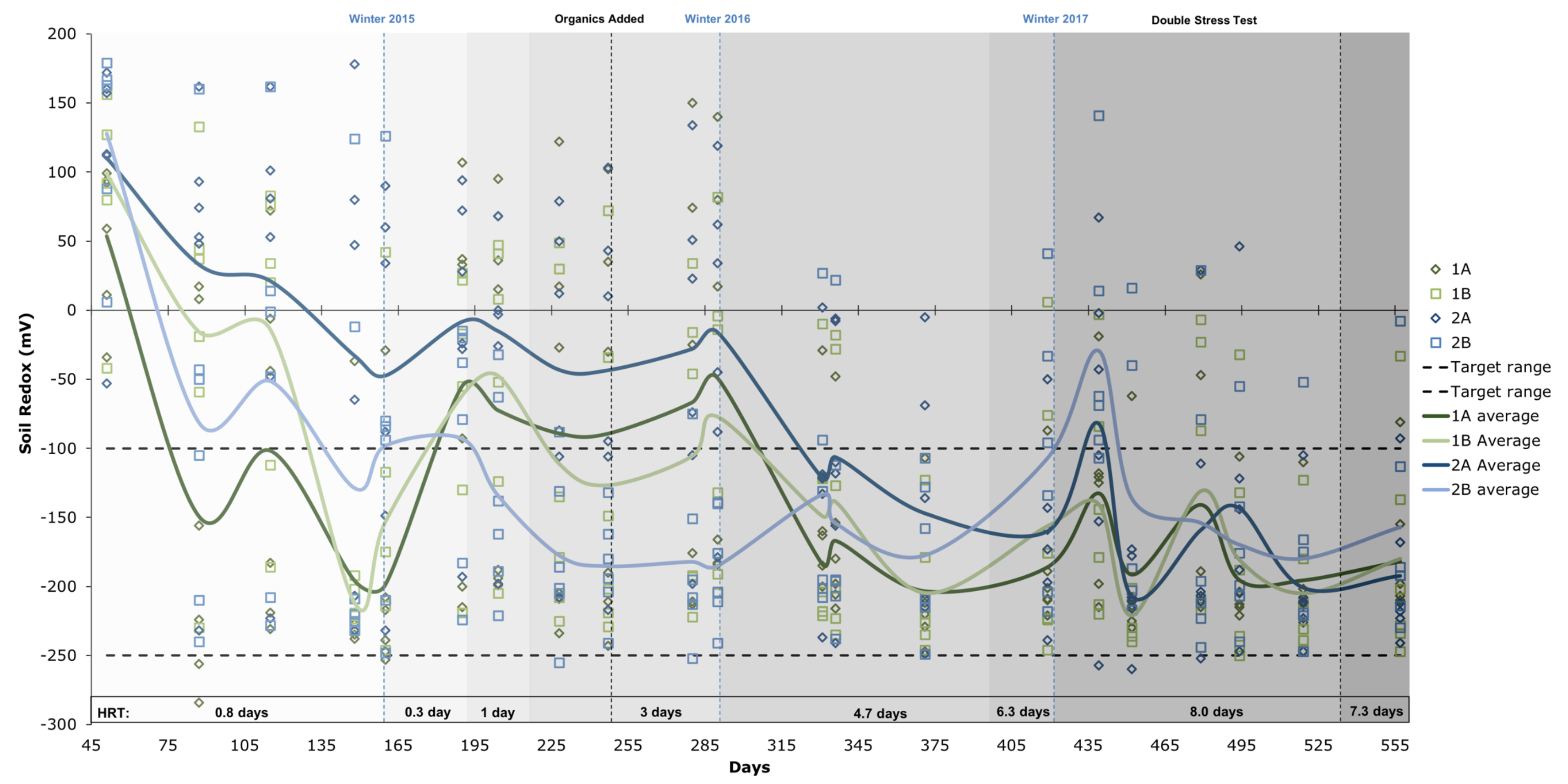


Figure 6 – Soil redox potential of each CWTS cell over time.

All demonstration-scale CWTS soil redox measurements are plotted. Targeted soil redox values based on pilot-scale testing are indicated with dotted lines. The blue dotted line indicates break in measurements for winter 2015, 2016, and 2017. Grey shading corresponds to periods of nominal HRT (days) in 2015 and 2016 indicate the nominal HRT. Grey shading corresponds to periods of nominal HRT (days) in 2017 and 2018 indicate the actual HRT (average of Series 1 and 2) using recorded water depths and flow rates during those time periods.

4.2 Water

Key findings (detailed below):

- While leaching of copper from substrates used in construction was remedied by the end of the commissioning-B period in 2017, copper leached from the soils into the water in early 2018, likely due to the drying out of the CWTS in the early spring/freshet of 2018. However, leaching had subsided by July 8, 2018 as the rate of treatment exceeded the rate of leaching. Copper is not expected to leach in 2019 operations provided that the CWTS remains flooded.
- Stagnation and iron addition can be used at full-scale to mitigate recovery length after periods of drought (or stagnation/slower HRT for high nitrate concentrations).
- During the 2018 operational period the demonstration-scale CWTS successfully treated all COCs.

4.2.1 Metal Leaching from Soils into Overlaying Water

Due to metals leaching from the soils, the treatment occurring within the CWTS was far greater than what was being observed by simply measuring the inflow and outflow points. Therefore, additional sampling locations were tested throughout the CWTS in 2017 and 2018 to identify these fluctuations. Details of the sampling methods can be found in Appendix A of the Minto Constructed Wetland Treatment Research Program – Demonstration Scale 2017 Update (Contango, 2017b). Graphs showing concentrations of copper throughout the CWTS are presented in Figure 7, while graphs for the remaining COCs can be found in Appendix B (Figures B1 to B4).

Since the beginning of operations of the demonstration-scale CWTS, significant concentrations of copper have been leaching from the CWTS soils used in construction (Contango, 2016, 2017a, and 2017b; Section 4.6). Once sufficient reducing conditions were established at the end of the 2017 commissioning-B period, copper leaching subsided as treatment occurred at a faster rate than leaching (Contango, 2017b). However, due to the drying out of the CWTS in early 2018, copper once again began leaching from the soils into the water in Series 2 (June 22, 2018 sampling date; Figure 7).

As corners in Series 1 are deeper than Series 2, it is likely that Series 2 dried out first and was therefore more affected by the drought than Series 1. However, at later sampling dates (July 8, 2018 onwards), copper was no longer leaching at a rate that the CWTS could not keep up with for treatment. Copper concentrations generally decreased by the end of the A cells and stabilized through B cells (Figure 7), indicating that treatment of copper was occurring and that copper leaching from the soils had subsided to a slower rate than treatment. Leaching of copper is not expected to be a concern in 2019 operations provided that the CWTS remains flooded throughout the 2018/2019 winter and early spring season. Therefore, it is recommended that the CWTS be periodically monitored throughout the 2018/2019 winter and early spring, with close observation in the spring to add water immediately once thawed, should the CWTS be dry. Leaching of constituents from the substrates used in construction is further described in Section 4.6.

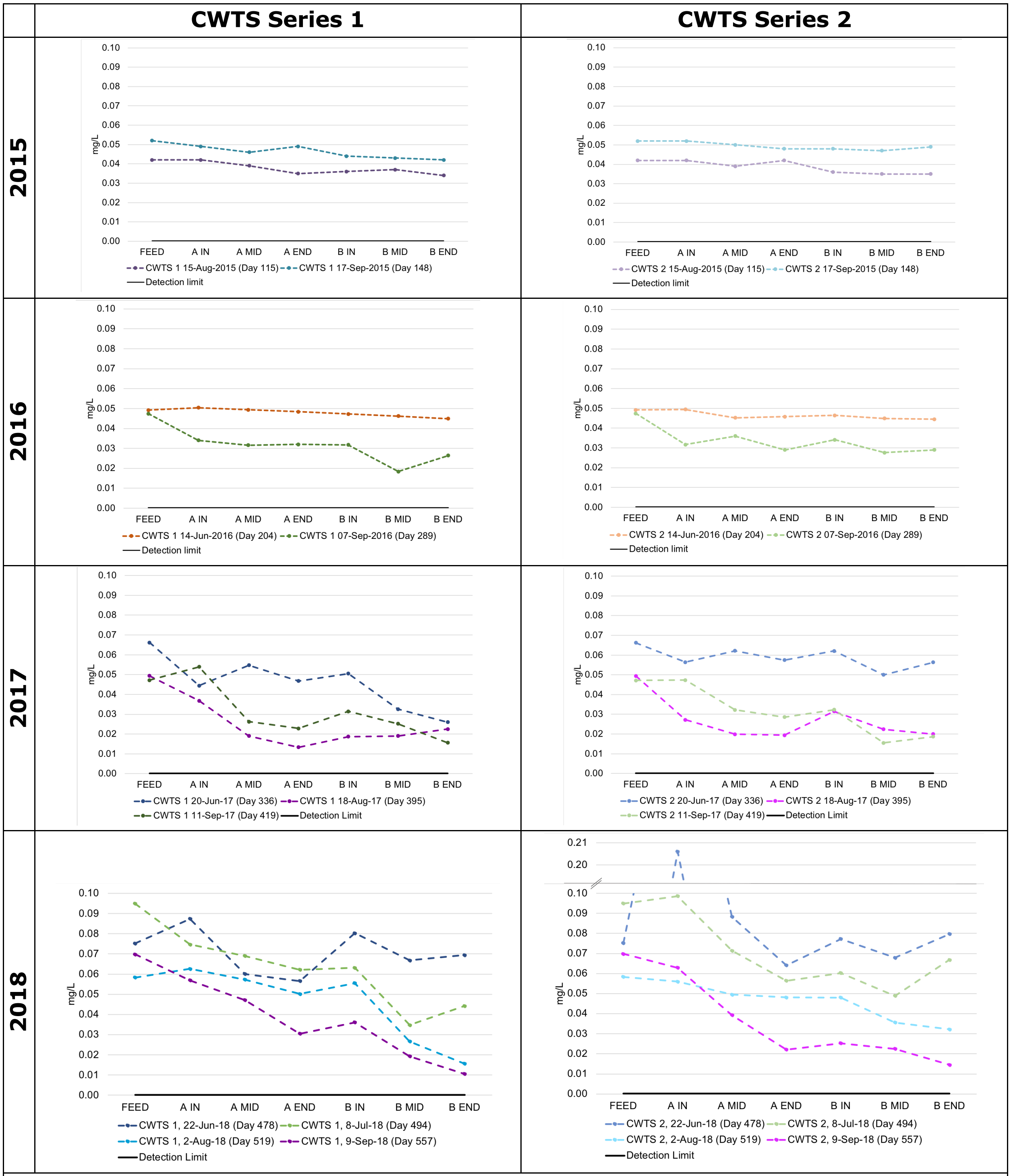


Figure 7 – Copper concentrations through the demonstration-scale CWTS.

Dissolved copper concentrations along the length of the CWTS in 2015 through 2018. Data shown for 11 timepoints, where water was sampled at seven locations through the flow path of the CWTS to assess for treatment fronts within the CWTS, or possible leaching of constituents from the soils into the CWTS. The Maxxam (2015 results) and ALS (2016 – 2018 results) detection limit (DL; black line) for copper is 0.0002 mg/L. Spikes in copper concentrations were observed in early sampling points in Series 2 of the CWTS in 2018 indicating leaching from the soils is occurring; however, later sampling points do not show any copper spikes and, therefore, leaching has subsided.

4.2.2 Performance During 2018 Double Stress Test Period

Due to the drying out of the CWTS as well as higher nitrate concentrations in early 2018, the performance of the CWTS was impacted, resulting in decreased removal of COCs. While these risks are unlikely to occur for an extended period of time during full-scale operations, there are measures that can be taken to mitigate the risks, based on data from the demonstration-scale CWTS. The issues identified, along with the risk to the CWTS, impact on performance, and mitigation actions are outlined in Table 6 and will be considered for full-scale CWTS implementation.

Table 6 – Risks, impacts, and mitigation measures based on issues identified during operations of the demonstration-scale CWTS.

Issue	Risk to CWTS	Potential Impact on Performance	Mitigation Measures for Full-Scale CWTS
High nitrate concentrations	Increase electron (carbon) demand	▪ Dependent on time of year, may overcome vegetation's ability to use as nutrient, forming an oxidative redox buffer, which increases carbon demand needed to treat metals and metalloids.	▪ Run at slower flow rates (longer HRT) to decrease the load of electron demand to the CWTS ▪ Add organics (carbon) to forebay (at full-scale) to produce excess electrons for treatment to account for unexpectedly high concentrations ▪ Prevent effects on metal treatment by having a strong pool of AVS to continue treatment through AVS buffering while Nitrate uses electrons from carbon in system (outcompeting sulphate for sulphides).
Drought in spring thaw	Soil exposure to oxygen, potential change in redox status if prolonged	▪ Oxidizing conditions may establish, impacting treatment of COCs. ▪ When water returns, no vegetation to draw water into root zone and commence treatment.	▪ Stagnate or increase HRT to re-establish reducing conditions ▪ Add iron to remove metals/metalloids with iron oxyhydroxides (which will eventually form sulphide minerals) ▪ Prevent effects by having strong AVS pool to provide redox buffering
Drought in summer		▪ Oxidizing conditions may establish, impacting treatment of COCs. ▪ When water returns, vegetation can rapidly draw water through root zone to return treatment.	

The period of time required for the CWTS to recover from the double stress test was variable for each series and COC based on treatment front, and amendments added to the CWTS (Table 7). During the double stress test period, while the CWTS recovered, the percent load removal of all COCs, except cadmium, were lower than the 2017 operational period (Table 8; Figure 8 to Figure 13). Additionally, with the exception of molybdenum, percent load removal in the drought recovery period for remaining COCs was higher in Series 1 (Table 8).

In both series, nitrate treatment was likely unaffected as the amount of removal remained stable throughout 2018 and the extent of removal was better than previous years, where the CWTS was not affected by a drought in the spring (Contango, 2017b). Treatment of selenium followed the same trend as nitrate, however, it was not treated until nitrate was depleted. This is due to the reaction order in an anaerobic system where nitrate is easier to reduce than selenium.

In Series 1, treatment of cadmium and zinc resumed concurrently (July 8, 2018) while in Series 2, zinc recovered before cadmium (Table 7). While zinc is expected to be treated following copper and cadmium via metal-sulphide formation, it can also sorb to mosses, thereby decreasing its recovery time. Copper and molybdenum treatment began improving in both series following the first evapotranspiration trial when flow to the CWTS was stopped and reducing conditions further established (Figure 9). However, the addition of iron to Series 1 enhanced the recovery of copper and molybdenum by 33 and 20 days, respectively, compared to Series 2 (no added iron; Table 7). Although copper treatment is expected to occur prior to cadmium, zinc, and molybdenum, leaching of copper from the soils in early 2018 increased the load of copper needing treatment (Section 4.2.1; Table 8). However, this is not expected to occur in the full-scale system provided soils with low concentrations of leachable copper are used.

Based on the recovery of COCs from the double stress test, stagnating the CWTS (demonstration-scale or full-scale) immediately following an upset may increase time of recovery by promoting re-establishment of reducing conditions (to aid in the formation of metal-sulphides.) Furthermore, while iron isn’t expected to be added in the full-scale CWTS long-term, it may also be used in conjunction with stagnation to decrease recovery time of the CWTS. Addition of iron promotes production of AVS for future use in metals treatment in an on-demand manner. To further encourage AVS production in the full-scale CWTS iron could be incorporated into the soils during construction.

Table 7 – Date of COC recovery from double stress test for Series 1 and 2.

COC	Series 1 (with iron)		Series 2 (without iron)	
	Period (days)	Date of recovery	Period (days)	Date of recovery
Cd	45	29-Jun-18	45	29-Jun-18
Cu	54	08-Jul-18	87	10-Aug-18
Mo	59	13-Jul-18	79	02-Aug-18
Se	12	27-May-18	24	08-Jun-18
Zn	45	29-Jun-18	31	15-Jun-18
Nitrate	Not applicable	Likely unaffected	Not applicable	Likely unaffected

4.2.3 Performance During 2018 Operational Period

In the 2018 operational period for the demonstration-scale CWTS (August 17 to September 9, 2018), dissolved cadmium, copper, selenium, and zinc treatment improved from the double stress test period (Table 8). Dissolved metals concentrations rather than total metals concentrations were used for the discussion in this report as total values are not representative of the metals concentrations in the CWTS water. During the operational period Series 1, which also received an additional recovery intervention strategy of iron addition achieved of the CWTS achieved an average decrease of 0.0214 µg/L for cadmium (Figure 8), 53.3 µg/L for copper (Figure 9), 8.16 µg/L for molybdenum (Figure 10), 3.15 µg/L for selenium (Figure 11), 16.1 µg/L for zinc (Figure 12) and 8.94 mg/L for nitrate. Series 2, an average decrease of 0.0214 µg/L for cadmium (Figure 8), 49.7 µg/L for copper (Figure 9), 7.06 µg/L for molybdenum (Figure 10), 3.20 µg/L for selenium (Figure 11), 16.1 µg/L for zinc (Figure 12) and 8.98 mg/L for nitrate. Percent removal of COCs are presented in Table 8 below, including percent removal of COCs adjusted for evapotranspiration. Evapotranspiration is further discussed in Section 4.5. Furthermore, nitrate outflow concentrations also decreased from feed water concentrations throughout the demonstration-scale CWTS. As nitrate concentrations were low during the operational period, nitrate was likely taken up by plants as a nutrient source (Figure 13). These results indicate that the CWTS can recover quickly from an upset event (double stress test). Beneficial conditions for the removal of constituents in the CWTS were re-established following the double stress test, and treatment of these constituents should continue through 2019.

Table 8 – Percent removal of dissolved constituents in the demonstration-scale CWTS.

COC (µg/L)		**Operational period[1]**	**Double Stress Test Period[2]**		**Post-Double Stress Test Period[3]**		**Operational Period[4]**	
		2017[5]	**2018**					
			Series 1	**Series 2**	**Series 1**	**Series 2**	**Series 1**	**Series 2**
Cd	In	0.0261	0.0266	0.0266	0.0254	0.0254	0.0264	0.0264
	Out	0.0092	0.0080	0.0107	0.0051	0.0053	0.0050	0.0050
	% removal[6]	**66**	**70**	**60**	**80**	**79**	**81**	**81**
	% ET[6]	**71**	**-**	**-**	**-**	**-**	**85**	**85**
Cu	In	49.1	58.9	63.1	66.5	63.2	65.8	65.8
	Out	17.3	43.2	53.8	17.2	16.9	12.5	16.1
	% removal[7]	**65**	**27**	**15**	**74**	**73**	**81**	**76**
	% ET[7]	**72**	**-**	**-**	**-**	**-**	**85**	**81**
Mo	In	6.3	10.6	10.3	10.1	10.5	10.5	10.5
	Out	2.7	10.9	8.98	2.17	3.01	2.38	3.48
	% removal	**57**	**0**	**13**	**79**	**71**	**77**	**67**
	% ET	**65**	**-**	**-**	**-**	**-**	**82**	**74**
Se	In	4.0	9.02	7.99	3.81	3.25	3.68	3.68
	Out	0.5	6.21	3.96	0.96	0.80	0.53	0.47
	% removal	**87**	**31**	**50**	**75**	**75**	**86**	**87**
	% ET	**89**	**-**	**-**	**-**	**-**	**88**	**90**
Zn	In	49.2	24.7[8]	25.3	18.8	19.1[6]	17.3	17.3
	Out	1.9	3.90[8]	6.48	1.38	1.75[6]	1.23	1.15
	% removal[6]	**96**	**84[8]**	**74**	**93**	**91[6]**	**93**	**93**
	% ET[6]	**97**	**-**	**-**	**-**	**-**	**94**	**95**
Nitrate								
NO_3 (mg/L)	In	**6.98**	**14.5**	**14.5**	7.51	7.51	8.99	8.99
	Out	**0.17**	**1.98**	**5.05**	0.02	0.01	0.05	0.01
	% removal	**98**	**86**	**65**	**100**	**100**	**99**	**100**
	% ET	**100**	**-**	**-**	**-**	**-**	**100**	**100**

% removal – percent load removal, not adjusted for evapotranspiration; % ET – percent load removal adjusted for evapotranspiration, calculated by methods described in Contango, 2017b; '-' – indicates that percent load removal adjusted for evapotranspiration was not calculated as it is not applicable to full-scale.

[1] Data for operational period was from August 18 to September 22, 2017.

[2] Data for double stress test period varied by COC and series, as shown in Table 7, with nitrate reported in this table as May 18-June 15, 2018 where nitrate concentrations were elevated causing stress on the system.

[3] Period after the double stress test and includes data to the end of the operational period (referred to here as post-double stress test period; varied by COC and series; Table 7).

[4] Operational period occurred from August 17, 2018 to September 9, 2018.

[5] Data from 2017 averaged for series 1 and 2 as both series were operated the same in 2017.

[6] Percent load removal for Cd and Zn are artificially low in 2018 due to outflow concentrations below the detection limit.

[7] Extent of copper removal was influenced by higher copper concentrations in the soils (Figure 14, Table 7).

[8] Data from June 22, 2018 was erroneous and therefore removed from calculations (dissolved concentration exceeded total concentration).

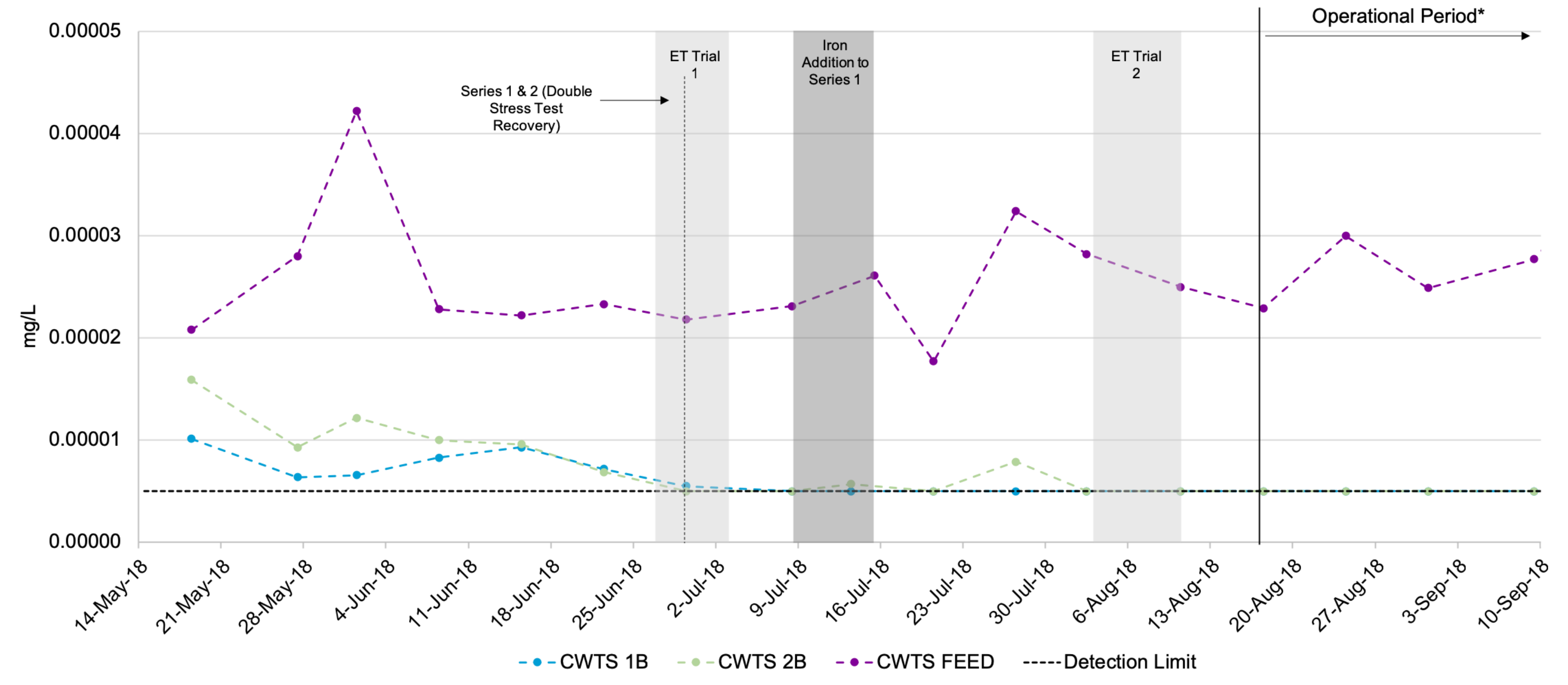


Figure 8 – Dissolved cadmium concentrations in the demonstration-scale CWTS in 2018.

'*' – The operational period refers to the time period when all COCs in Series 2 (no iron added) were being treated. However, cadmium recovered before this date (Table 7). The ALS detection limit for cadmium is 0.000005 mg/L. ET – evapotranspiration. Flow to the CWTS was shut off for the addition of iron to cells 1A and 1B on July 8, 2018. Flow was restarted on July 15, 2018.

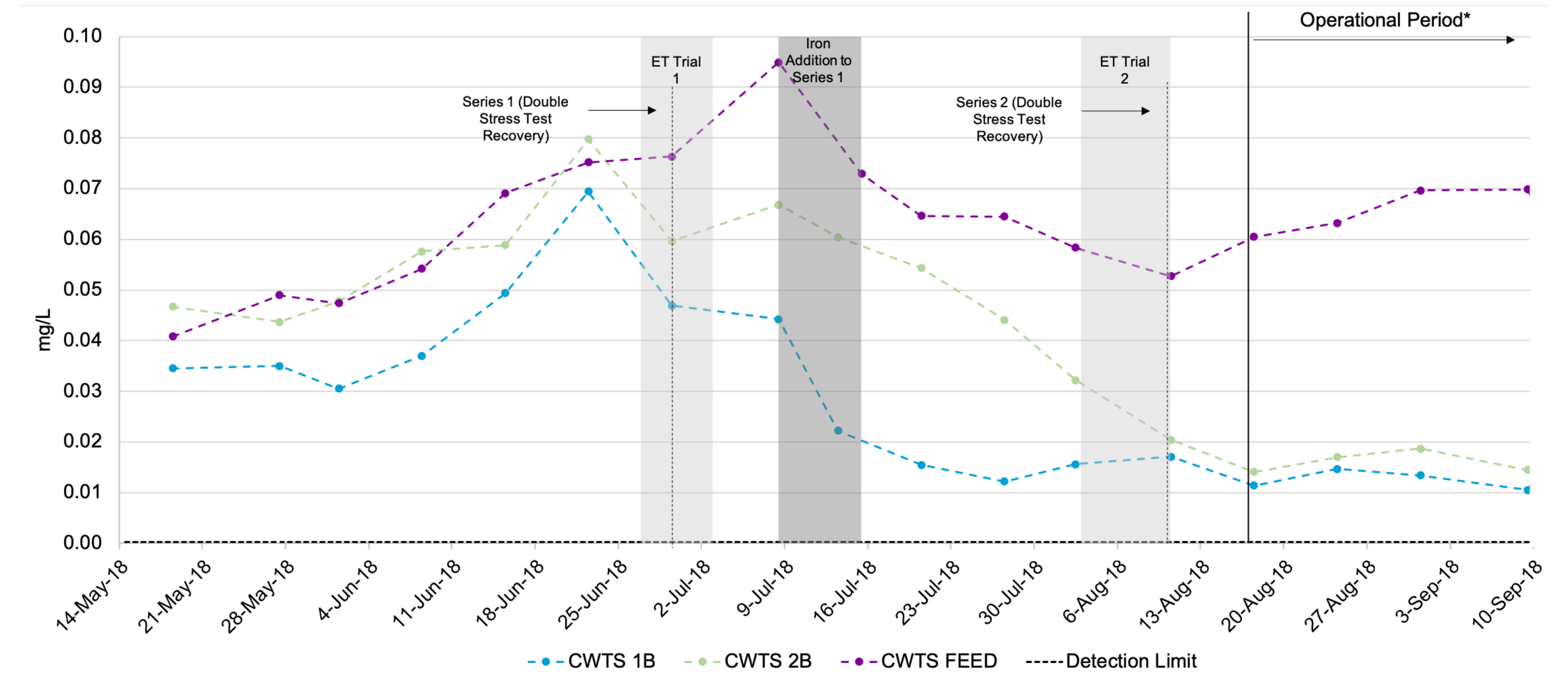


Figure 9 – Dissolved copper concentrations in the demonstration-scale CWTS in 2018.

'*' – The operational period refers to the time period when all COCs in Series 2 (no iron added) were being treated. However, copper in Series 1 recovered before this date (Table 7). The ALS detection limit for copper is 0.0002 mg/L. ET – evapotranspiration. Flow to the CWTS was shut off for the addition of iron to cells 1A and 1B on July 8, 2018. Flow was restarted on July 15, 2018.

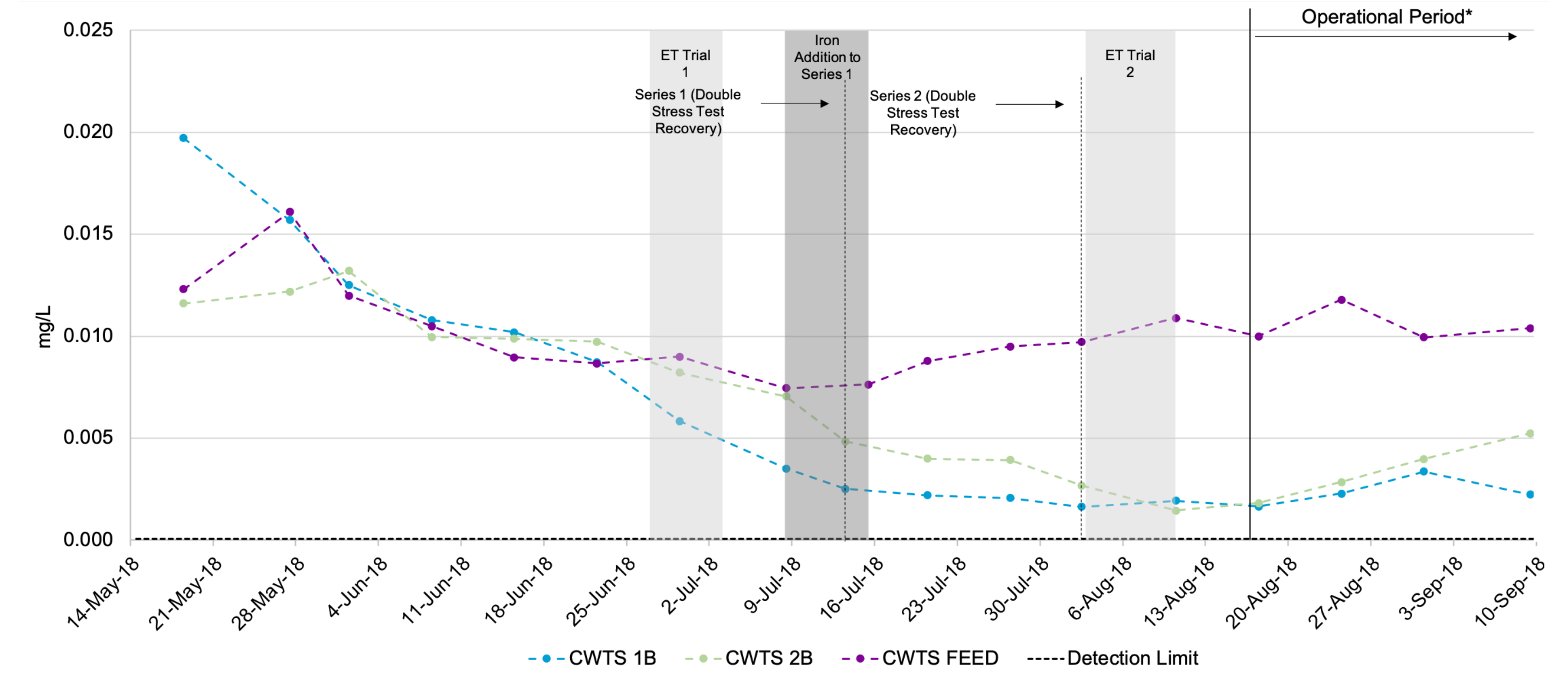


Figure 10 – Dissolved molybdenum concentrations in the demonstration-scale CWTS in 2018.
'*' – The operational period refers to the time period when all COCs in Series 2 (no iron added) were being treated. However, molybdenum recovered before this date (Table 7). The ALS detection limit for molybdenum is 0.000050 mg/L. ET – evapotranspiration. Flow to the CWTS was shut off for the addition of iron to cells 1A and 1B on July 8, 2018. Flow was restarted on July 15, 2018.

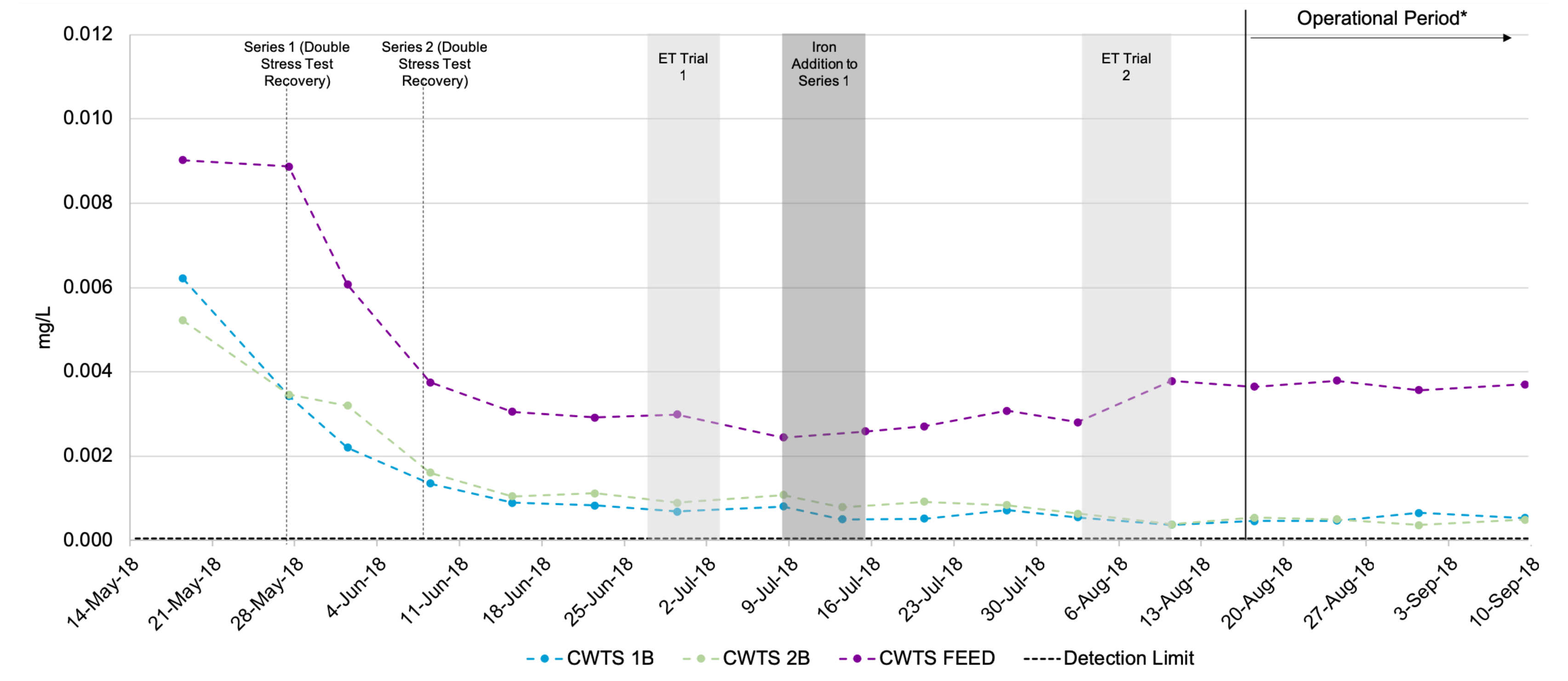


Figure 11 – Dissolved selenium concentrations in the demonstration-scale CWTS in 2018.

'*' – The operational period refers to the time period when all COCs in Series 2 (no iron added) were being treated. However, selenium recovered before this date (Table7). The ALS detection limit for selenium is 0.000050 mg/L. ET – evapotranspiration. Flow to the CWTS was shut off for the addition of iron to cells 1A and 1B on July 8, 2018. Flow was restarted on July 15, 2018.

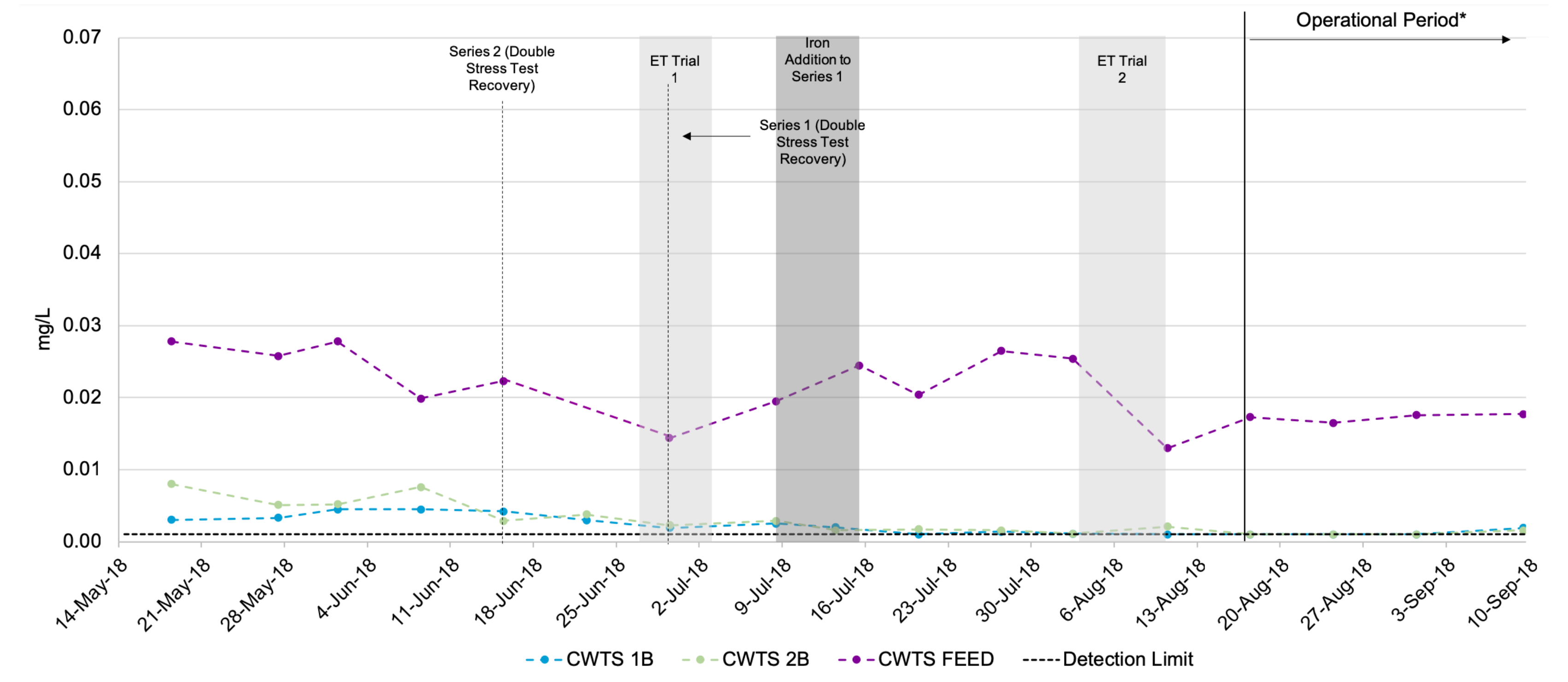


Figure 12 – Dissolved zinc concentrations in the demonstration-scale CWTS in 2018.
'*' – The operational period refers to the time period when all COCs in Series 2 (no iron added) were being treated. However, zinc recovered before this date (Table 7). The ALS detection limit for zinc is 0.001 mg/L. ET – evapotranspiration. Flow to the CWTS was shut off for the addition of iron to cells 1A and 1B on July 8, 2018. Flow was restarted on July 15, 2018. Data from June 22, 2018 was removed as the total zinc was higher than dissolved.

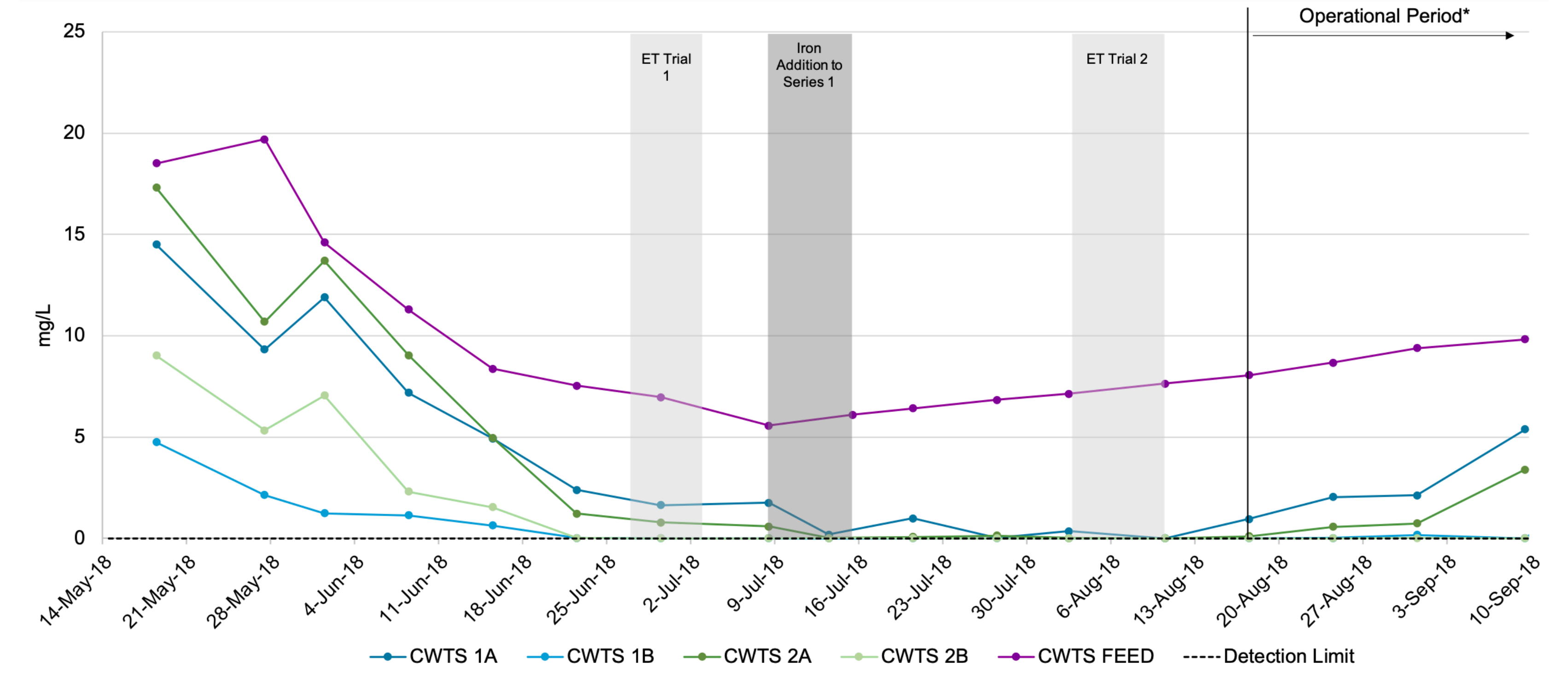


Figure 13 – Nitrate as N concentrations in the demonstration-scale CWTS in 2018.

The ALS detection limit for nitrate is 0.025 mg/L. ET – evapotranspiration. Flow to the CWTS was shut off for the addition of iron to cells 1A and 1B on July 8, 2018. Flow was restarted on July 15, 2018.

4.3 Hydraulic Retention Time

The operational hydraulic retention time (HRT) of the demonstration-scale CWTS for 2018 was calculated for each series using Equation 1. Equation 1 uses the flow rate (Q) from the operational period and the actual depth of each CWTS cell. The actual depth is calculated using the measured depths (an average of two depth sticks in each cell and, therefore, depths may vary) and a water depth correction factor of 0.01 meters determined from the tracer study conducted in 2017 (Contango, 2017b). Therefore, the average HRT for the operational period calculated separately for each series was 7.60 days and 7.09 days, for Series 1 and 2, respectively. The operational HRTs were then used in the calculation of removal rate coefficients in Section 4.4.2.

$$\text{Operational HRT} = \frac{A \times \text{actual depth}}{Q}$$

Equation 1 – Equation for calculation of hydraulic retention time.

Operational HRT is the confirmed hydraulic retention time; *A* is the area of the CWTS; actual depth was calculated from the measured depth + 0.01 m correction factor; *Q* is the flow rate.

4.4 Treatment Effectiveness

Key findings (detailed below):

- The lowest concentrations consistently achievable for the treatment design (performance limits confirmed by t-test) were reached for cadmium after 3.80 days for Series 1 and 3.54 days for Series 2 and for copper after 3.54 days (Series 2 only).
- Removal rate coefficients (RRCs, *k*) have been developed that can be used for full-scale sizing.
- Copper leaching from soils decreased from the drought recovery period but is still likely making the RRC artificially low in this CWTS; however, the RRC is expected to improve in 2019 as leaching continues to decrease.

4.4.1 Performance Limit

The performance limit (referred to as thermodynamic minimum in previous reports) is the lowest concentration consistently achievable for a given treatment design and water chemistry. Once the performance limit is reached, making the CWTS bigger will not result in further decrease of outflow concentration (although outflow load may continue to decrease as water volume decreases through evapotranspiration). The performance limit was determined for each COC using the operational period, and were then also visually compared to the average concentrations of COCs at seven sampling locations throughout the CWTS from one time point during the operational period, to further evaluate and confirm whether concentrations appeared to have leveled off (Appendix B, Figures B5 to B9 for remaining COCs). Unfortunately, due to the double stress test, there were not enough time points in the operational period in 2018 for this data to be used in the statistical analyses to further refine the expected HRT for the performance limits. This can be refined in 2019, by varying flow rates.

Based on the results of the t-test for A cell and B cell concentrations, it was determined that the performance limit was achieved for dissolved cadmium (both series) and copper (Series 2 only), by the end of the A cells in the demonstration-scale CWTS. The detection limit was reached for all except one timepoint during the operational period for cadmium by the outflow of cell A, suggesting that faster flows would be needed to accurately determine the HRT at which the performance limit was met. The performance limits for copper (Series 1 only), molybdenum, nitrate, selenium, and zinc were not yet statistically achieved, suggesting that a larger CWTS would achieve lower concentrations of these constituents (Appendix B, Figures B5 to B9). Results for copper should also be taken with consideration if leaching of residual copper from the soil continues, as there is more copper treatment ongoing than can be noted by just the water concentrations. However, by July 8, 2018, copper soil leaching had decreased (Section 4.2.1).

Interestingly, once nitrate, cadmium, and copper were treated, zinc, selenium and molybdenum begin to have an increase in treatment. This phenomenon is referred to as a treatment front, which generally abides by reaction orders (i.e., nitrate treatment before sulphate, sulphide exchange reaction kinetics, etc.; Morse and Luther III, 1999). Additionally, as selenium is easier to reduce than sulphate, it is often thought that selenium would be reduced before the remaining chalcophiles. However, due high concentrations of sulphate, sulphate and selenium reduction occurred concurrently (which is expected). Furthermore, due to copper leaching from soils, copper was not treated exclusively before other chalcophile metals, which would generally be expected in a full-scale CWTS with stable soils.

4.4.2 Removal Rate Coefficients

An important factor for CWTS design is the rate of treatment, also known as the removal rate coefficient (RRC; k). The RRC is based on the treatability of a specific compound and the HRT of the CWTS, both of which are site-specific based on water chemistry, CWTS designs, and characteristics of the CWTS. Information regarding calculation of RRCs can be found in previous reports (Contango, 2017b).

In pilot-scale testing specific for the Minto CWTS, the RRC for selenium was a zero-order reaction kinetic; however, optimizations of the operation of the system through the demonstration-scale commissioning enabled a first-order RRC to be maintained in 2017 (both series) and in Series 2 in 2018. The reaction kinetic of selenium in Series 1 was is not reported as iron dosing in Series 1 temporarily changed the treatment mechanism and reaction order. Additionally, higher DO in cell 1A could affect microbial reduction of selenium, thereby changing the reaction kinetic (Section 0). Therefore, cadmium, copper, nitrate, selenium (Series 2), and zinc, are calculated as first-order kinetics, while molybdenum followed a zero-order kinetic. In other words, the reaction rate for molybdenum is a linear rate and does not depend on concentration, whereas the reaction rates for cadmium, copper, selenium (Series 2), zinc, and nitrate are proportional to concentration (a half-life type of reaction).

In 2017 and 2018, RRCs for cadmium and copper (Series 2 only in 2018) were calculated using outflow concentrations and HRT from the A cells as they had reached their performance limit at the end of A cells (Section 4.4.1; Table 9; Contango, 2017b). RRCs for the remaining COCs in 2017 were therefore calculated using outflow concentrations and HRTs from the B cells (Contango, 2017b; Table 9). Although the performance limit was not reached in the B cells for zinc (both series) and nitrate (Series 2), RRCs were calculated using outflow concentrations and HRTs from the A cells as outflow concentrations from the B cells were consistently at the detection limit. The remaining constituents did not reach their performance limit and were not consistently at the detection limit in the A or B cell. Therefore, outflow concentrations and HRTs from the B cells were used. RRCs for selenium and nitrate for Series 1 were not calculated in 2018 as nitrate treatment in Series 1 was impacted by decreased plant growth and the addition of iron to Series 1 temporarily changed the treatment mechanism and reaction order for selenium. The RRCs were therefore not representative of what would be expected in a fully functioning system.

Table 9 – Cells used for removal rate coefficient calculations.

COC	2017		2018	
	Series 1	Series 2	Series 1	Series 2
Cadmium	A	A	A	A
Copper	A	A	B	A
Molybdenum	B	B	B	B
Selenium	B	B	-	B
Zinc	B	B	A	A
Nitrate	B	B	-	A

A cells were used if COCs reached their performance limit by the end of the A cell or were consistently achieving detection limit concentrations in the B cell.
'-' indicates that an RRC was not calculated.

An RRC was calculated for all COCs during the operational period (August 17 to September 9, 2018) which can be used to refine future sizing and performance estimations of a full-scale CWTS (Table 10). RRCs were then compared to the average RRCs calculated from another pilot-scale copper study completed in the Yukon and the demonstration-scale CWTS operational period of 2017 (Table 10). RRCs for cadmium in the 2018 demonstration-scale CWTS were depressed because flow rates did not provide the resolution needed to determine an accurate RRC. Additionally, RRCs for copper in the demonstration-scale CWTS are also depressed due to copper leaching from soils used in construction of the system. While the treatment rate for copper exceeded the leaching rate by August 17, 2018 (i.e., leaching was said to have subsided), it is likely that some copper continued to leach from the soils but was masked by increased performance of the CWTS. Therefore, the RRCs for copper are expected to continue to improve in 2019. In general, RRCs are generally similar to those in 2017 (Table 10; Contango, 2017b). Treatment of molybdenum is notable as the RRC nearly doubled in 2018 compared to 2017. The RRCs applied here are intended to be conservative estimates for conceptual sizing purposes and will need to be refined through further demonstration-scale (on site) testing.

Table 10 – Removal rate coefficients (k) for constituents of concern.

COC	Pilot[1] k*day^{-1}	Other Yukon Cu Pilot k*day^{-1}	2017 Demonstration[2] (Operational) k*day^{-1}		2018 Demonstration[3] (Operational) k*day^{-1}		Recommended[4] k*day^{-1}
	Total	**Dissolved**	**Dissolved**	**Total**	**Dissolved Series 1**	**Dissolved Series 2**	**Dissolved**
First order removal rate coefficients							
Cd	1.14	0.50	>0.52[5]	>0.23[5]	>0.42[5]	>0.41[5]	0.47
Cu	1.17	0.50	>0.31[6]	>0.14[6]	>0.22[6]	>0.35[6]	0.29
Mo	0.101	N/A	N/A	N/A	N/A	N/A	N/A
Se	N/A	0.46	0.32	0.31	N/A	0.29	0.30
Zn	1.14	0.48	0.51[6]	0.39[6]	0.57	0.45	0.51
Nitrate	0.56	N/A	0.59	N/A	-[7]	0.57	0.58
Zero order removal rate coefficients							
Mo	N/A	N/A	0.0006	0.0006	0.0011	0.0010	0.0010
Se	0.0018	N/A	N/A	N/A	-[8]	N/A	N/A

N/A – an RRC is not available. All RRCs are for first-order reaction kinetics except for molybdenum in the 2017 & 2018 demonstration-scale CWTS, which has a zero-order reaction rate kinetic. The A cells were used for RRC calculations for cadmium and copper for Series 1 and 2 in 2017 and cadmium and zinc in 2018. Additionally, the A cells were used for RRC calculations for Series 2 in 2018 only, as well as for copper and nitrate. The B cells were used for all other RRC calculations.

[1] Values calculated from data in Contango, 2014b (pilot-scale report) for *C. aquatilis* + moss with low nitrogen scenario.

[2] Analytical results from August 18 – September 22, 2017 were used.

[3] Analytical results from August 18 – September 14, 2018 were used.

[4] Recommended RRCs are developed from averaged dissolved concentrations of 2017 & 2018 demonstration-scale CWTS operational periods. This is a modification and correction to the erroneous dissolved recommended RRCs as reported in Table 5 of the 2017 Demonstration-Scale Report (Contango, 2017b).

[5] RRCs for cadmium in 2017 and 2018 were artificially low because low flow rates did not provide the resolution needed to determine a RRC, so the lowest potential k value based on available data is reported here. The available data had 100% and 75% of sample points at the detection limit in 2017 and 2018 respectively.

[6] RRC's for copper in demonstration-scale CWTS are artificially low due to copper leaching from soils used in construction of the system. Therefore, RRCs are expected to improve once leaching has subsided.

[7] An RRC was not calculated for NO_3 in Series 1 due to extensive plant damage and less NO_3 being used as a nutrient.

[8] An RRC was not calculated for selenium in Series 1 due iron addition temporarily changing the treatment mechanism and reaction order.

4.5 Evapotranspiration in the Demonstration-Scale CWTS

Key findings (detailed below):

- The 2018 evapotranspiration trials were unsuccessful due to precipitation throughout each trial; however, the 2017 trials revealed a significant loss of water, which will impact calculations of loads to the receiving environment (making them lower than previously estimated).
- Unlike 2017 trials, leaching of copper was not observed during periods of no flow in 2018, indicating copper leaching has improved.

Total evapotranspiration from the system is the combined effects of open water evaporation and plant transpiration and is further described in previous reports (Beebe et al., 2014; Contango, 2017b). The purpose of calculating the evapotranspiration of a system is to understand the amount of water lost, which in turn concentrates elements measured at the outflow. Thus, the actual outflow load reduction performed by the wetland should consider the difference in concentration at outflow, corrected for evapotranspiration. Due to significant precipitation during each evapotranspiration trial conducted in 2018 (two trials total), we were unable to calculate an evapotranspiration rate. Therefore, the rate of water lost by evapotranspiration determined in 2017 (5.4 L/m^2/day) was used to adjust load removal calculations as previously described (Contango, 2017b). The average ambient temperature on-site for this time period was 9.2°C, and so the evapotranspiration rates from the 2017 trials (average ambient temperature of 9.6°C during the first evapotranspiration trial in 2017) are expected to be relevant to the operational period in 2018.

Evapotranspiration has shown to have a significant effect on the calculation of constituent load to the receiving environment (Table 8). Therefore, future models for assimilative capacity in the downstream receiving environment should take into account not only the predicted outflow concentrations from the CWTS using removal rate coefficients (Section 4.4.2), but also adjust the load accounting for evapotranspiration.

4.6 Soils

Key findings (detailed below):

- In 2018, leachable copper concentrations in soils decreased in the top 0-10 cm while total copper concentrations were within ranges previously measured.
- Most constituents, including copper, have shifted primarily into stable reduced and residual minerals fractions in the soil.
- Acid volatile sulphides (AVS) provide buffering capacity to the soils and continued treatment through cold temperatures. AVS concentrations have been non-detectable in the CWTS due to low iron concentrations in substrates and water. While a small amount was detected in 2017 and 2018, Series 1 was amended with iron in attempt to improve AVS concentrations.
- While Series 1 was amended with iron, it is unclear if the addition of iron was sufficient to increase AVS concentrations, but it is planned to add more in 2019.

Although unintentional, the high initial leachable copper concentrations in the CWTS soils allowed for additional testing to be carried out on the CWTS (Appendix B, Table B1, and B2). Results of these test methods during the operational period are discussed in the following sections, while definitions of extractable fractions from the sequential extraction procedure for the speciation of metals can be found in Appendix B, Table B3 (Tessier et al., 1979).

When compared to early 2016 and 2017 results, leachable copper concentrations in soils decreased in the CWTS through 2018 (Figure 14), while total copper concentrations remained within ranges previously measured. In general, soils in the demonstration-scale CWTS continued to reduce leachable copper throughout 2018. Additional soil sampling locations and more frequent sampling is recommended in 2019 to confirm that copper leaching from the soils has stopped.

Sequential extraction analysis shows that despite elevated initial leachable copper concentrations, the soils have become more stable (less leachable) over time in the CWTS setting as the soils have aged, shifting from oxidized to reduced, mineral forms (Figure 15; Appendix B, Figures B10 and B11). This beneficial aging of soils to a less soluble mineralized form of sulphide is expected for this type of treatment CWTS design (Contango, 2017b). It should also be noted that copper leached from the original substrate into the water and therefore put additional treatment demands on the CWTS.

Additional reserve treatment capacity can be stored in a CWTS through creation of a reserve of AVS (newly formed amorphous iron sulphides; Contango, 2017b). An excess of AVS suggests the metals would be non-bioavailable and not likely to leach. In the case of Minto, where the soils used in construction had excess copper, the appearance of measurable AVS would also indicate that the copper in the soils is nearing an endpoint of transformation to sulphide forms.

AVS has not been measured in desired concentrations in the demonstration-scale CWTS (small amounts measured in 2017 for the first time; Contango, 2017b) as much of it was used to sequester total copper in the copper-rich soils. AVS can also serve as a buffer to oxidation should the soils of a reducing (sulphide producing) CWTS be exposed to oxygen (e.g., briefly drying out), thereby making sequestered metals less likely to re-solubilize. Therefore, iron was added to Series 1 in 2018 to create excess AVS to combat impacts of the drought in early 2018. However, only small amounts of AVS were measured in cell A in both series (September), indicating that the added iron was not sufficient to treat constituents in the water, as well as produce AVS. As ratios of simultaneously extractable metals to AVS (ΣSEM:AVS) were similar in both series, it is unclear if the addition of iron increased AVS in cell 1A. However, as there was an observed difference in treated copper between Series 1 and 2 after the addition of iron (i.e., treatment was better in Series 1), it is recommended that iron be stoichiometrically added in 2019 (Section 4.2.2).

In October 2018, ΣSEM:AVS ratios for cells 1A and 2A increased to greater than one, indicating AVS depletion in the colder temperatures due to decreased microbial activity. As leachable copper in the soils is still consuming the sulphides, treatment performance is expected to improve as copper is transformed into more stable fractions. Once the ΣSEM:AVS ratio of all cells is consistently less than one, we do not expect any further copper leaching to occur, and overall treatment within the CWTS should improve until this benchmark is reached.

Zinc mineral forms have become stable over time, with most of these constituents found in the reduced or mineral form (fraction 4 and 5) by the end of 2018 (Appendix B, Figures B12 and B13). Cadmium concentrations are at or near detection limits for all fractions (Appendix B, Figures B14 and B15). Molybdenum was mostly found in the most stable residual mineral fraction 5, which contained around 40% of the total molybdenum in the samples (Appendix B, Figures B16 and B17). Selenium was at or near the detection limit for all fractions at the end of 2018 (Appendix B, Figures B18 and B19).

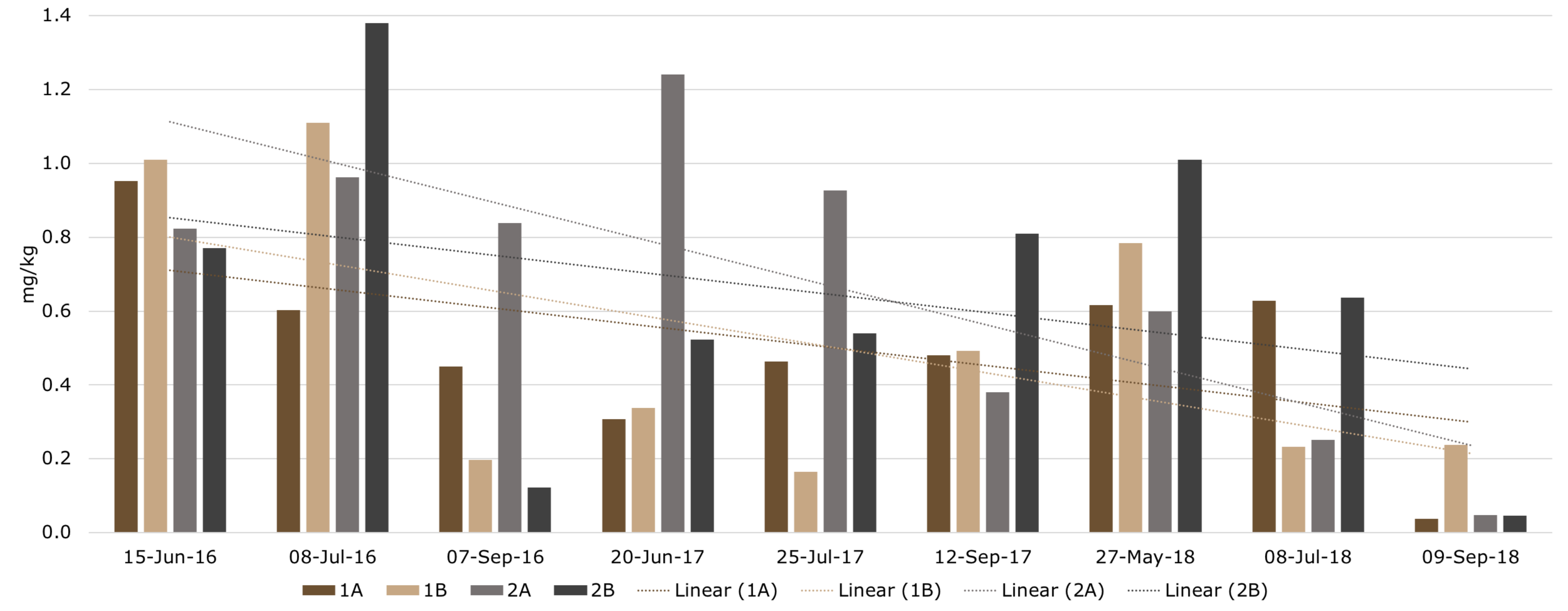


Figure 14 – Leachable copper concentrations in soils over time in the demonstration-scale CWTS.

Figure shows concentrations in shallow soil (0-10 cm). Trendlines (dotted lines) show a general decrease in leachable copper over time.

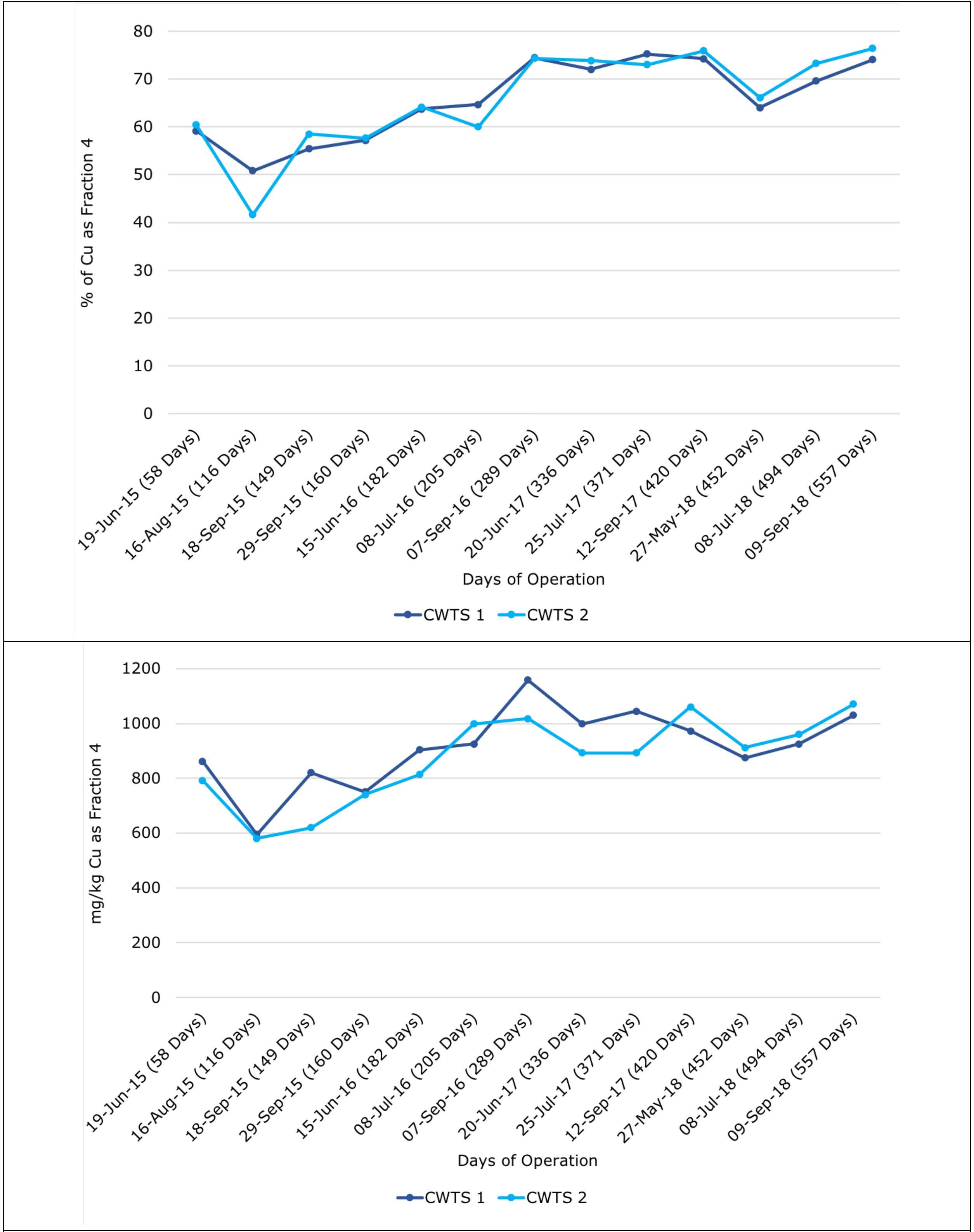


Figure 15 – Copper as sequential leach fraction 4 over time.

Copper in the form of the targeted Fraction 4 (sulphide mineral form and bound to organics), increased in the CWTS over time as the soils matured. Additional information can be found in Appendix B.

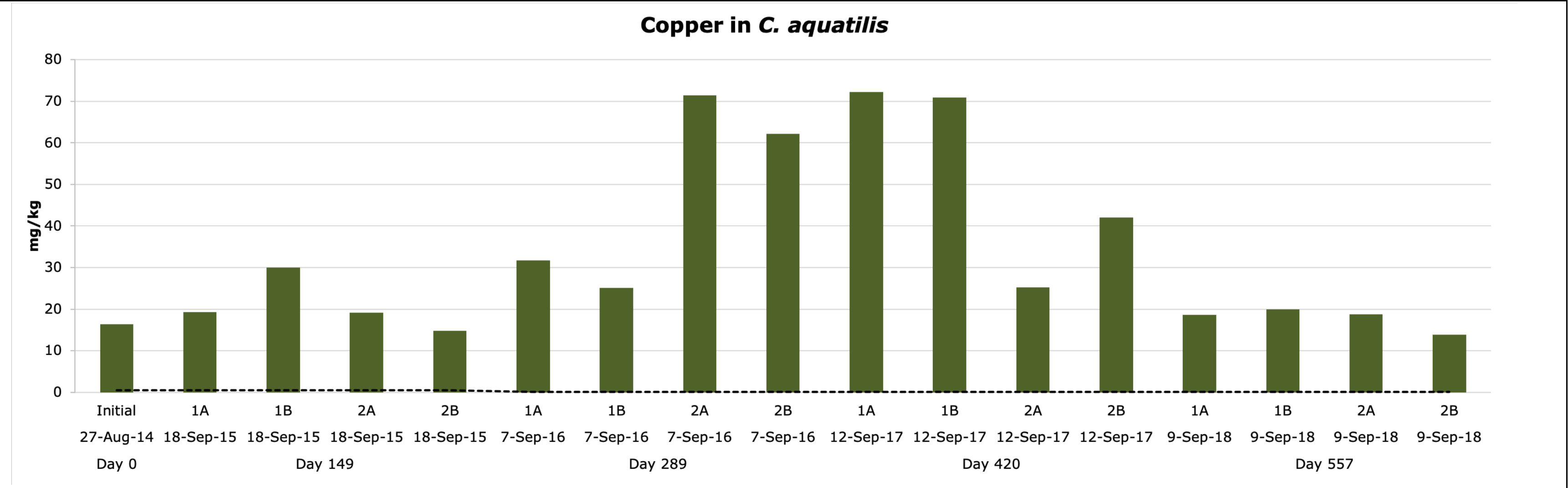
4.7 Metals Uptake

Key findings (detailed below):

- Overall, uptake of metals in *C. aquatilis* was low and generally lower in 2018 than in 2017 demonstration-scale CWTS, with the exception of selenium in cell 1A which was slightly higher in 2018.
- Targeted treatment mechanisms are becoming more robust, rendering elements non-bioavailable.

Concentrations of the COCs in *C. aquatilis* and moss from the demonstration-scale CWTS in 2018 were compared to previous years. *C. aquatilis* and moss in the demonstration-scale CWTS, from 2015 to 2018, had greater copper concentrations than the pilot CWTS, likely reflecting the bioavailable copper that was in the soils used for construction (Contango, 2014b). Concentrations of copper in *C. aquatilis* at the end of 2018 were similar or lower than 2016 and 2017 concentrations (Figure 16), indicating reduced copper bioavailability. In 2017, the moss had higher copper concentrations in the A cells than in the B cells, indicating more treatment earlier in the CWTS as it matures (Figure 16). In 2018, however, the copper sorbed to moss was lower than in 2017 with the exception of cell 1B. Over time, constituents sorbed to mosses will form reduced minerals, rendering them less bioavailable.

Cadmium concentrations in *C. aquatilis* and moss were similar or lower in 2018 compared to 2017, except for higher concentrations in moss in cell 1B (Appendix B, Figure B20). Similar or higher selenium concentrations were observed in *C. aquatilis* in 2018 as in 2017, however, similar or lower selenium concentrations were sorbed to moss (Appendix B, Figure B21). Concentrations of molybdenum in moss generally increased from 2017 to 2018 with the exception of cell 1A, indicating more molybdenum was treated through sorption in 2018. Concentrations of molybdenum in *C. aquatilis* were similar or decreased (Appendix B, B22). In 2018, concentrations of zinc were generally similar in *C. aquatilis* from 2017 (Appendix B, Figure B23); however, uptake in *C. aquatilis* was higher in cell 1A. As moss in cell 1A was sparse compared to other cells, it is likely that more zinc was taken up by plants to accommodate the lower sorption area available in 2018. Concentrations of zinc were similar or lower in moss from 2017, except for cells 1B in where concentrations of zinc increased. It is recommended that more moss be added to cell 1A in 2019 to provide area for sorption of COCs.



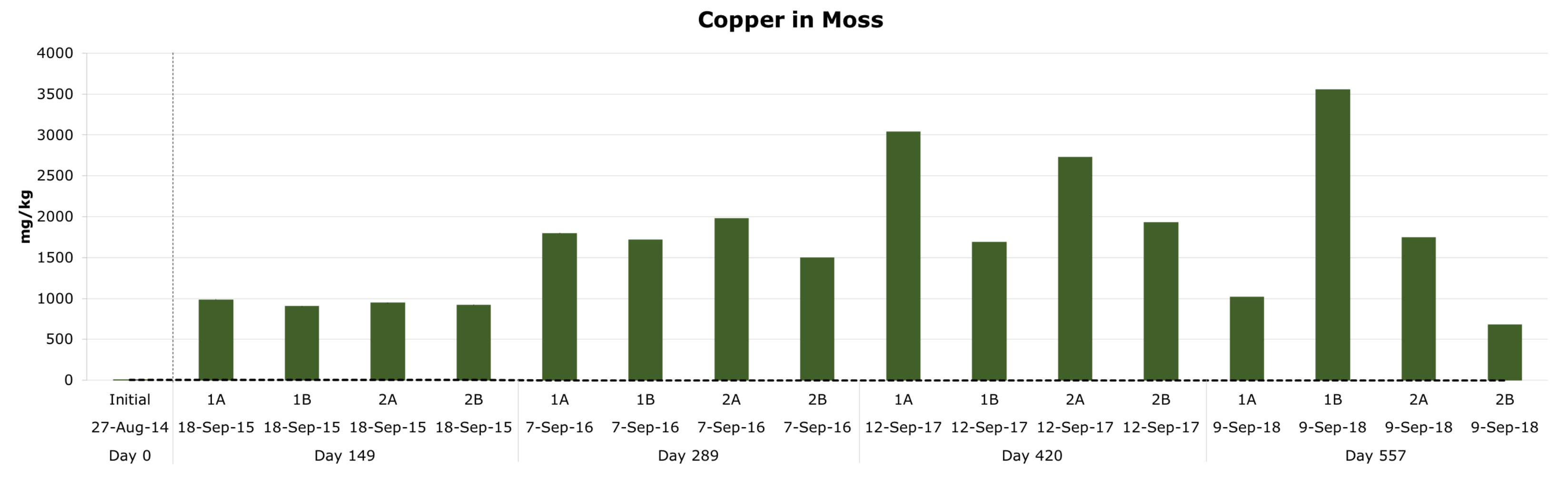


Figure 16 – Copper concentrations in plants.

The 2014 detection limit (DL; horizontal dotted line) for copper is 0.5 mg/kg, the 2015 DL is 0.050 mg/kg, and the 2016-2018 DL is 0.010 mg/kg. The initial timepoint is the average of the three *C. aquatilis* replicates at construction. The vertical dashed line separates the initial timepoint (following CWTS construction) and remaining timepoints.

4.8 Pesticide Application (and Monitoring of Aphids)

Key findings (detailed below):

- An aphid infestation occurred in 2016 and 2017. While some efforts were made in 2017 to control the aphid population, the spraying regimen was not maintained and, therefore, aphids remained. However, no long-term detrimental effect on *C. aquatilis* viability was observed, despite the persistence of aphids.
- In 2018, early and consistent application of insecticidal soap greatly reduced the abundance and length of an aphid infestation as well as improved containment of the aphids.
- Pesticide application is not expected to be needed in the full-scale CWTS as it will not be in an isolated location (Contango, 2017b).

Since the demonstration-scale CWTS is constructed of an emergent macrophyte monoculture of *C. aquatilis* in a relatively isolated area (i.e., away from other vegetation and potential sources of insects), it is more susceptible to infestation by pests such as aphids (Dixon, 1971; Riley et al., 1995; Foottit and Maw, 1997; Contango, 2017b). Furthermore, due to its isolated location, the CWTS it is unlikely to attract predatory insects such as ladybugs, lacewings, and parasitic wasps to control aphid populations (Flint, 2001; Russel and Diaz, 2015; Finnamore, 1997; Contango, 2017b).

An aphid infestation of the CWTS occurred in 2016 and 2017 and, while efforts were made in 2017 to control population (through application of insecticide), the ongoing spraying regimen was not maintained and aphids remained. However, no short-term detrimental effect on *C. aquatilis* viability was observed. Therefore, due to the aphid infestation in 2017, vegetation was replanted in areas with sparse *C. aquatilis* on July 8, 2018. The stronger insecticidal soap (Trounce's Yard and Garden Insecticide) was applied biweekly starting May 14, 2018 and switched to Safer's End-All insecticidal soap on July 16, 2018 (when Trounce ran out at site). This treatment was effective until early August 2018 (exact date unknown) when aphids appeared in cell 2A only. To control the aphid population in cell 2A and to protect the other cells, insecticidal soap was then applied to all cells on a weekly schedule (starting August 24, 2018). The applied insecticide was switched to Scott's EcoSense Bug B Gone on September 21, 2018 when End-all ran out at site. By September 24, 2018, live aphids were no longer observed in cell 2A. Therefore, early application of insecticidal soap greatly reduced the abundance and length of an aphid infestation as well as improved containment of the aphids. In 2019, it is recommended to continue applying Trounce's Yard and Garden Insecticide early in the season on a biweekly schedule, as well as to ensure enough Trounce is supplied on site for the year (approximately 100 L).

While the demonstration-scale CWTS has experienced aphid infestations, this is not expected to occur in the full-scale CWTS and minimal insect control is expected (Rodgers et al., 2002). The full-scale CWTS will be built in an area with surrounding vegetation, thereby providing habitat for natural predators of aphids. With the demonstration CWTS currently located 50 m away from trees or other vegetation, there is little to no opportunity for natural predators to inhabit the area or incentive to travel the distance to the CWTS. The large buffer area

(MVFE) around the demonstration-scale CWTS allows the aphids to colonize more robustly than anticipated in the full-scale CWTS onsite, which would not have the same buffer zone.

Figure 17 – Aphids observed on *C. aquatilis* of cell 2A.

Presence of aphids on *C. aquatilis* leaves observed in August 2018.

4.9 Detritus Study

Key findings (detailed below):

- Decomposition of *C. aquatilis* is occurring in the CWTS and contributing to reducing conditions.
- Only partial decomposition of total *C. aquatilis* biomass from the previous year is occurring in an operational season, resulting in an accumulation of organic matter over time (accretion) which is an important process in the CWTS as it buries treated minerals making them more stable.
- Decomposition of *C. aquatilis* occurs quickly when initially submerged in the CWTS with 56% decomposition occurring after 34 days. Decomposition slows overtime with an average of 85% decomposition occurring after 446 days (including one winter season/freezing period).

The detritus study initiated in 2017 was continued through 2018 to assess decomposition rates of *C. aquatilis* in the CWTS over time as well as to determine the steady state of carbon contribution from algae growth on CWTS materials (Chimney and Pietro, 2006; Hammerly et al., 1989). Additional details describing the methods can be found in Appendix A. The study began on June 21, 2017 when six bags of oven dried *C. aquatilis* and six of polyester filter fiber material were submerged into each cell of the CWTS to determine the algae growth rate (Figure 18).

On July 25, 2017, September 11, 2017, July 9, 2018, and September 10, 2018 (after 34, 82, 383, and 446 days of submersion in the CWTS, respectively) one bag filled with *C. aquatilis* and one bag with the polyester fiber were sacrificed from each CWTS cell and the dried weights compared to initial sample weights. This resulted in four replicates for each treatment and sampling date.

The results show that decomposition occurs quickly immediately after *C. aquatilis* is submerged into the CWTS, with 56% decomposition occurring after 34 days. This detritus decomposition rate (and all other decomposition rates discussed herein) has been adjusted for by subtracting the weights of algal growth from the corresponding polyester fiber filled bag (Table 11). After 82 days (on September 11, 2017), 64% of *C. aquatilis* had decomposed and is representative of the decomposition that would be expected after one operational season of the CWTS (i.e., from start up in the spring to shut down in the fall). This suggests that the plant material is successfully being broken down in the CWTS promoting reducing conditions. Additionally, as plant material did not completely decompose after 446 days, this suggests that accretion in the wetland is also occurring as it indicates more organics are produced in a year than decomposes. This accretion, which is the gradual accumulation of additional layers of organic matter, aids in building new soils in the CWTS. Accretion is an important process in the CWTS as it buries treated minerals making them more stable and maintains low overall concentrations of metals.

Three bags of each material remain in each cell for future sampling. The detritus study will continue in 2019 to continue monitoring decomposition and accretion rates over time.

Figure 18 – Detritus study bags.

Left are mesh bags filled with sedges and polyester fiber fill stuffing in 2017, prior to submersion in the CWTS (June 21, 2017). Right is a mesh bag with decomposed sedges and polyester fiber fill stuffing on July 8, 2018.

Table 11 – Results of the 2018 *C. aquatilis* detritus study.

Days since beginning of study	Decrease in weight of *C. aquatilis* through decomposition[1]								Average Decomposition					
	1A		1B		2A		2B		A Cells		B Cells		All Cells	
	g	%	g	%	g	%	g	%	g	%	g	%	g	%
2017														
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
34	2.9	57	2.7	54	2.9	59	2.6	52	2.9	58	2.7	53	2.8	56
82	3.3	65	3.0	61	3.3	67	3.1	63	3.3	66	3.1	62	3.2	64
2018														
383	3.8	76	1.7	34[2]	4.8	96	3.2	64	4.3	86	2.5	49	3.4	68
446	5.5	Full decompo-sition	3.9	78	4.9	97	3.3	66	5.2	99%	3.6	72	4.4	85

Initial weight of bags prior to being placed in CWTS was 5 g.

[1] Weight decrease of *C. aquatilis* corrected by subtracting the increase in weight from the polyester fiber fil to account for algae growth.

[2] May have been affected by more algae growth than on control bags.

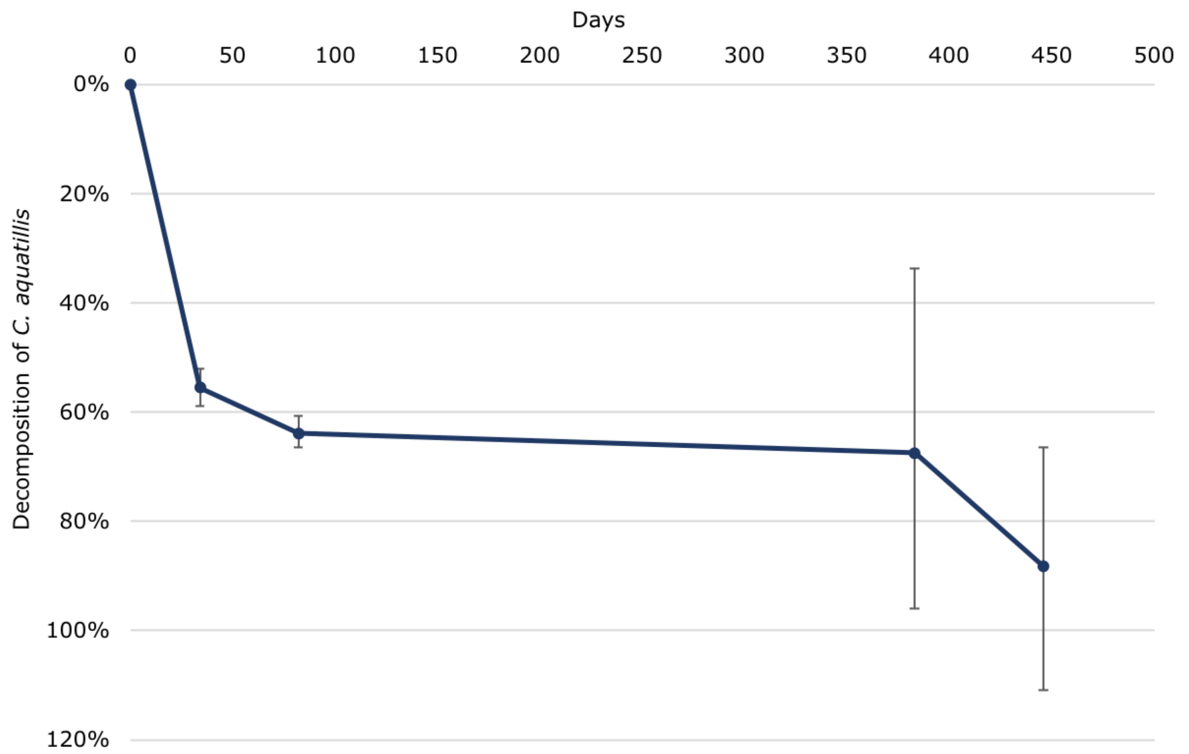


Figure 19 – *C. aquatilis* decomposition over time.

Decomposition was measured by the decrease in weight over time of the *C. aquatilis* samples compared to the initial weight. The decomposition rate was corrected for algae growth by subtracting the increase in weight of the polyester filter foam from the dry weight of the *C. aquatilis* samples over time. Error bars indicate the variation in results for each time point.

4.10 Vegetation Productivity Study

Key findings (detailed below):

- The *C. aquatilis* in the CWTS produced 0.802 kg/m^2 (dry weight) of above water biomass per year.
- This same amount of dry biomass should be supplemented to the full-scale CWTS (e.g., as straw) while going through maturation and filling in with vegetation for first 1-3 years after initial planting to expedite commissioning.

A 1 m^2 plot of above water *C. aquatilis* was harvested in 2018 (Appendix A, Section A6.7) to determine the amount of organic matter that is input into the wetland each year. The tests indicated that approximately 0.802 kg/m^2 (dry weight) of above water biomass is produced by the *C. aquatilis* per year. This same amount of dry biomass should be supplemented to the full-scale CWTS (e.g., as straw) while going through maturation and filling in with vegetation for first 1-3 years after initial planting to expedite commissioning.

4.11 Beneficial Microbes

Key findings (detailed below):

- Similar to 2017, root samples harboured the highest abundances of sulphide-producing bacteria (SPB), selenium-reducing bacteria (SeRB), and denitrifying bacteria in 2018.
- Microbial communities were not affected by the double stress test period, with the exception of SPB in roots, where proportions were lower following the drought. However, by the end of 2018, proportions of SPB in roots increased to levels measured in the 2017 operational period.

4.11.1 Sulphide-producing Bacteria

Sulphide production is a key biogeochemical mechanism for water treatment in the CWTS at Minto Mine and is carried out by sulphide-producing bacteria (SPB) through the reduction of sulphur-containing compounds. These SPB thrive in anaerobic conditions with soil redox ranges between -100 and -250 mV (Contango, 2015b; Mitsch and Gosselink 2007). In these redox ranges, bacterial sulphide-production through reduction of sulphur compounds is expected, alongside increases in the proportion (percentage) and abundance of these microbes. Further information regarding these mechanisms can be found in the Minto Demonstration-scale 2017 Update Report (Contango, 2018).

Diversity of SPB in all sample types (soil, roots, moss, and detritus) was generally similar to the 2017 operational period, where soil harboured the highest number of SPB, followed by root and detritus, then moss (Table 12).

Table 12 – Average number of different types of sulphide-producing bacteria in 2014/2015, 2016, 2017, and 2018.

Sample Type	2014 & 2015	2016	2017	2018
Detritus	NT	11	16	15
Moss	11	9	15	14
Root	11	13	14	15
Soil	13	17	18	17

NT – not tested. The number of different types is based on counting the number of operational taxonomic units (clustered at 97% identity) that are classified as known sulphide-producing bacteria. Organism classifications and data analysis methods have been updated from previous memo (Contango, 2017b). Therefore, additional bacteria were identified as sulphide-producing bacteria in historical samples at Minto and numbers presented herein are higher than those reported in the Minto Demonstration-scale 2017 Update Report (Contango, 2018).

Proportions of SPB in root, detritus, and moss, were generally similar to 2017, while SPB in soils were similar to or higher than 2017 (Figure 20). Proportions in *C. aquatilis* roots were initially lower than 2017 but increased to within 2017 ranges (Figure 21), while inferred abundances remained stable (Appendix B, Figure B24). Lower initial proportions of SPB indicates that roots were likely more impacted by the initial drying out of the CWTS in the early spring/freshet but began to recover by September. However, on average, roots harboured the highest inferred abundances of SPB (followed by detritus, moss, and soils; Appendix B, Figure B24). Proportions and inferred abundances of SPB in detritus were more variable within the different cells but generally remained within ranges observed in 2017 (Figure 22; Appendix B, Figure B24).

Proportions of SPB in moss in July were similar to 2017, while proportions in September were substantially lower (Figure 23). Inferred abundances of SPB in moss in September were also lower than July, however, they were within ranges observed in 2017. While sampling methods for moss requires a composite of the top (oxidizing zones) and bottom (sulphide reducing zones; Section 2.6.2) of moss, it is possible that samples collected in September contained more of the top of the moss than the bottom where SPB would be expected to thrive.

The microbial analysis of various sample types in the CWTS therefore indicates that despite the drought, SPB proportions and inferred abundances were able to recover in most sample types and diversity of SPB was unaffected by the double stress test. Soil redox and microbial populations will continue to be monitored for stability or further improvement in 2019. Additionally, a sampling procedure will be provided to Minto staff in 2019 to ensure consistency of sampling methods, particularly for moss.

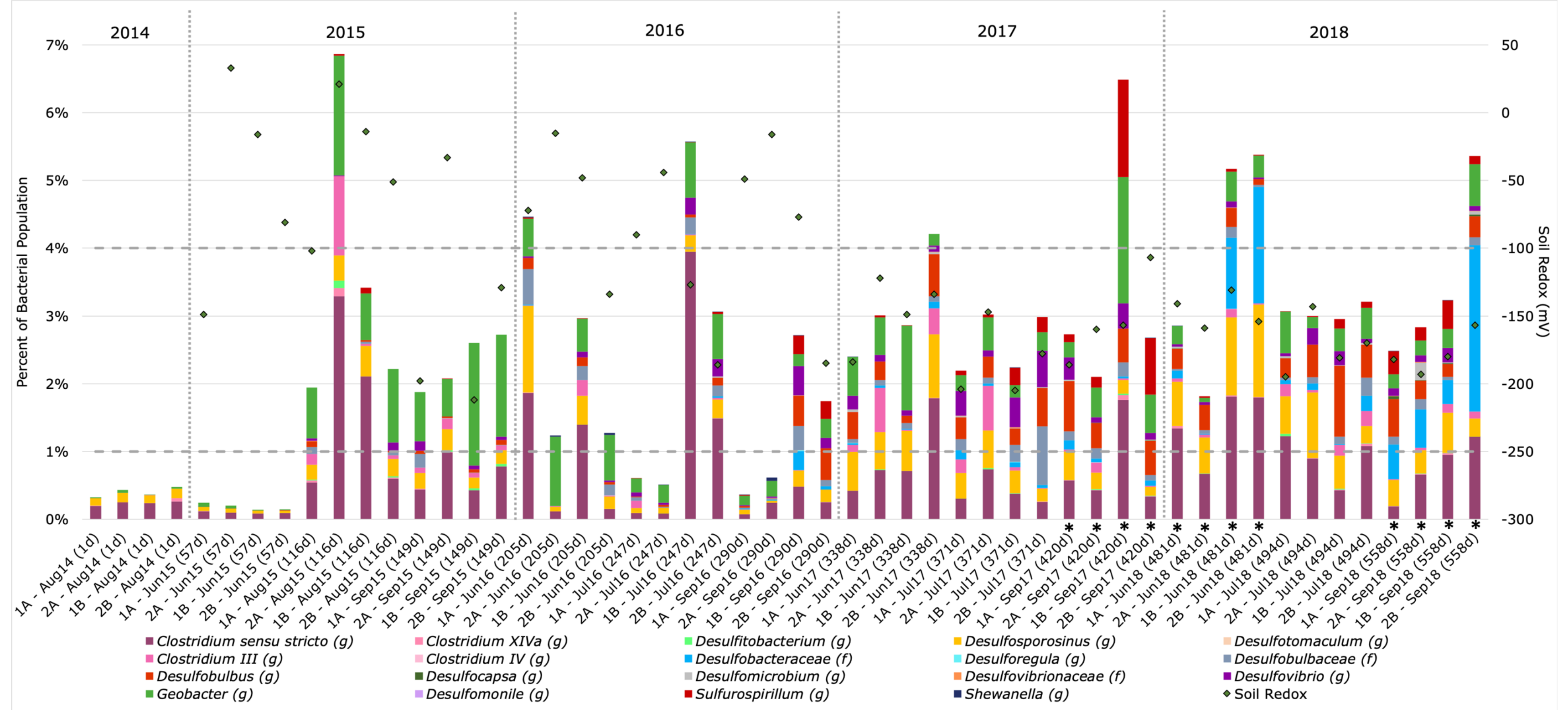


Figure 20 – Percentage and identity of sulphide-producing bacteria in soil and corresponding soil redox measurements.

The primary y-axis provides the percentage of the bacterial population (relative abundance) that corresponds to sulphide-producing bacteria through the reduction of sulphate, sulphite, thiosulphate, and sulphur. The secondary y-axis provides the soil redox measurements corresponding to the microbiology sampling date. Where soil redox measurements were not available, the date closest to the sampling date was plotted. Horizontal dashed lines indicate the targeted soil redox range. Organism classifications and data analysis methods have been updated from previous memo (Contango, 2017b). Therefore, additional bacteria were identified as sulphide-producing bacteria in historical samples at Minto. Percentage of bacteria is based on identification via genetic sequencing. Organisms are either classified to the genus (g) or family level (f). An asterisk (*) indicates dates were microbiological samples were collected by Minto staff. Remaining samples were collected by Contango. A sampling standard operating procedure will be provided in 2019 to standardize sampling methods.

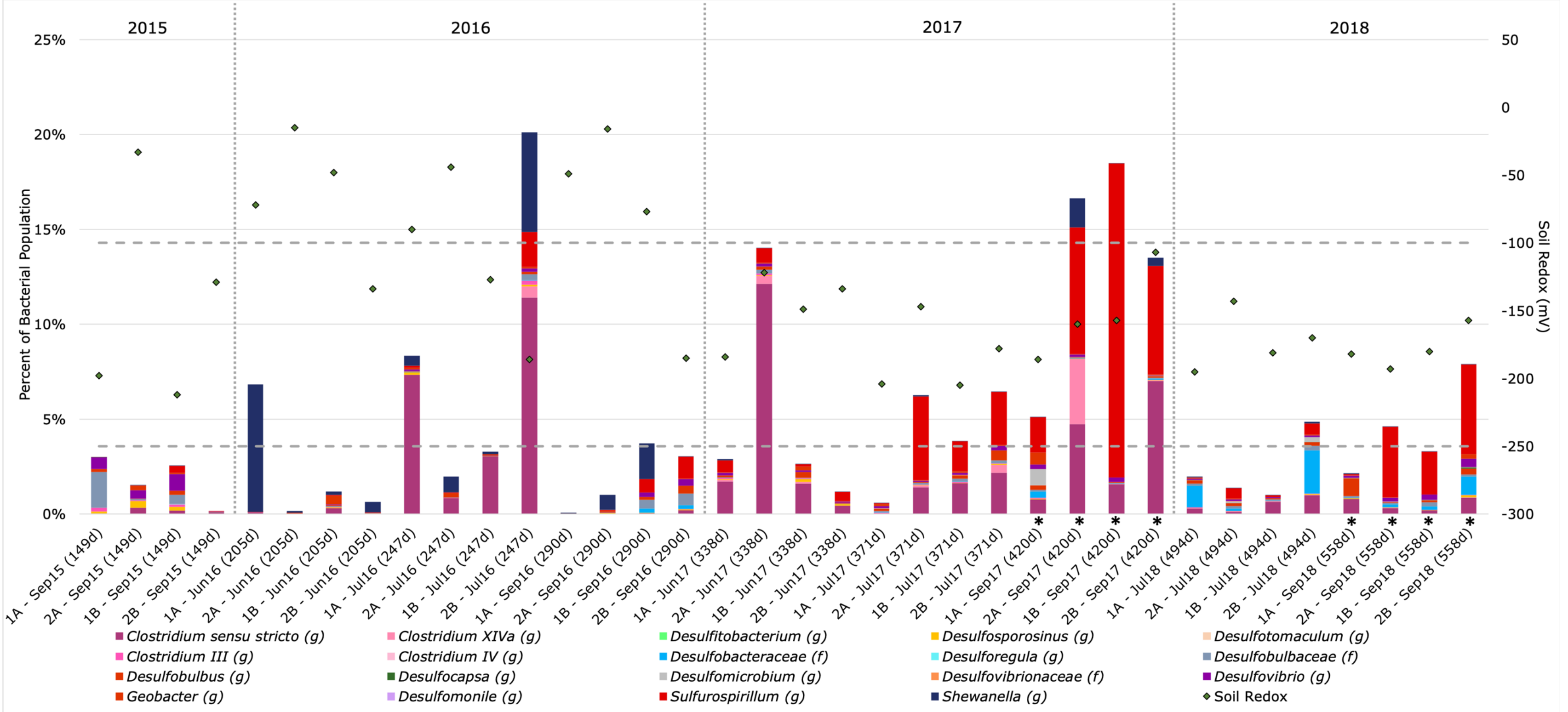


Figure 21 – Percentage and identity of sulphide-producing bacteria in root and corresponding soil redox measurements.

The primary y-axis provides the percentage of the bacterial population (relative abundance) that corresponds to sulphide-producing bacteria through the reduction of sulphate, sulphite, thiosulphate, and sulphur. The y-axis for root is different from other sample types as the percentage of sulphide-producing bacteria were much higher in many root samples. The secondary y-axis provides the soil redox measurements corresponding to the microbiology sampling date. Where soil redox measurements were not available, the date closest to the sampling date was plotted. Horizontal dashed lines indicate the targeted soil redox range. Organism classifications and data analysis methods have been updated from previous memo (Contango, 2017b). Therefore, additional bacteria were identified as sulphide-producing bacteria in historical samples at Minto. Percentage of bacteria is based on identification via genetic sequencing. Organisms are either classified to the genus (g) or family level (f). An asterisk (*) indicates dates were microbiological samples were collected by Minto staff. Remaining samples were collected by Contango. A sampling standard operating procedure will be provided in 2019 to standardize sampling methods.

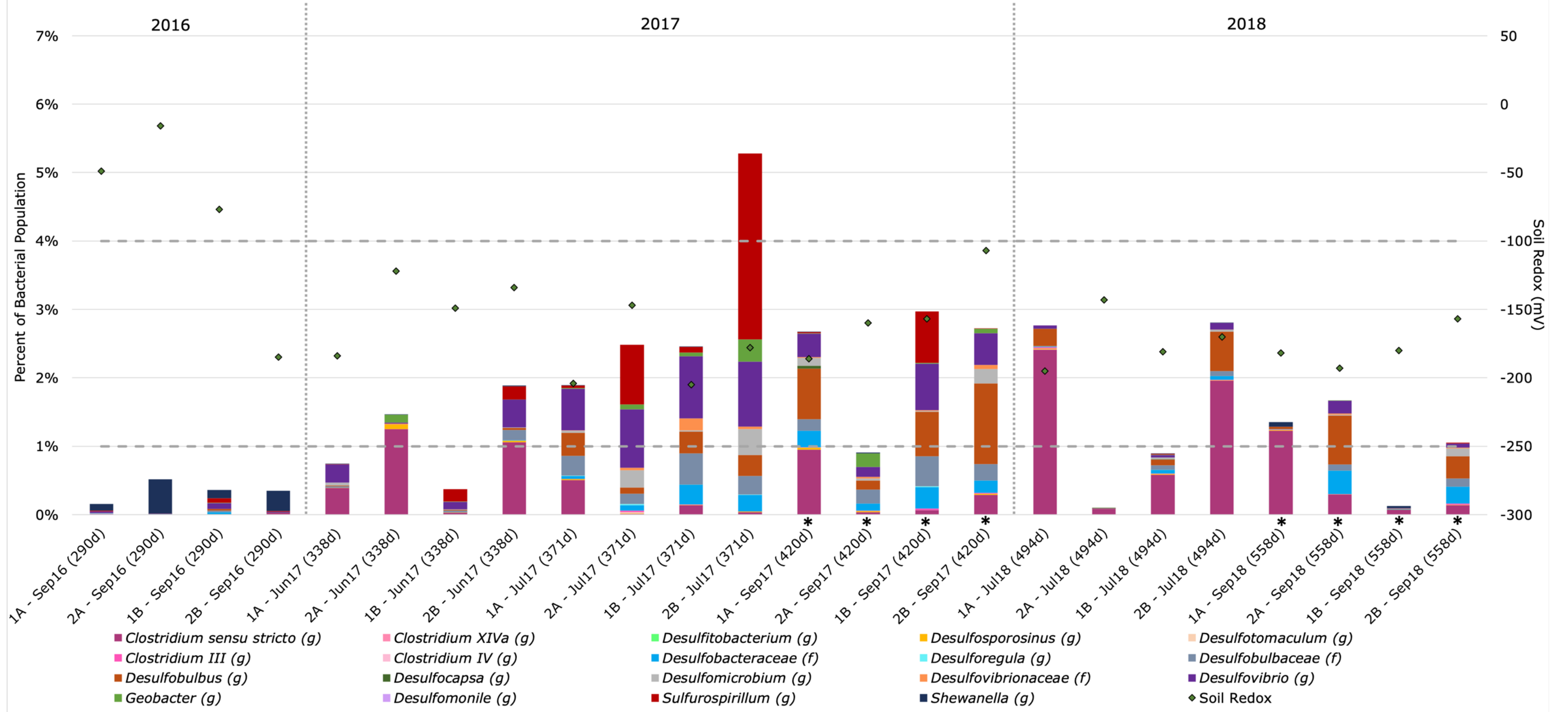


Figure 22 – Percentage and identity of sulphide-producing bacteria in detritus and corresponding soil redox measurements.

The primary y-axis provides the percentage of the bacterial population (relative abundance) that corresponds to sulphide-producing bacteria through the reduction of sulphate, sulphite, thiosulphate, and sulphur. The secondary y-axis provides the soil redox measurements corresponding to the microbiology sampling date. Where soil redox measurements were not available, the date closest to the sampling date was plotted. Horizontal dashed lines indicate the targeted soil redox range. Organism classifications and data analysis methods have been updated from previous memo (Contango, 2017b). Therefore, additional bacteria were identified as sulphide-producing bacteria in historical samples at Minto. Percentage of bacteria is based on identification via genetic sequencing. Organisms are either classified to the genus (g) or family level (f). An asterisk (*) indicates dates were microbiological samples were collected by Minto staff. Remaining samples were collected by Contango. A sampling standard operating procedure will be provided in 2019 to standardize sampling methods.

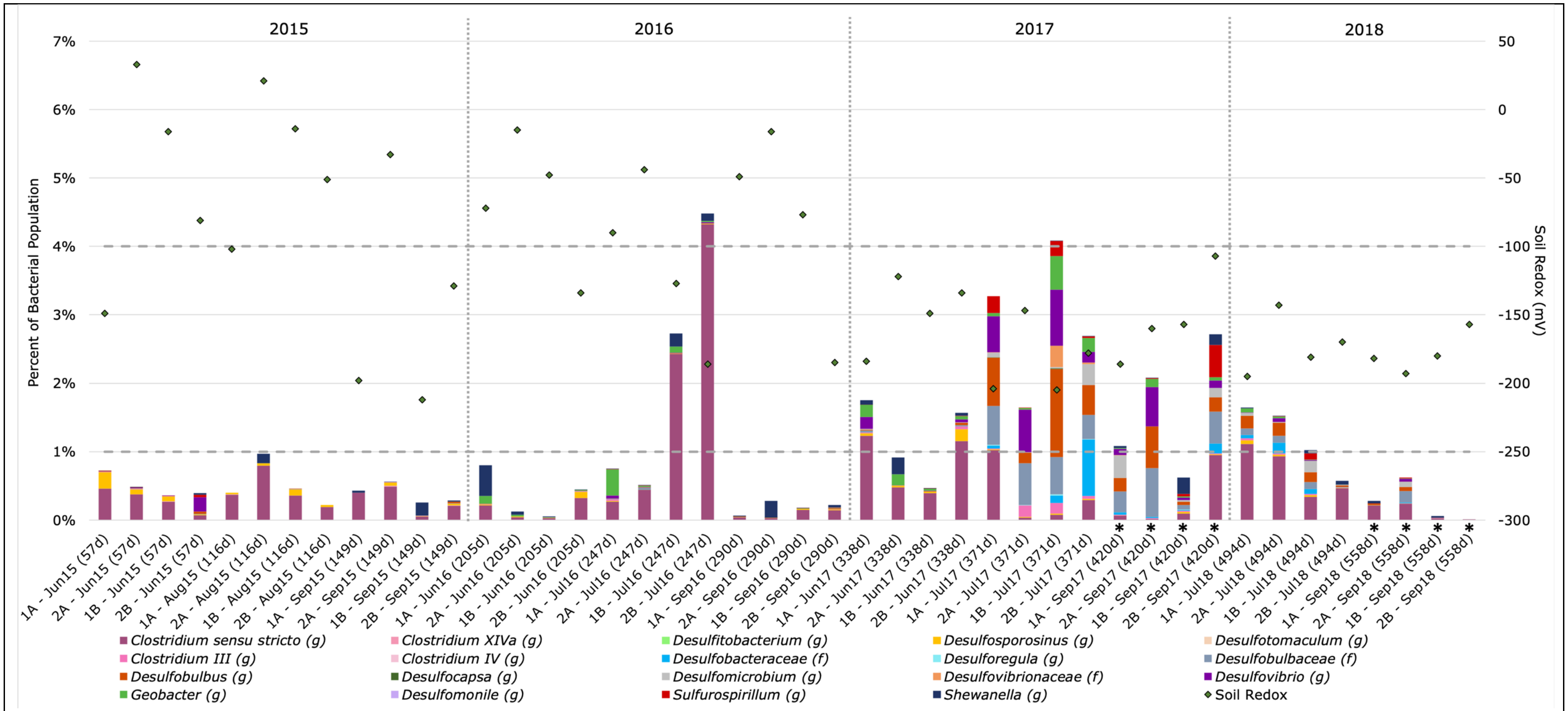


Figure 23 – Percentage and identity of sulphide-producing bacteria in moss and corresponding soil redox measurements.

The primary y-axis provides the percentage of the bacterial population (relative abundance) that corresponds to sulphide-producing bacteria through the reduction of sulphate, sulphite, thiosulphate, and sulphur. The secondary y-axis provides the soil redox measurements corresponding to the microbiology sampling date. Where soil redox measurements were not available, the date closest to the sampling date was plotted. Horizontal dashed lines indicate the targeted soil redox range. Organism classifications and data analysis methods have been updated from previous memo (Contango, 2017b). Therefore, additional bacteria were identified as sulphide-producing bacteria in historical samples at Minto. Percentage of bacteria is based on identification via genetic sequencing. Organisms are either classified to the genus (g) or family level (f). An asterisk (*) indicates dates were microbiological samples were collected by Minto staff. Remaining samples were collected by Contango. A sampling standard operating procedure will be provided in 2019 to standardize sampling methods.

4.11.2 Selenium-reducing Bacteria

The targeted selenium treatment pathways in the Minto CWTS include direct reduction in the water column of selenate (Se(VI)) to selenite (Se(IV) and sorption to moss, detritus, and soils, and subsequent microbial reduction of soluble (sorbed) selenite (Se(IV)) to insoluble elemental selenium (Se (0)). This reductive process can also be achieved directly in the water column, but is more effective when associated with mosses and biofilms due to their sorptive properties that bring the selenium in contact with beneficial selenium-reducing bacteria (SeRB). Selenium reduction biogeochemical processes are achieved within the range of soil redox conditions targeted for sulphate-reduction as suggested by pilot-scale testing and literature (Contango, 2014b).

SeRB were detected in all sample types, with *C. aquatilis* roots harbouring the highest inferred abundances of SeRB on average in 2018, followed by moss, detritus, and soil (Appendix B, Figure B25). While analytical methods for quantification in 2018 and previous years are not directly comparable, inferred abundances of SeRB are generally similar or higher to abundances the operational period in 2017 (Contango, 2017b). The high inferred abundances of SeRB in the CWTS indicates that environmental conditions conducive to SeRB proliferation have been created within the CWTS. Moreover, the abundances of SeRB were unaffected by the CWTS drying out and remained stable over time in through 2018. SeRB will continue to be monitored through 2019 operation of the demonstration-scale CWTS.

4.11.3 Denitrifying Bacteria

Nitrate is not a COC however it is being evaluated as it has the potential to be elevated during operations and early closure owing to residuals from blasting activities. Even if not in exceedance of water quality guidelines in terms of receiving environment objectives, nitrate often requires treatment to subsequently achieve treatment of other constituents such as selenium and metals through sulphide production. Nitrate can be removed from water through denitrification by different types of microbes, including nitrate reducing bacteria which can reduce nitrate (NO_3) to nitrite (NO_2), and also denitrifying organisms that are capable of fully reducing nitrate to nitric oxide (NO), nitrous oxide (N_2O), and dinitrogen gas (N_2, which is the most abundant gas in air).

As observed in 2016 and 2017, denitrifying organisms were found associated with all sample types in the demonstration-scale CWTS (Appendix B, Figure B26). *C. aquatilis* roots harboured the highest inferred abundance of denitrifiers, followed by moss, detritus, and soil. These results indicate denitrifying bacteria were not affected by the drought and have continued to establish in the CWTS as expected. Denitrifying bacteria will continue to be monitored in 2019, alongside performance testing.

5. Summary of Results

When designed and implemented in a strategic and scientifically guided manner, a CWTS can treat many constituents in a predictable manner. The design incorporates processes to precipitate insoluble species of these constituents for sequestration into the soils of the wetland. This treatment mechanism captures the constituents and stores them in stable form in the soil. This study addressed several important operating considerations and provided new management tactics to recover from drought and high nitrate scenarios. A summary of key findings from the 2018 studies and recommendations to meet the objectives are listed in Table 13.

Table 13 – Key findings and corresponding section for 2018 demonstration-scale CWTS testing.

Key Finding	Section
▪ Dissolved oxygen (DO) increased during the double stress test period and operations in 2018. Elevated DO is likely the result of photosynthesis of algae, which had increased growth due to fertilizer addition. Despite the DO levels being in aerobic ranges, stable reducing conditions were achieved in CWTS soils within the targeted range. ▪ Other than the day that the CWTS was refilled (May 14, 2018), soil redox was unaffected by the drought. Average soil redox values were more reducing (and stable in the targeted range) in 2018 than 2017.	4.1
▪ While leaching of copper from substrates used in construction was remedied by the end of the commissioning-B period in 2017, copper leached from the soils into the water in early 2018, likely due to the drying out of the CWTS in the early spring/freshet of 2018. However, leaching had subsided by July 8, 2018 as the rate of treatment exceeded the rate of leaching. Copper is not expected to leach in 2019 operations provided that the CWTS remains flooded. ▪ Stagnation and iron addition can be used at full-scale to mitigate recovery length after periods of drought (or stagnation/slower HRT for high nitrate concentrations). ▪ During the 2018 operational period the demonstration-scale CWTS successfully treated all COCs.	4.2
▪ The lowest concentrations consistently achievable for the treatment design (performance limits confirmed by t-test) were reached for cadmium after 3.80 days for Series 1 and 3.54 days for Series 2 and for copper after 3.54 days (Series 2 only). ▪ Removal rate coefficients (RRCs, *k*) have been developed that can be used for full-scale sizing. ▪ Copper leaching from soils decreased from the drought recovery period but is still likely making the RRC artificially low in this CWTS; however, the RRC is expected to improve in 2019 as leaching continues to decrease.	4.4
▪ The 2018 evapotranspiration trials were unsuccessful due to precipitation throughout each trial; however, the 2017 trials revealed a significant loss of water, which will impact calculations of loads to the receiving environment (making them lower than previously estimated). ▪ Unlike 2017 trials, leaching of copper was not observed during periods of no flow in 2018, indicating copper leaching has improved.	4.5
▪ In 2018, leachable copper concentrations in soils decreased in the top 0-10 cm while total copper concentrations were within ranges previously measured. ▪ Most constituents, including copper, have shifted primarily into stable reduced and residual minerals fractions in the soil.	4.6

Key Finding	Section
▪ Acid volatile sulphides (AVS) provide buffering capacity to the soils and continued treatment through cold temperatures. AVS concentrations have been non-detectable in the CWTS due to low iron concentrations in substrates and water. While a small amount was detected in 2017 and 2018, Series 1 was amended with iron in attempt to improve AVS concentrations. ▪ While Series 1 was amended with iron, it is unclear if the addition of iron was sufficient to increase AVS concentrations, but it is planned to add more in 2019.	
▪ Overall, uptake of metals in *C. aquatilis* was low and generally lower in 2018 than in 2017 demonstration-scale CWTS, with the exception of selenium in cell 1A which was slightly higher in 2018. ▪ Targeted treatment mechanisms are becoming more robust, rendering elements non-bioavailable.	4.7
▪ An aphid infestation occurred in 2016 and 2017. While some efforts were made in 2017 to control the aphid population, the spraying regimen was not maintained and, therefore, aphids remained. However, no long-term detrimental effect on *C. aquatilis* viability was observed, despite the persistence of aphids. ▪ In 2018, early and consistent application of insecticidal soap greatly reduced the abundance and length of an aphid infestation as well as improved containment of the aphids. ▪ Pesticide application is not expected to be needed in the full-scale CWTS as it will not be in an isolated location (Contango, 2017b).	4.8
▪ Decomposition of *C. aquatilis* is occurring in the CWTS and contributing to reducing conditions. ▪ Only partial decomposition of total *C. aquatilis* biomass from the previous year is occurring in an operational season, resulting in an accumulation of organic matter over time (accretion) which is an important process in the CWTS as it buries treated minerals making them more stable. ▪ Decomposition of *C. aquatilis* occurs quickly when initially submerged in the CWTS with 56% decomposition occurring after 34 days. Decomposition slows overtime with an average of 85% decomposition occurring after 446 days (including one winter season/freezing period).	4.9
▪ The *C. aquatilis* in the CWTS produced 0.802 kg/m^2 (dry weight) of above water biomass per year. ▪ This same amount of dry biomass should be supplemented to the full-scale CWTS (e.g., as straw) while going through maturation and filling in with vegetation for first 1-3 years after initial planting to expedite commissioning.	4.10
▪ Similar to 2017, root samples harboured the highest abundances of sulphide-producing bacteria (SPB), selenium-reducing bacteria (SeRB), and denitrifying bacteria in 2018. ▪ Microbial communities were not affected by the double stress test period, with the exception of SPB in roots, where proportions were lower following the drought. However, by the end of 2018, proportions of SPB in roots increased to levels measured in the 2017 operational period.	0

6. Next Steps for 2019

A conceptual testing plan was developed at the beginning of the demonstration-scale CWTS program and has been refined and adapted based on performance and scientific findings during the commissioning and operational periods of the demonstration-scale CWTS. The demonstration-scale CWTS is expected to run until at least the end of 2019 to assess performance under a wider range of conditions. In 2019, a flow rate schedule will be developed targeting different HRTs based on predicted HRTs for full-scale performance. The overriding objective of the demonstration-scale program in 2019 is to assess performance under conditions that would be similar to the full-scale CWTS. Table 11 outlines the action plan for CWTS optimization and testing for 2019 based on the performance results through 2018.

A multi-year plan is provided in Appendix C, and includes work performed to date, as well as a schedule of activities for 2019.

Table 14 – Minto 2019 demonstration-scale CWTS action items.

Timing	Task	Purpose
Jan – Apr 2019	Visually inspect CWTS monthly	▪ The CWTS is recommended to be monitored monthly to ensure there is consistent ice cover.
Apr 2019	Develop a flow rate schedule for 2019	▪ The flow rates will fluctuate based on expected amounts of water for full-scale CWTS (scaled to size) to evaluate the performance of the CWTS at different key periods.
	Develop sampling plan for 2019	▪ The sampling plan will include sampling types, parameters, frequency, and locations. These results will inform the performance of the CWTS. ▪ Sampling of the in, mid, and out locations for water and two locations through each cell (near depth sticks) for soil to better assess removal of constituents through the CWTS cells. ▪ Dissolved oxygen measurements will be taken at various locations and depths through the CWTS cells to obtain a more thorough understanding of aerobic zones within the CWTS. ▪ Pictures of the CWTS will be taken from all four corners of each cell to better monitor plant growth and development, as well as monitor algae growth and aphid presence.
	Provide Minto with updated standard operating procedures (SOPs) for monitoring and sampling the CWTS and training for microbial sampling	▪ SOPs will include how to take progress pictures of each CWTS cell, take YSI and depth stick measurements, re-install depth stick that had fallen over in 2018 (cell 1A), record data and label samples, collect water, soil, moss, and plants for ALS and Contango microbial samples, sample bags for detritus study, and spray for aphids. ▪ Training will be provided for microbial sampling to ensure consistent methods are used (either during first Contango site visit, or by video conference).
May 2019	Add sandbags to the end of the CWTS cells to increase the water depth to 20-30cm.	▪ Raising the water levels will maintain desired reducing conditions in the CWTS and make for better consistency of depths in all cells.

Timing	Task	Purpose
	Monitor water levels in CWTS, add water with water truck if needed	▪ The CWTS is recommended to be monitored weekly to add water to each cell immediately upon spring thaw to prevent the CWTS from drying out.
	Start water flow to the CWTS	▪ Begin 2019 demonstration-scale CWTS program.
	Contango site visit (provide training, add iron to Series 1, conduct spring microbial sampling event)	▪ Provide training for new Minto staff for monitoring and sampling of CWTS to ensure consistency of methods. ▪ Collect seasonal microbial samples. ▪ Add iron as instructed by Contango to Series 1 to aid in creation of excess acid volatile sulphides.
	Implement aphid control using insecticide on a routine schedule	▪ Begin applications in early May when vegetation begins to turn green to control the aphid population before an infestation occurs.
Ongoing through 2019 sampling season	Routine sampling program	▪ Follow sampling plan from May to September 2019 for routine collection of water, soil, microbial, plant, and detritus samples.
	Monitor for the presence of aphids in the CWTS	▪ Determine if the aphid presence is isolated to the CWTS (if present at all), and if more aggressive control measures are needed.
	Fertilize plants (if necessary) and add moss to cell 1A	▪ To help plant growth and development if needed. To revegetate areas where moss is sparse.
Jul 2019	Conduct evapotranspiration trial	▪ Although 2017 data suggests minimal release of metals from soils, another evapotranspiration trial during the operational period needs to be conducted to confirm metals leaching has subsided. Completing the evapotranspiration study in July will provide information on evapotranspiration rates in warmer months and the effects of seasonality.
	Contango site visit (conduct summer microbial sampling event)	▪ Collect seasonal microbial samples.
Aug 2019	Develop plan for final sampling event	▪ Additional samples will be collected upon termination of the demonstration-scale CWTS to evaluate parameters such as mass balance of constituents.

Timing	Task	Purpose
Sep 2019	Contango site visit (harvest soil and moss for additional tests off-site, conduct fall microbial sampling event)	▪ Collect soil sample (volume not yet determined) and bring back to Contango's temperature-controlled facilities. Soil will be subjected to several stress tests (stagnation, drought, flood, freezing, and leach tests) to assess stability of metals in the event of an upset event. ▪ Collect all above water biomass of C. aquatilis and all moss in a 1 m2 plot to determine quantity of biomass per m2 for each C. aquatilis and moss. ▪ Collect seasonal microbial samples.
	Final sampling event	▪ Additional samples will be collected prior to decommissioning of the CWTS.
February 2020	Report	▪ Final Demonstration-scale CWTS Report.

7. Closure

We trust the information herein satisfies your present requirements. Should you have any questions, please contact the persons listed below. We appreciate the opportunity to provide the services detailed in this report, and look forward to discussing any comments you may have.

Regards,

Contango, an AEG company

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Appendix A8
Minto Mine Constructed Wetland Treatment Research Program - Demonstration Scale 2019 Update

Appendix A – Methods

Table of Contents

List of Tables

List of Figures

Methods from 2019 are described here, along with a brief summary of construction and operational details from previous years. More detail from previous years is available in Appendix A of the Minto Constructed Wetland Treatment Research Program – Demonstration-scale Update Reports from 2015 to 2018 (Contango 2016a; Contango 2017a; Contango 2017b; Contango 2019).

A1. System Layout and Dimensions

The demonstration-scale constructed wetland treatment system (CWTS) includes two series in parallel with two cells in each series and a final catchment basin that both series flow into. Dimensions and construction details are available in Contango, 2015. In 2019, the two parallel series were operated the same to serve as replicates for data analysis, while in previous years, the two series had different inputs to allow for comparison of different management techniques, such as Fe-EDTA studies on soils leaching copper or iron addition for drought recovery (Contango, 2016a; Contango, 2019).

A2. Vegetation Used in Planting

The demonstration-scale CWTS was planted with *Carex aquatilis* (aquatic sedge) and aquatic mosses from the W10 area of the Minto Site. The plant selection and borrow source was previously determined through the site assessment (Contango, 2014a). During construction, five *C. aquatilis* plants were planted per square meter, with moss tied to stakes that outlined the 1 m x 1 m grid for planting (details provided in Contango, 2015).

A3. Aphid Monitoring and Pesticide Application

Application of pesticide (Bug-B-Gone) on *C. aquatilis* in each cell occurred weekly, starting on May 30, 2019, then bi-weekly, starting July 11, 2019, as a preventative measure tested in 2018 (Contango, 2019).

A4. Water Source

The same water source (W62) was used for the demonstration-scale CWTS in 2019 as was used in 2016 - 2018. The original water source used in 2015 (W36) was changed due to the Mill Valley Fill Extension Stage 2 construction and decommissioning of the W36 collection sump.

A4.1 Water Depth Measurements

Depth sticks installed in the CWTS in June 2016 were used to measure the water depth over time (Contango, 2017a). Sandbags were added to the CWTS gradually from May 5-July 17, 2019 to increase the water level to a target of 30-40 cm depth. After the first sandbags were added, the depth was allowed to stabilize before adding more sandbags. This was done until the targeted depth was measured. The depth stick in cell 1A was corrected to proper depth during the first seasonal site visit on May 29-30, 2019. The measured depths were used for further calculations regarding cell volume and HRT (Section A11).

A5. Flows Rates

Flow rates were fluctuated over 2019 to target the following hydraulic retention times (HRTs):

- 5 day HRT (May 15-22, 2019; August 16-September 5, 2019)
- 2.5 day HRT (May 23-July 2, 2019)
- 1.2 day HRT (July 3-30, 2019)
- 0.8 day HRT (August 3-15, 2019)

The 5 day HRT was targeted for continuity of HRTs previously tested in the demonstration-scale CWTS (5 and 7.25 day HRT for the 2017 and 2018 operational period, respectively; Contango 2017b; Contango 2019). The 0.8 to 2.5 day HRTs were calculated based on expected flow reporting to the full-scale CWTS. The targeted nominal HRT was calculated using the actual water depth in each series, plus the correction factor obtained from the 2017 tracer study (Contango, 2017b). The actual water depth used to calculate the targeted HRT was measured prior to starting the HRT scenario since the depth increased gradually as sandbags were added slowly until target depths were reached.

A6. Timeline and Sampling Schedule

Major events and operational adjustments or amendments for 2019 are listed in Table A1. Details for events up to 2017 and through 2018 can be found in Contango, 2017b and Contango, 2019, respectively. The actual dates as well as effective days of operation are provided, which adjusts for time that the CWTS was not receiving water when it was frozen or not flowing. The effective days of operation allows for comparison to expected timelines from pilot-scale testing, and for planning and scheduling for the full-scale system. The operational testing plan was conceptually developed prior to beginning construction of the demonstration-scale CWTS and the sampling schedule for each year was refined annually. Actual dates of sampling were adjusted for timing of spring thaw and winter freeze-up, and the associated ability to have the pumps operating at the W62 sump to supply water to the demonstration-scale CWTS.

Table A1 – Events and sampling activities in 2019.

Event	Key Activity	Flow Rate Recorded m^3/day (GPM)		Dates	Effective Days of Operation (start date = August 27, 2014)
		Series 1	Series 2		
CWTS water depth maintained	Prevented CWTS drought at spring thaw	n/a	n/a	April 5-8, 2019	-
	Added WTP water	n/a	n/a	April 16-May 1, 2019	-
	Added W62 water	n/a	n/a	May 2-14, 2019	-
Water depth raised	Added sandbags gradually to target 30 - 40 cm water depth above substrate	n/a	n/a	May 5-July 17, 2019	-
Start flow	Flow started to target a 5 day HRT	3.27 (0.60)	2.02 (0.37)	May 15, 2019	577
Flow rates increased	Adjusted flow to target a 2.5 day HRT	7.14 (1.31)	4.42 (0.81)	May 22, 2019	584
Contango Site Visit #10 & spring seasonal sampling	Tested soils, water, detritus bags, and sampled microbiology[1]	7.25 (1.33)	7.14 (1.31)	May 29-30, 2019	591-592
Moss transplanted from W10	Replenish cells 1A and 2A moss	n/a	n/a	May 30, 2019	592
Aphid spraying started	Applied insecticide once every week	n/a	n/a	May 30, 2019	592
Flow rates increased	Adjusted flow to target a 1.2 day HRT	21.15 (3.88)	13.74 (2.52)	July 3, 2019	627
Insecticide regimen changed	Applied insecticide every two weeks	n/a	n/a	July 11, 2019	634
Aphids observed on 1A	Resolved with spraying regimen	n/a	n/a	July 26, 2019	649
Contango Site Visit #11 & summer seasonal sampling	Tested soils, water, detritus bags, and sampled microbiology[1]	20.71 (3.80)	15.26 (2.80)	July 29-30, 2019	652-653
Storm event	Stopped flow due to source issues	*	*	July 30-31, 2019	653-654
Flow rates increased after flow re-established	Cleared excess TSS in tank, flow blockages and adjusted flow to target a 0.8 day HRT.	31.29 (5.74)	24.31 (4.46)	August 3, 2019	657
Intermittent ice formation on CWTS surface	No action performed	n/a	n/a	August 14-28, 2019	668-682
Target flow rates decreased	Adjusted flow to target a 5 day HRT	6.11 (1.12)	4.80 (0.88)	August 15, 2019	669
Aphids observed on 2A	Resolved with spraying regimen	n/a	n/a	August 27, 2019	681
Contango Site Visit #12 & fall seasonal sampling	Tested microbiology, soils, water, *C. aqualtilis* and moss, mass balance, and vegetation plot	5.45 (1.00)	4.25 (0.78)	September 4-5, 2019	689-690
Winterize CWTS	Flow stopped & wetland closed	0	0	September 12, 2019	697

'*' – indicates that no flow rate was given or that flow rate was unmeasurable or variable; however, cells remained flooded throughout. n/a – flow rate not applicable.

[1] Microbiology samples were collected and bio-banked.

A7. Sampling and Analyses Methods

A7.1 Routine Monitoring of Explanatory Parameters

Explanatory parameters are quantifiable aspects of a CWTS environment that can be used to assess feasibility of treatment for a range of constituents, and therefore ‘explain’ the performance of a CWTS. These parameters were monitored on a weekly basis from spring thaw in May 2019 to freeze up in September 2019, with an increased monitoring frequency during the fastest HRT scenario. Methods are described in Appendix A of Contango, 2017b.

A7.2 Water Sampling and Analyses

Water sampling occurred on a weekly basis from spring thaw in May 2019 to freeze up in September 2019, with an increased sampling frequency during the fastest HRT scenario. Additional parameters were also tested at least once per HRT scenario. At least one full HRT period was allowed to pass before each sampling event, including after flow rates were adjusted. Frequencies and sampling parameters are outlined in Table A2. Grab samples were collected as described in Appendix A of Contango, 2017b.

After it was observed that copper was leaching from the CWTS substrates into the water, an additional sampling structure was designed to sample at the inflow, mid-point, and outflow of each cell. Details of this sampling method are described in Appendix A of Contango, 2017b. Water was sampled for total and dissolved metals from the inflow, mid-point, and outflow of each cell monthly in 2019 (May 29, June 18, July 23, August 12, and September 4, 2019).

Table A2 – Summary of 2019 water sampling analytical parameters, frequencies, and locations.

Analytical Parameters	Frequency of Sampling	Sample Locations
Dissolved and total metals	Weekly[1]	Outflow of each cell and feed
Ammonia		
Nitrate		
Nitrite		
Hardness ($CaCO_3$)		
Sulphate (SO_4)		
Flow rate	Daily	Feed
pH, DO, ORP, Conductivity (*in situ*), Temperature	Weekly[1]	All cells and feed
Anion Sum	Minimum once per HRT scenario	Outflow of each cell and feed
Cation Sum		
Ion Balance		
Total Dissolved Solids (TDS)		
Chloride (Cl)		
Nitrogen (Total)		
Alkalinity		
pH		
Conductivity		
Chemical Oxygen Demand (COD)		
Total Organic Carbon (TOC)		
Total Kjeldahl Nitrogen (TKN)		
Total Suspended Solids (TSS)		
Dissolved Organic Carbon (DOC)		
Bicarbonate (HCO_3)		
Carbonate (CO_3)		
Hydroxide (OH)		

[1] Sample frequency was increased during the fastest HRT scenario. At least one full HRT period was allowed to pass before each sampling event, including after flow rates were adjusted.

A7.3 Soil Sampling and Analyses

Soil sampling was conducted three times in 2019 (May 30, July 30, and September 5, 2019), while *in situ* relative soil redox was measured at least once per HRT scenario. A sample of the CWTS soil was collected for analyses as outlined in Table A3. Each CWTS cell was a composite of the top 0-10 cm from both sides of the CWTS sampled near the inflow, mid-point (September only), or outflow during each sampling event. An additional soil sample was collected on September 5, 2019 and brought to Contango to determine a wet and dry weight from a known volume of soil for analyses associated with evaluating the fate and distribution of constituents of concern (COCs) within the CWTS (Section A12).

Table A3 – Summary of 2019 soil sampling analytical parameters, frequencies, and locations.

Parameters	Frequency of Sampling	Sample Locations
Relative soil redox (*in situ*)	Minimum once per HRT scenario	All probes (6 per cell)
Analyses completed on soil sample		
SAR[4], pH, EC[4], %sat[4], Ca[4], Mg[4], Na[4], K[4], Cl[4], SO$_4$[4]	Seasonally (3x per year)	From a depth of 0-10 cm near the inflow, mid-point (September only) and outflow.
Available NPK and sulphur[4]		
Bicarbonate (HCO$_3$)		
Carbonate (CO$_3$)		
Total Organic Carbon (TOC)[4]		
Metals Analysis (Total)[1]		
Sulfur by LECO		
Metals Leach[1,3]		
Acid Volatile Sulphides (AVS)[1,2] and Simultaneously Extracted Metals (SEM)[1,2]		
Sequential Leaching (5 Acid Test)[1,4]		
Analyses completed on special leach		
Bromide (Br)	Seasonally (3x per year)	From a depth of 0-10 cm near the inflow, mid-point (September only) and outflow.
Chloride (Cl)		
Sulphate (SO$_4$)		
Fluoride (F)		
Alkalinity		
Bicarbonate (HCO$_3$)		
Carbonate (CO$_3$)		
Hydroxide (OH)		
Dissolved Organic Carbon (DOC)		
Ammonia		
Nitrate		
Nitrite		
Total Dissolved Solids (TDS)		

[1] Only select parameters were possible for the May 30th, 2019 samples, and therefore parameters were prioritized for testing.

[2] Only the May 30th, 2019 outflow sample was tested.

[3] For the May 30th, 2019 samples, parameters were tested using reverse osmosis water instead of the special leach water provided as no additional special leach water was available for re-testing. Results were removed from further analysis.

[4] Parameters were not part of planned testing for the September 5, 2019 mid-point soil sample.

To assess the effect of the elevated copper in the soils used in construction and the high initial copper concentrations on CWTS functionality, four soil analytical test methods have been used as described in Appendix A of Contango, 2017b. Three of these analytical test methods were used in 2019:

1. Total concentration of elements in the soils by CRC ICPMS.
2. The concentration of metals that are being released from the soil into the overlying water column by specialized leach method.
3. Stability and form of elements in soils by a sequential extraction procedure for the speciation of particulate trace metals (Tessier et al., 1979).

A7.4 Plant Sampling and Analyses

Moss and above water *C. aquatilis* samples from each cell were collected for metals analysis at the final sampling event of the demonstration-scale CWTS (September 2019) as described in Appendix A of Contango, 2017b. Analyses of tissue samples are outlined in Table A4 (reported in mg/kg dry weight). The tissue samples were homogenized and sub-sampled prior to digestion. In 2019, moss samples were collected for analysis of metals from a 4 m^2 area. A sub-sample of the 4 m^2 area harvest was brought to Contango and dried to determine the moisture content of moss. This information was used in calculations of fate and distribution of COCs within the CWTS (Section A12). *C. aquatilis* samples were also collected from a known area to evaluate fate and distribution of COC within the CWTS as described in Section A7.7.

Table A4 – Summary of 2019 plant sampling analytical parameters, frequencies, and locations.

Analytical Parameters	Plants Sampled	Location	Frequency of Sampling
Total Metals by ICPMS	*Carex aquatilis*	Composite of four locations in each cell	Year end
	Aquatic moss	Composite sample from 4 m^2 plot in each cell	

A7.5 Microbial Sampling and Analysis

Four microbial sample types (soil, roots, detritus, and moss) were collected from each cell in the CWTS three times in 2019 during the each seasonal sampling event (May, July, and September). Microbial samples from May and July were biobanked (i.e., stored but not processed), while quantification and DNA based analyses (genetic sequencing) were conducted for all sample types collected in September 2019. Methods for sample collection for each sample type is described in Appendix A of Contango, 2017b.

A7.5.1 Quantification Analyses

In 2018, Contango's microbial quantification analyses progressed from growth-based analyses (MPN) to a new technology that enabled improved quantification (quantitative polymerase chain reaction; qPCR). Consequently, the soil samples collected in June 2018, and all samples collected in July 2018 were analyzed using both growth-based and genetic qPCR microbial analyses to compare the two methods. While not directly comparable, the results of the comparison indicated that qPCR analyses were better suited to move forward with. In 2019, microbial samples were analyzed by qPCR quantification only. Therefore, only results from 2018 and 2019 qPCR analyses are shown in graphs and overall trends for all years are described.

Methods for MPN and qPCR analyses are described in Appendix A of Contango, 2017b and Appendix A of the Minto Constructed Wetland Treatment Research Program – Demonstration-scale 2018 Update (Contango, 2019), respectively.

A7.5.2 Genetic Sequencing Analyses

DNA was extracted and sequenced as described in Appendix A of Contango, 2017b.

A7.6 Detritus Decomposition Trials

A detritus decomposition trial was performed between 2017 and 2019 to assess decomposition rates of *C. aquatilis* and algae growth on organic materials in the demonstration-scale CWTS over time (Chimney and Pietro, 2006; Hammerly et al.,1989). Methods are described in Appendix A of Contango, 2017b.

On May 29 and July 29, 2019 (after 708 and 768 days of submersion in the CWTS, respectively), one bag filled with polyester filter fiber and one bag filled with *C. aquatilis* was removed from each cell, dried, and weighed as described in Appendix A of Contango, 2017b. In 2019, detritus decomposition was measured and assessed from the change in weight of *C. aquatilis* leaves in the mesh bag only and was not adjusted for the increase in dry weight of the polyester fiber. Additional data acquired in 2019 suggested that the increase in weight of the poly filter fiber had a positive bias on *C. aquatilis* decomposition due to excess algae and debris on the poly filter fiber (as described in the main report Section 6.2.1.). This updated method for assessing decomposition was applied to past detritus samples collected since 2017 for comparison across years.

A7.7 Vegetation Study

A vegetation plot harvest was completed in 2018 and 2019 to assess the amount of above water biomass (*C. aquatilis)* that grows per year per m^2 in a mature CWTS. The results from the vegetation plot harvest were applied to the area of each cell in the CWTS to estimate the amount of *C. aquatilis* that would contribute organic matter into the CWTS each year. A 1 m^2 quadrant was delineated in cell 1A of the demonstration-scale CWTS and all the above water *C. aquatilis* was harvested within the quadrant (Figure A1). The *C. aquatilis* was weighed and placed in a drying oven at 50^{o}C until a constant mass was observed. The dry weight of the *C. aquatilis* was then adjusted for the size of the CWTS to calculate the total biomass of *C. aquatilis* added to the CWTS in a year. Finally, the total biomass addition was compared to the decomposition rate (Section A7.6) to establish organic matter addition to the CWTS. The dry weight from the 1 m^2 plot collected on September 5, 2019 was also used to evaluate fate and distribution of COC within the CWTS (Section A12).

Figure A1 – Vegetation plot harvest 2019.
Photo on the left shows vegetation plot harvest area delineated with wooden stakes. Photo on the right shows the area that was harvested. Photos were taken September 5, 2019.

A8. Data Analysis method

During the operational period of 2019, treatment of cadmium, copper, molybdenum, nitrate, selenium, and zinc was assessed for each HRT scenario. Total metals concentrations were monitored and while there were instances where the total concentration of COC in the feed water was elevated compared to the dissolved concentrations, both total and dissolved concentrations were similar by the outflow indicating that the CWTS is filtering solid forms of COC as intended. Additionally, the higher flow rates in 2019 did not result in elevated levels of total concentrations at the outflow, with a brief exception where cadmium concentrations increased slightly but were still an order of magnitude below CCME guidelines. Therefore dissolved metals concentrations rather than total metals were predominantly used for the discussion in this report as dissolved values are more representative of metals treatment through transformation and transfer from the CWTS water. Selenium was one exception where total concentrations were used, as dissolved selenium concentrations were often (over 40% of measurements) greater than the measured total selenium concentrations when using standard analytical methods (including the feed water source). This can sometimes occur when there is interference with the measurement for dissolved selenium, and digestion of the field filtered sample prior to ICP-MS can provide more accurate results (Wozniak, 2018). A comparison was performed near the end of the 2019 season to compare total selenium concentrations to dissolved concentrations with and without digestion. This analysis confirmed that dissolved concentrations with digestion were within 4-13% of total concentrations (within method error), while without digestion were 27-69% greater than total concentrations. These results will be discussed with Minto and the analytical service provider to evaluate testing methods for 2020.

A9. Performance Limit Calculations

The performance limit (previously referred to as thermodynamic minimum) is the lowest concentration consistently achievable for a given treatment design and water chemistry. These calculations were conducted as described in Appendix A of Contango, 2017b.

A10. Load Removal Calculations

Load removals are calculated both with and without adjustment for evapotranspiration. The evapotranspiration adjustment converts the calculation of load removed during each HRT scenario to the actual amount of load removed, taking into consideration the amount of water lost from the demonstration-scale CWTS through evapotranspiration. Load removal was determined using equations to calculate the initial load removed with and without adjustment for evapotranspiration as described in Appendix A of Contango, 2017b.

A11. Removal Rate Coefficients and HRT Calculations

An important factor for CWTS design is the rate of treatment, also known as the removal rate coefficient (*k*). The removal rate coefficient is based on the treatability of a specific compound and the HRT of the CWTS, both of which are site-specific based on water chemistry, CWTS designs, and characteristics of the CWTS. These calculations were conducted using removal rate coefficient (*k*) equations as described in Appendix A of Contango, 2017b.

A12. Mass Balance Calculations

The fate and distribution of COC were evaluated through mass balance calculations. The load of a constituent entering and exiting the CWTS in a given year as well as over the lifespan of the demonstration-scale CWTS was calculated using total COC concentrations. The load of a COC that was removed by each series through filtration, sorption, and transformation is the difference between the load entering and exiting the CWTS. The concentration of a COC in plant tissues (*C. aquatilis* and moss; Section A7.4) as well as the top 10 cm of soils at the end of the 2019 demonstration-scale season (Section A7.3) were used to evaluate the fate and distribution of COC. For multiple COC, the load removed in the CWTS is within method error of the starting concentration in the substrate.

A13. References

All references provided in main report.

Appendix B – Additional Tables and Figures

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B1. Water Results

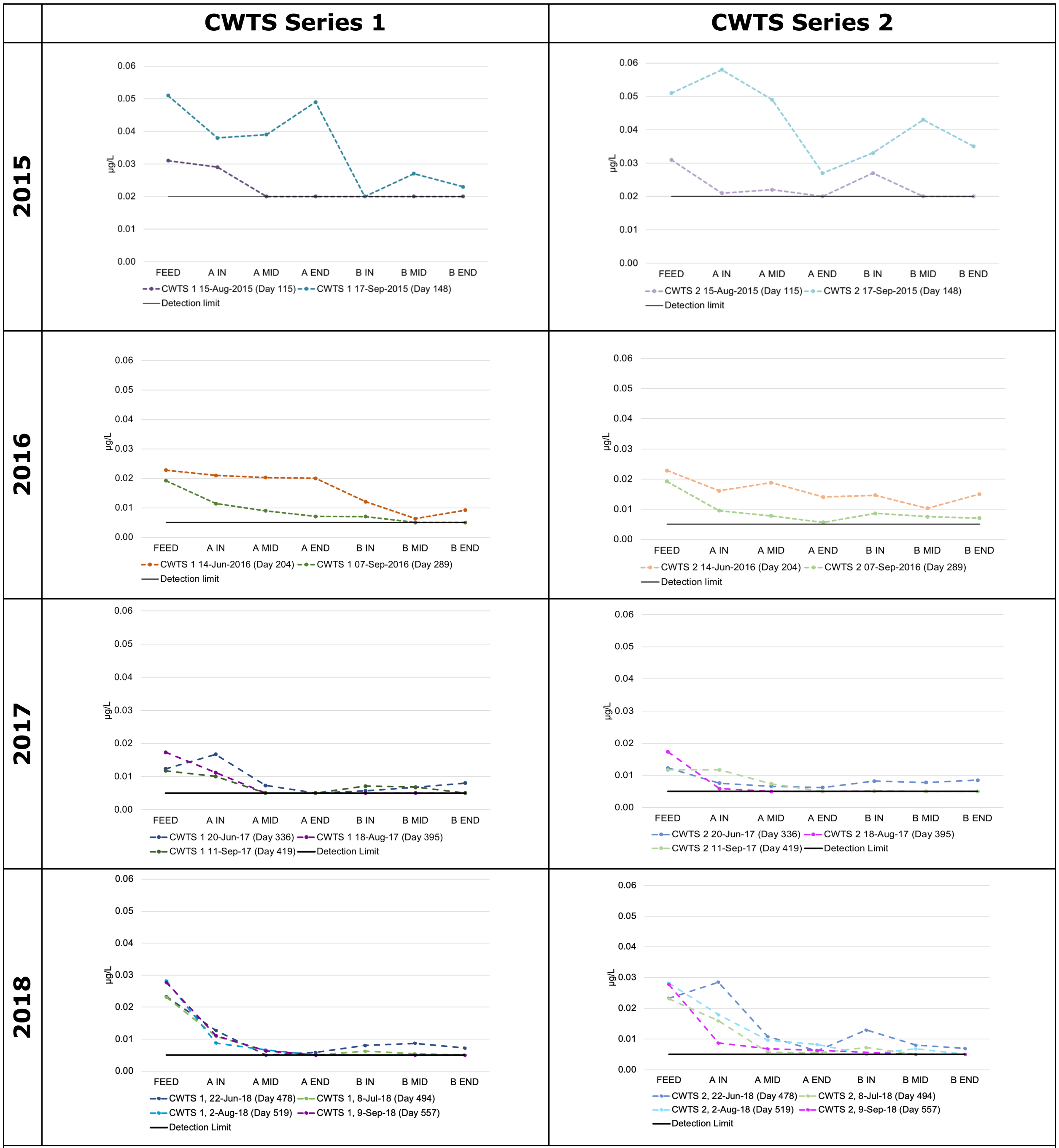
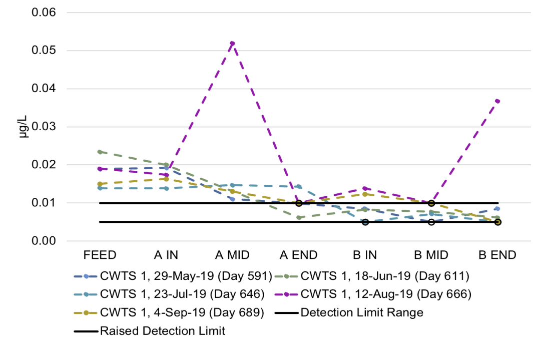


Figure B1 – Cadmium concentrations through the demonstration-scale CWTS. Dissolved cadmium concentrations (converted to µg/L) along the length of the CWTS in 2015 through 2019 at select time points which included additional sampling locations. The Maxxam (2015 results) detection limit (DL; black line) for cadmium is 0.020 µg/L. The ALS (2016-2018 results) DL for cadmium is 0.005 µg/L. Detection limits in 2019, however, ranged due to dilution by ALS when analyzing the sampling. DL range in 2019 is indicated by two solid black line, as well as solid black lines around data points that are at DL. The HRT at end of the B cell varies with date in 2019 based on different HRT scenarios that were tested. Elevated dissolved cadmium concentrations at the 1A midpoint and 1B endpoint location on August 12, 2019 also had elevated total concentrations and may have resulted from sampling.

2019



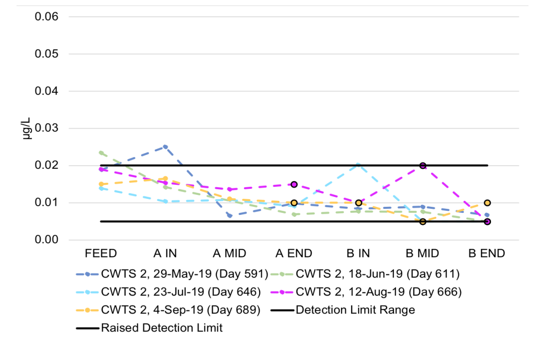
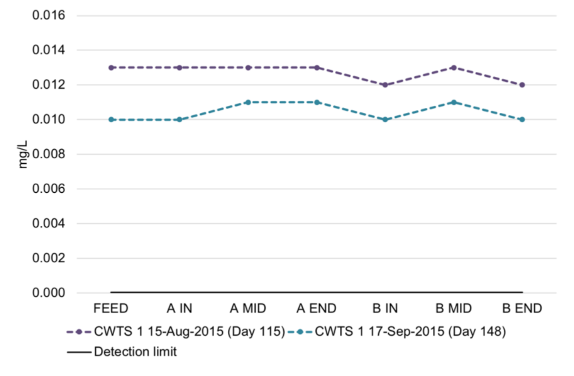
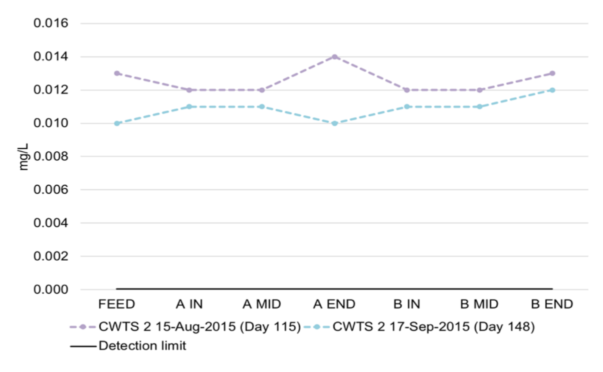


Figure B1 continued – Cadmium concentrations through the demonstration-scale CWTS.
Dissolved cadmium concentrations (converted to µg/L) along the length of the CWTS in 2015 through 2019 at select time points which included additional sampling locations. The Maxxam (2015 results) detection limit (DL; black line) for cadmium is 0.020 µg/L. The ALS (2016-2018 results) DL for cadmium is 0.005 µg/L. Detection limits in 2019, however, ranged due to dilution by ALS when analyzing the sampling. DL range in 2019 is indicated by two solid black line, as well as solid black lines around data points that are at DL. The HRT at end of the B cell varies with date in 2019 based on different HRT scenarios that were tested. Elevated dissolved cadmium concentrations at the 1A midpoint and 1B endpoint location on August 12, 2019 also had elevated total concentrations and may have resulted from sampling.

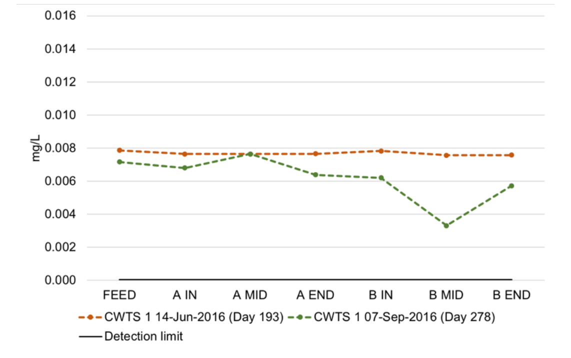
CWTS 1 **CWTS 2**

2015





2016



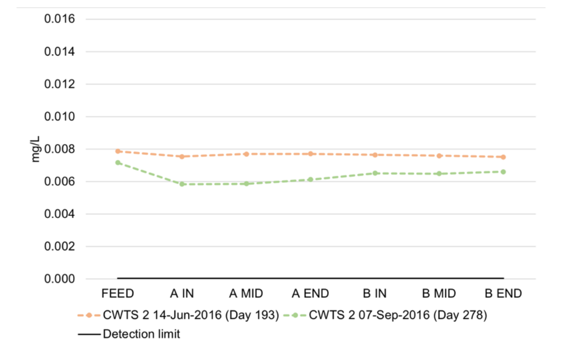


Figure B2 – Molybdenum concentrations through the demonstration-scale CWTS.
Dissolved molybdenum concentrations along the length of the CWTS in 2015 through 2019 at select time points which included additional sampling locations. The Maxxam (2015 results) detection limit (DL; black line) for molybdenum is 0.00020 mg/L. The ALS (2016-2019 results) DL for molybdenum is 0.000050 mg/L. The HRT at end of the B cell varies with date in 2019 based on different HRT scenarios that were tested.

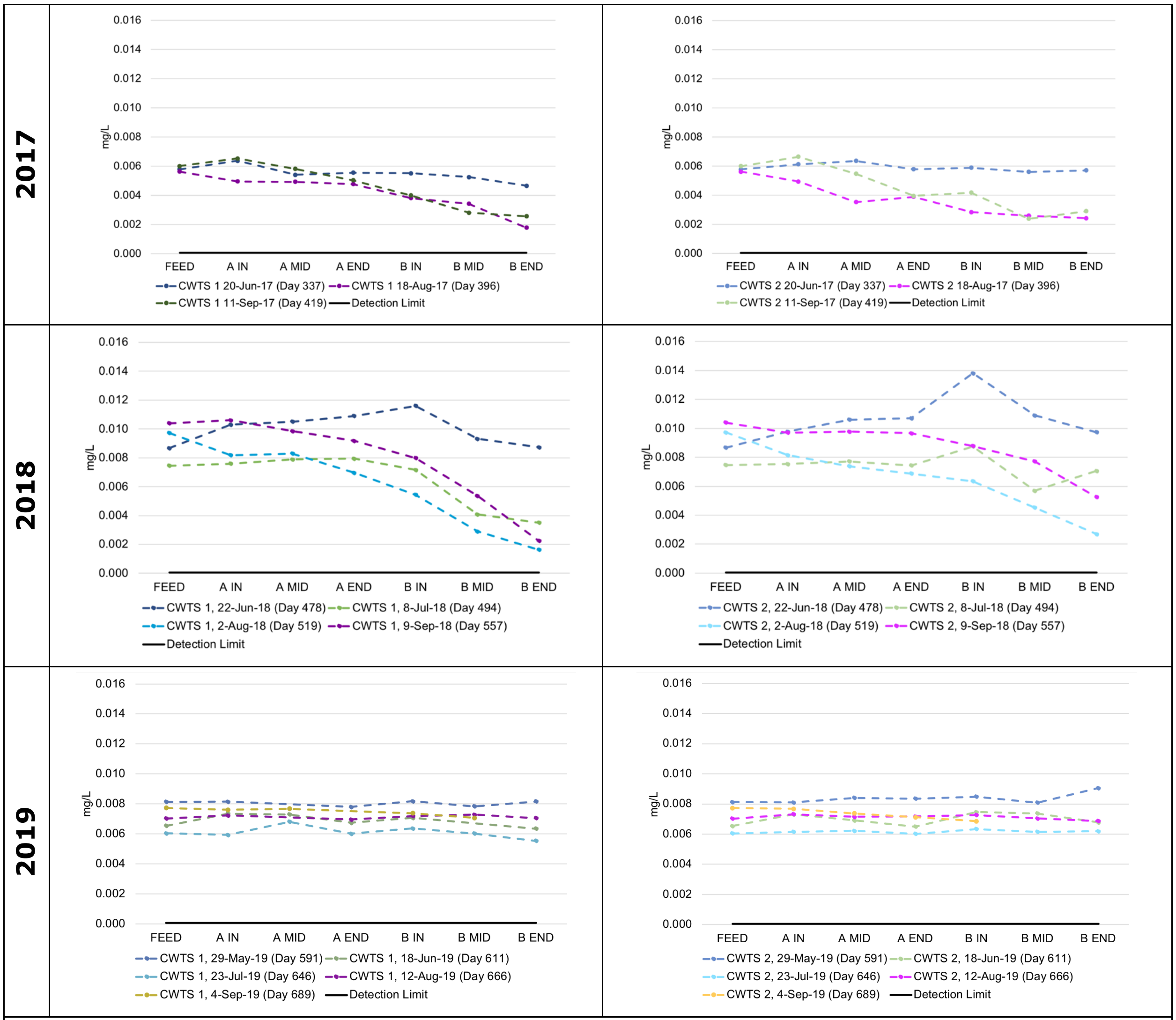


Figure B2 continued – Molybdenum concentrations through the demonstration-scale CWTS

Dissolved molybdenum concentrations along the length of the CWTS in 2015 through 2019 at select time points which included additional sampling locations. The Maxxam (2015 results) detection limit (DL; black line) for molybdenum is 0.00020 mg/L. The ALS (2016-2019 results) DL for molybdenum is 0.000050 mg/L. The HRT at end of the B cell varies with date in 2019 based on different HRT scenarios that were tested.

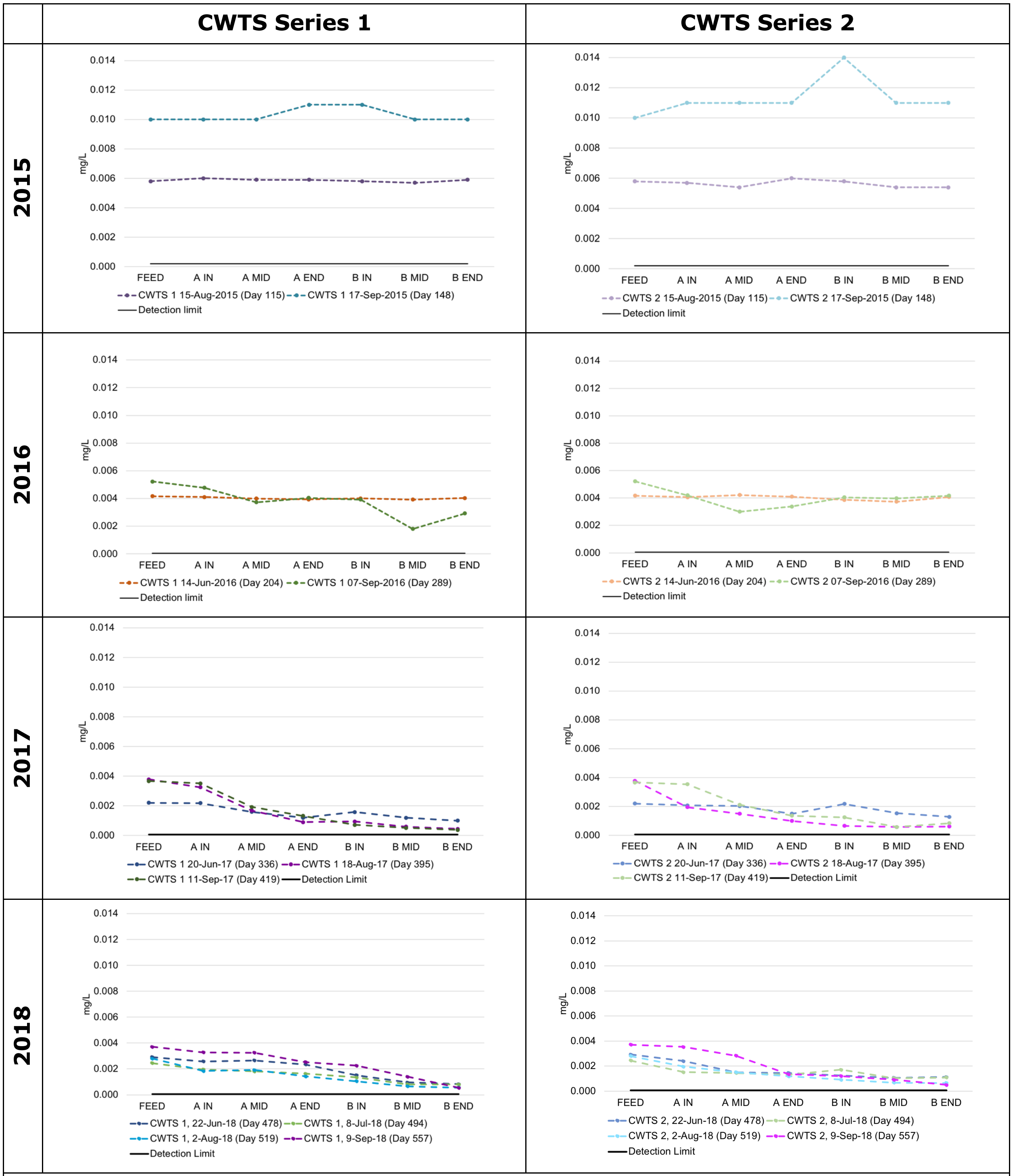


Figure B3 – Selenium concentrations through the demonstration-scale CWTS. Dissolved selenium concentrations along the length of the CWTS in 2015 through 2019 at select time points which included additional sampling locations. Total selenium concentrations are plotted for 2019. The Maxxam (2015 results) detection limit (DL; black line) for selenium is 0.00020 mg/L. The ALS (2016-2019 results) DL for selenium is 0.000050 mg/L. The HRT at end of the B cell varies with date in 2019 based on different HRT scenarios that were tested.

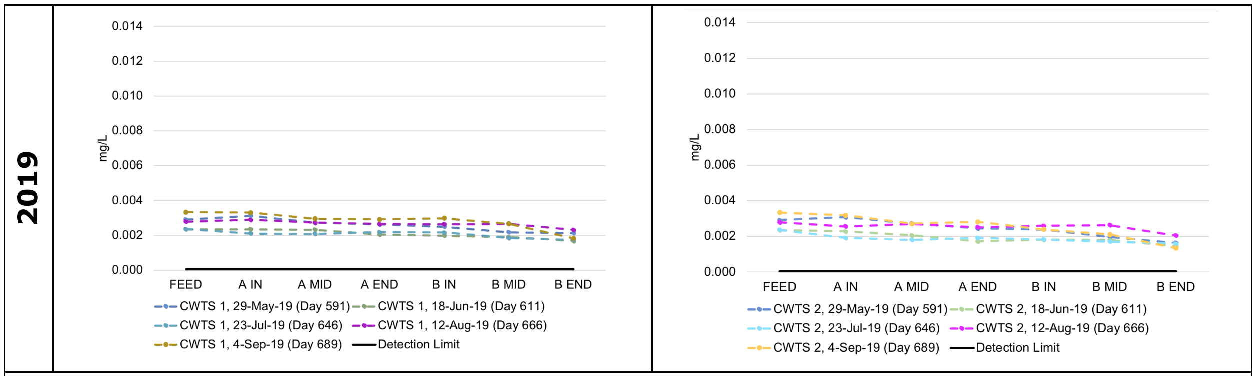


Figure B3 continued – Selenium concentrations through the demonstration-scale CWTS.

Dissolved selenium concentrations along the length of the CWTS in 2015 through 2019 at select time points which included additional sampling locations. Total selenium concentrations are plotted for 2019. The Maxxam (2015 results) detection limit (DL; black line) for selenium is 0.00020 mg/L. The ALS (2016-2019 results) DL for selenium is 0.000050 mg/L. The HRT at end of the B cell varies with date in 2019 based on different HRT scenarios that were tested.

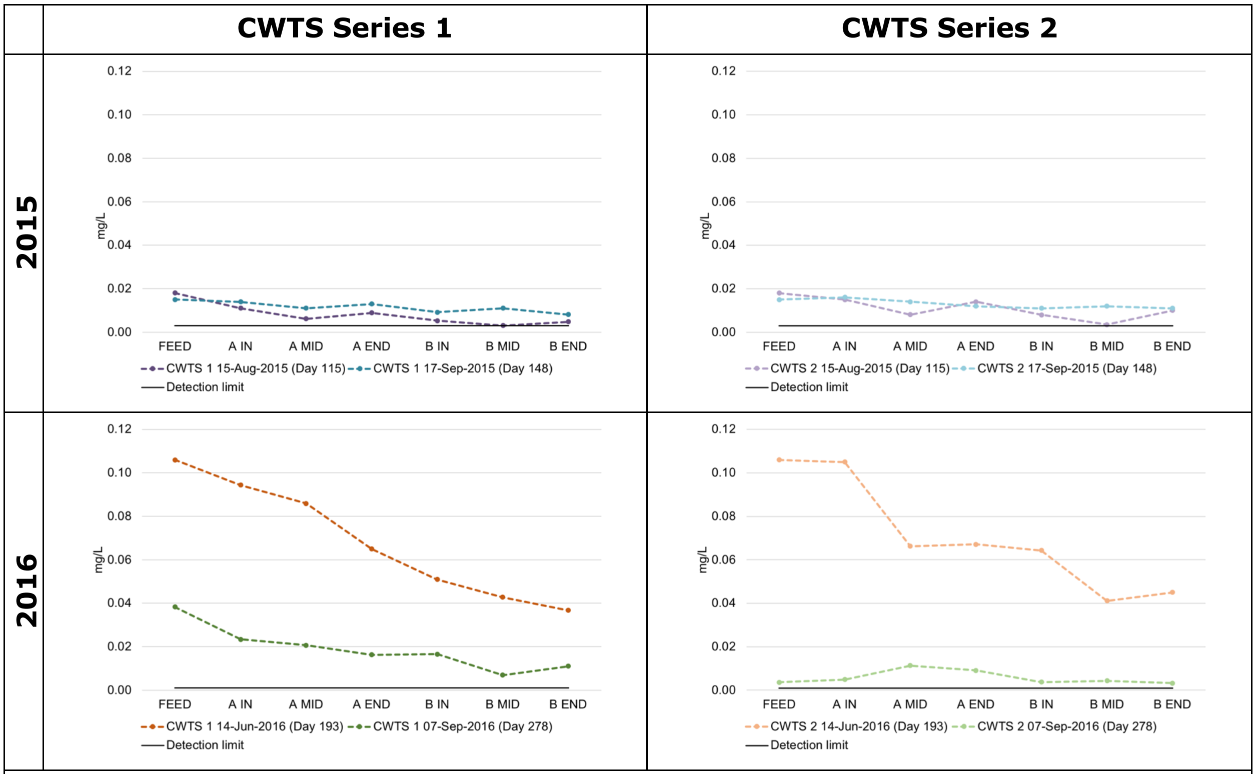


Figure B4 – Zinc concentrations through the demonstration-scale CWTS.

Dissolved zinc concentrations along the length of the CWTS in 2015 through 2019 at select time points which included additional sampling locations. The Maxxam (2015 results) detection limit (DL; black line) for zinc is 0.0030 mg/L. The ALS (2016-2018 results) DL for zinc is 0.0010 mg/L. The HRT at end of the B cell varies with date in 2019 based on different HRT scenarios that were tested.

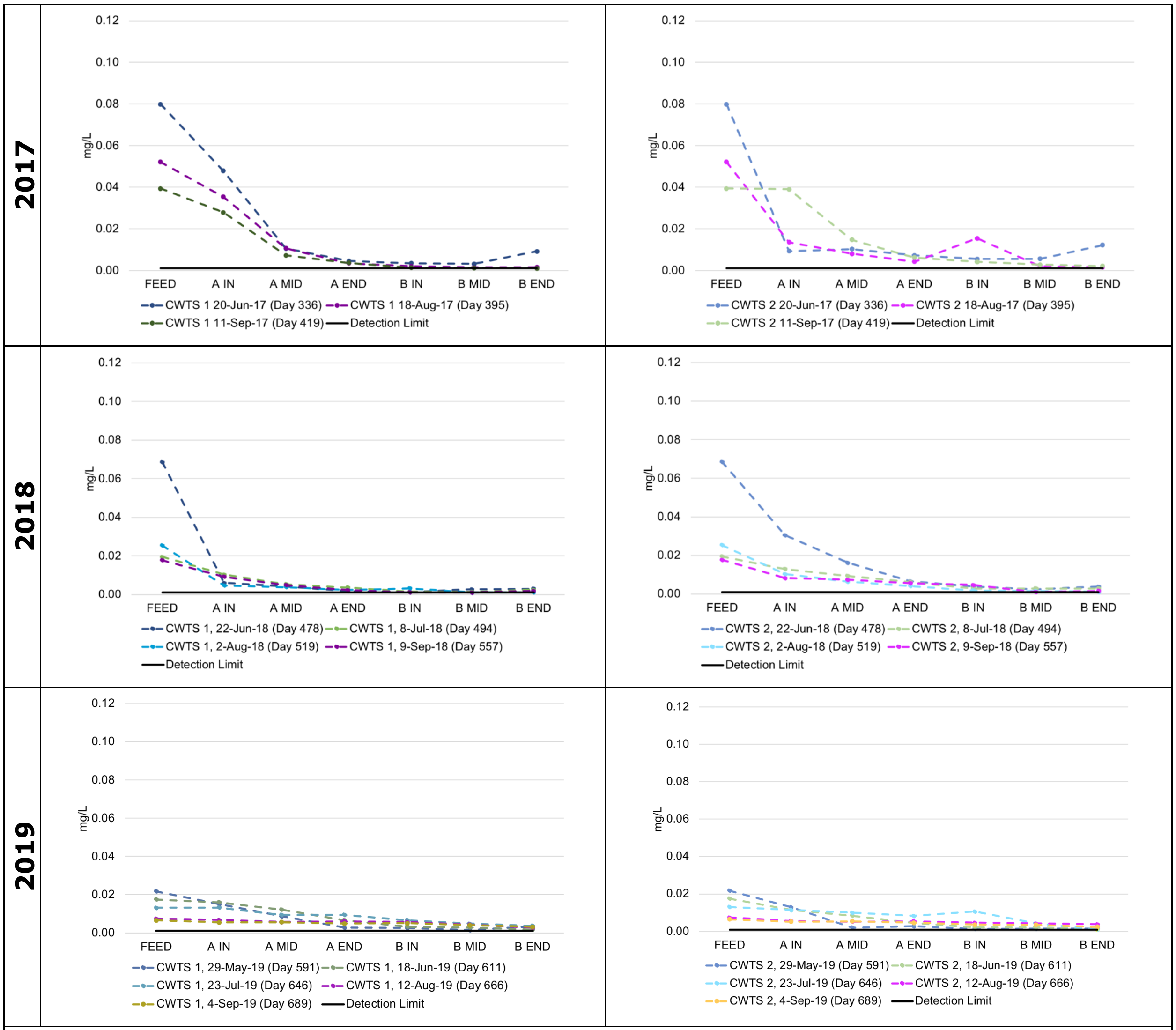


Figure B4 continued – Zinc concentrations through the demonstration-scale CWTS.

Dissolved zinc concentrations along the length of the CWTS in 2015 through 2019 at select time points which included additional sampling locations. The Maxxam (2015 results) detection limit (DL; black line) for zinc is 0.0030 mg/L. The ALS (2016-2018 results) DL for zinc is 0.0010 mg/L. The HRT at end of the B cell varies with date in 2019 based on different HRT scenarios that were tested.

B2. Soil Results

Table B1 – Total and leachable soil copper concentrations in Series 1 since first year of operations.

CWTS Cell	Sampling Date	Days in Operation	Sample Depth (cm)	Total Cu (mg/kg)	SPLP Cu (mg/L)	Leachable Cu (mg/kg)
1A	28-Aug-14	1	Initial Composite	-	0.298 (0.148-0.608)	-
	19-Jun-15	58	0-5	960	0.055[1]	-
	16-Aug-15	116	10-20	950	0.187	-
	18-Sep-15	149	10-20	1300	0.049	-
	29-Sep-15	160	10-20	910	0.069	-
	15-Jun-16	194	0-10	1440	-	0.953
	15-Jun-16	194	10-20	1210	-	0.66
	8-Jul-16	217	0-10	1430	-	0.603
	8-Jul-16	217	10-20	1730	-	0.832
	7-Sep-16	247	0-10	1290	-	0.449
	20-Jun-17	336	0-10	1470	0.315	0.308
	25-Jul-17	371	0-10	1630	0.529	0.463
	12-Sep-17	420	0-10	1490	0.590	0.481
	27-May-18	452	0-10	1510	-	0.616
	8-Jul-18	494	0-10	1420	-	0.628
	9-Sep-18	557	0-10	1160	-	0.038
	30-May-19	592	0-10	1140	-	-[2]
	30-Jul-19	653	0-10	1270	-	0.078
	5-Sep-19	690	0-10	1410	-	0.244
1B	28-Aug-14	1	Initial Composite	-	0.298 (0.148-0.608)	-
	19-Jun-15	58	0-5	1400	0.033[1]	-
	16-Aug-15	116	10-20	1400	0.209	-
	18-Sep-15	149	10-20	830	0.065	-
	29-Sep-15	160	10-20	880	0.059	-
	15-Jun-16	194	0-10	1130	-	1.01
	15-Jun-16	194	10-20	1240	-	0.822
	8-Jul-16	217	0-10	1250	-	1.11
	8-Jul-16	217	10-20	1620	-	1.21
	7-Sep-16	247	0-10	1190	-	0.197
	20-Jun-17	336	0-10	1290	0.450	0.338
	25-Jul-17	371	0-10	1100	0.290	0.165
	12-Sep-17	420	0-10	1100	0.716	0.492
	27-May-18	452	0-10	1930	-	0.784
	8-Jul-18	494	0-10	1430	-	0.232
	9-Sep-18	557	0-10	1580	-	0.238
	30-May-19	592	0-10	1230	-	-[2]
	30-Jul-19	653	0-10	1060	-	0.137
	5-Sep-19	690	0-10	1830	-	0.436

The blue shading indicates samples that were taken from a shallower depth (0-5 cm and 0-10 cm) while white shading indicates a deeper 10-20 cm depth.

[1] Samples collected in June 2015 were at a shallow depth (0-5 cm) and copper content had therefore likely already been removed by washing from the faster flows of the CWTS system.

[2] Not included because reverse osmosis water was used instead of special leach water that was provided.

Table B2– Total and leachable soil copper concentrations in Series 2 since first year of operations.

CWTS Cell	Sampling Date	Days in Operation	Sample Depth (cm)	Total Cu (mg/kg)	SPLP Cu (mg/L)	Leachable Cu (mg/kg)
2A	28-Aug-14	1	Initial Composite	-	0.298 (0.148-0.608)	-
	19-Jun-15	58	0-5	1175	0.037[1]	-
	16-Aug-15	116	10-20	660	0.139	-
	18-Sep-15	149	10-20	880	0.081	-
	29-Sep-15	160	10-20	1000	0.073	-
	15-Jun-16	194	0-10	1100	-	0.823
	15-Jun-16	194	10-20	1280	-	0.900
	8-Jul-16	217	0-10	1450	-	0.963
	8-Jul-16	217	10-20	1150	-	1.68
	7-Sep-16	247	0-10	1290	-	0.838
	20-Jun-17	336	0-10	1820	0.381	1.24
	25-Jul-17	371	0-10	1290	0.419	0.927
	12-Sep-17	420	0-10	1440	0.389	0.381
	27-May-18	452	0-10	1100	-	0.600
	8-Jul-18	494	0-10	1480	-	0.252
	9-Sep-18	557	0-10	1630	-	0.048
	30-May-19	592	0-10	1360	-	-[2]
	30-Jul-19	653	0-10	1150	-	0.063
	5-Sep-19	690	0-10	1340	-	0.258
2B	28-Aug-14	1	Initial Composite	-	0.298 (0.148-0.608)	-
	19-Jun-15	58	0-5	1100	0.039[1]	-
	16-Aug-15	116	10-20	1000	0.201	-
	18-Sep-15	149	10-20	830	0.078	-
	29-Sep-15	160	10-20	540	0.059	-
	15-Jun-16	194	0-10	1040	-	0.771
	15-Jun-16	194	10-20	1310	-	1.16
	8-Jul-16	217	0-10	1070	-	1.38
	8-Jul-16	217	10-20	1180	-	1.25
	7-Sep-16	247	0-10	1520	-	0.123
	20-Jun-17	336	0-10	1110	0.283	0.523
	25-Jul-17	371	0-10	1240	0.477	0.540
	12-Sep-17	420	0-10	1140	0.596	0.809
	27-May-18	452	0-10	1430	-	1.01
	8-Jul-18	494	0-10	1260	-	0.637
	9-Sep-18	557	0-10	1670	-	0.046
	30-May-19	592	0-10	1680	-	-[2]
	30-Jul-19	653	0-10	1030	-	0.119
	5-Sep-19	690	0-10	1420	-	0.141

The blue shading indicates samples that were taken from a shallower depth (0-5 cm and 0-10 cm) while white shading indicates a deeper 10-20 cm depth.

[1] Samples collected in June 2015 were at a shallow depth (0-5 cm) and copper content had therefore likely already been removed by washing from the faster flows of the CWTS system.

[2] Not included because reverse osmosis water was used instead of special leach water that was provided.

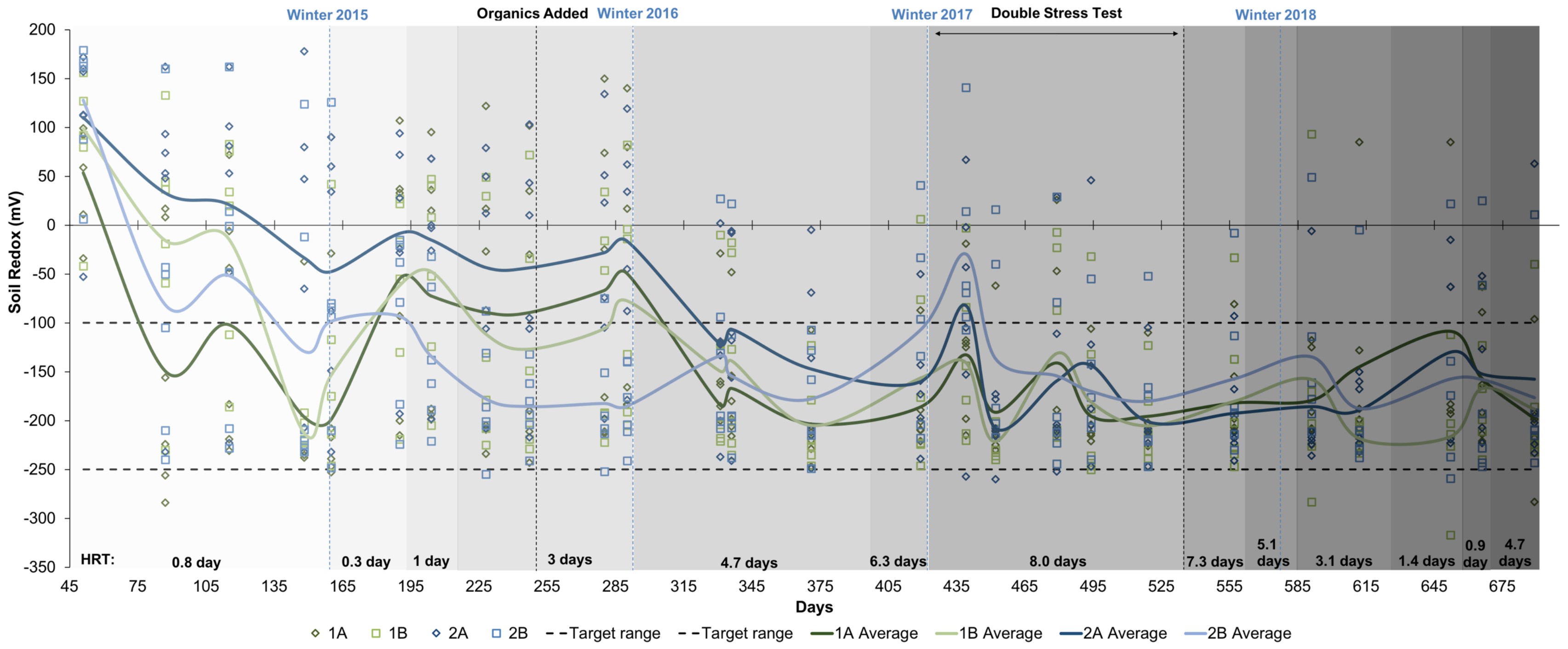


Figure B5 – Soil redox potential of each CWTS cell over time.
All demonstration-scale CWTS soil redox measurements are plotted. Targeted soil redox values based on pilot-scale testing are indicated with dotted lines. The blue dotted lines indicate breaks in measurements for winter. Grey shading corresponds to different HRT scenarios. HRT scenarios in 2015 and 2016 indicate the nominal HRT (days). HRT scenarios in 2017, 2018, and 2019 indicate the actual HRT (average of Series 1 and 2 in days) calculated using measured water depths and flow rates during those time periods.

Table B3 – Summary of fractions from sequential extraction procedure for the speciation of metals[1].

Fraction	Description	COCs unstable when
1	Exchangeable fraction for adsorbed minerals	Readily released (i.e., soluble and exchangeable)
2	Mineral fraction bound to carbonates or solubilized at pH 5	Decreased pH
3	Oxidized mineral fraction bound to Fe-Mn oxides	Reducing conditions
4	Reduced mineral fraction and sulphides	Oxidizing conditions
5	Residual mineral fraction (primary and secondary minerals)	Not expected to be released in solution over time under conditions normally encountered in nature

[1] Method based on Tessier et al., 1979.

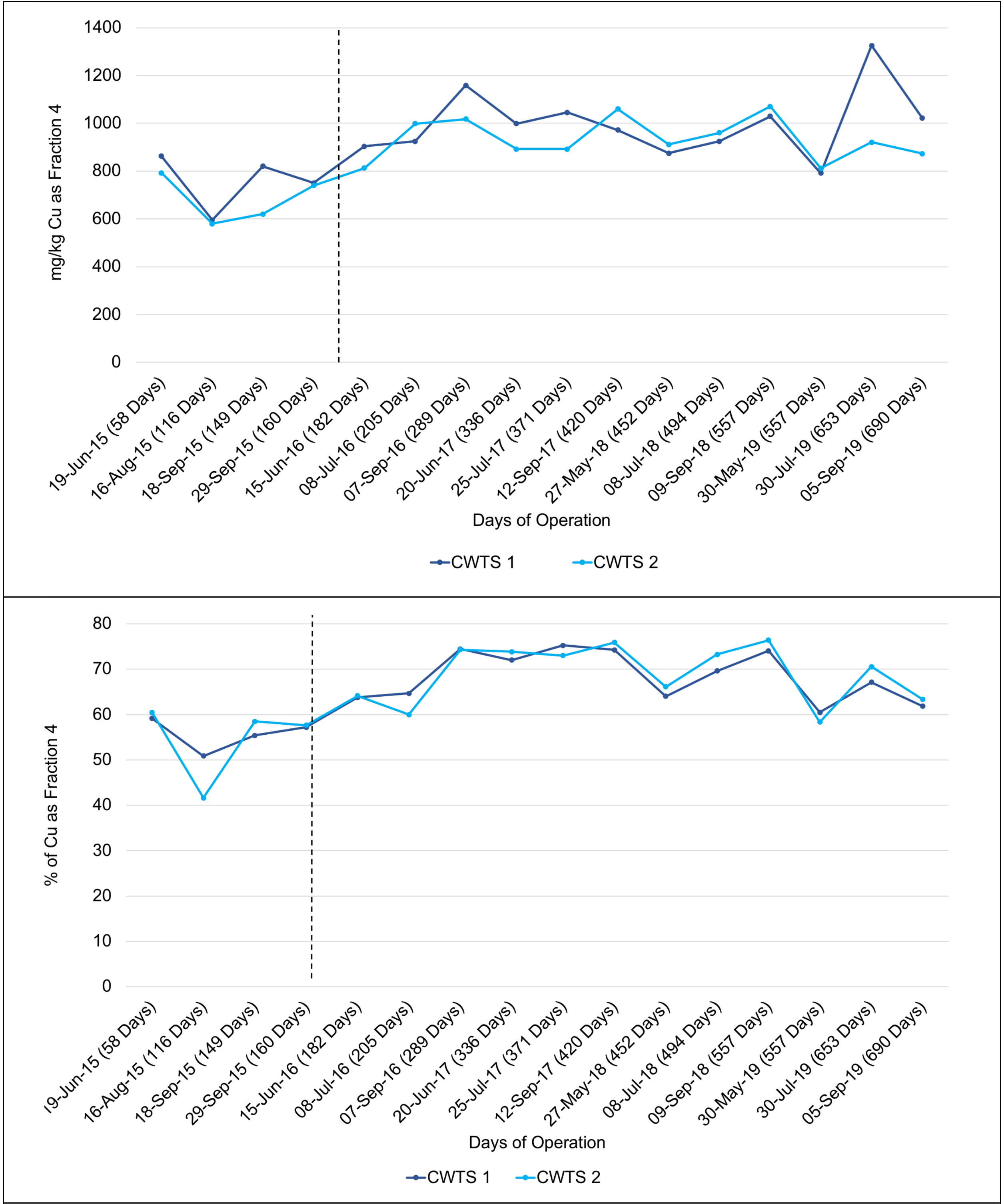


Figure B6 – Copper in CWTS soils as sequential leach fraction 4 over time.
Copper in the form of the targeted fraction 4 (sulphide mineral form and bound to organics) in CWTS substrate (top) or expressed as a percent (bottom) over time. Fraction 4 increased in the CWTS over time as the soils matured. The vertical dashed line separates Maxxam (2015) and ALS (2016-2019) analytical providers.

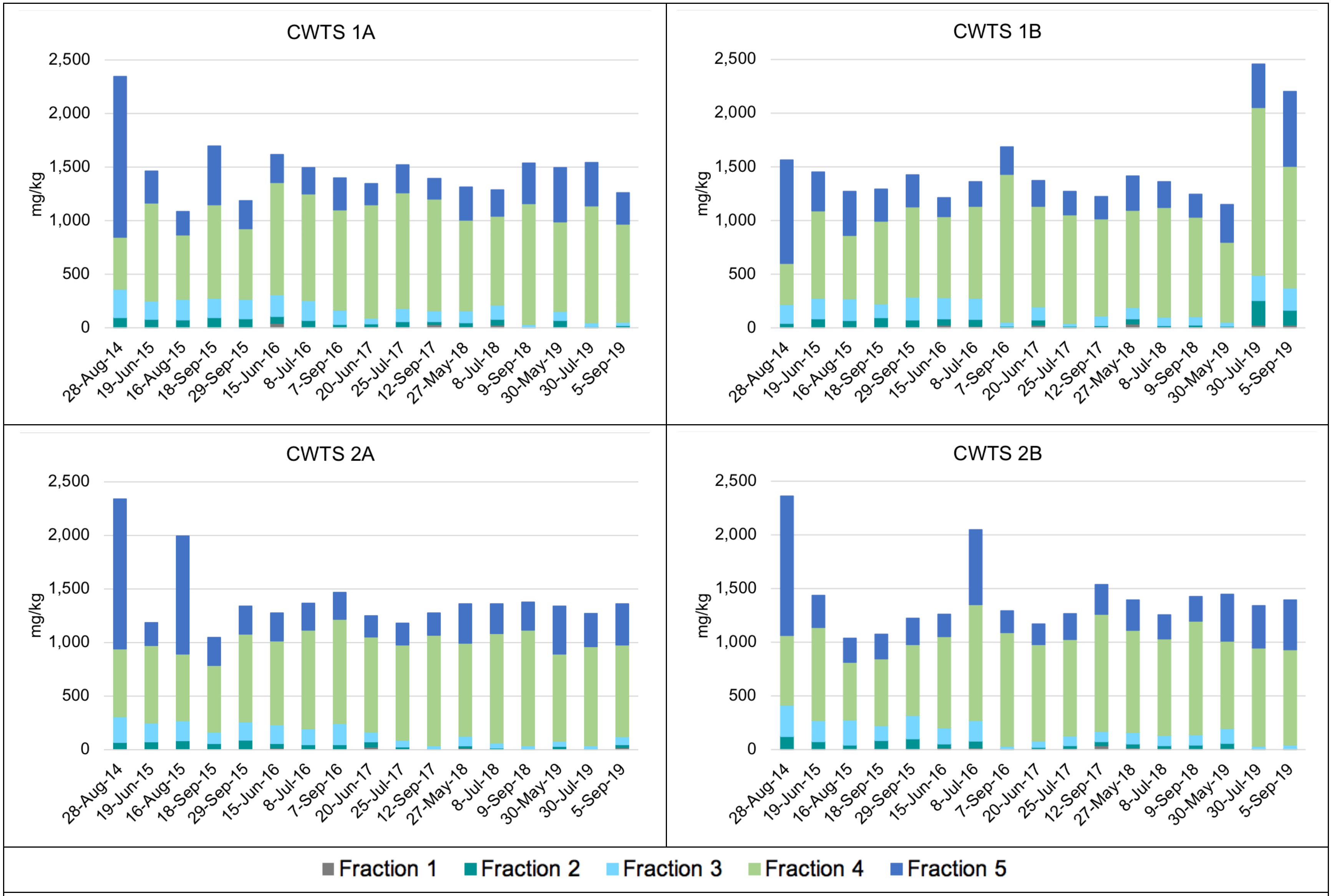


Figure B7 – Sequential leach fraction distribution of copper in CWTS substrate over time (2014-2019).
Fractions are defined in Table B3. The detection limit for copper is 0.50 mg/kg for all fractions.

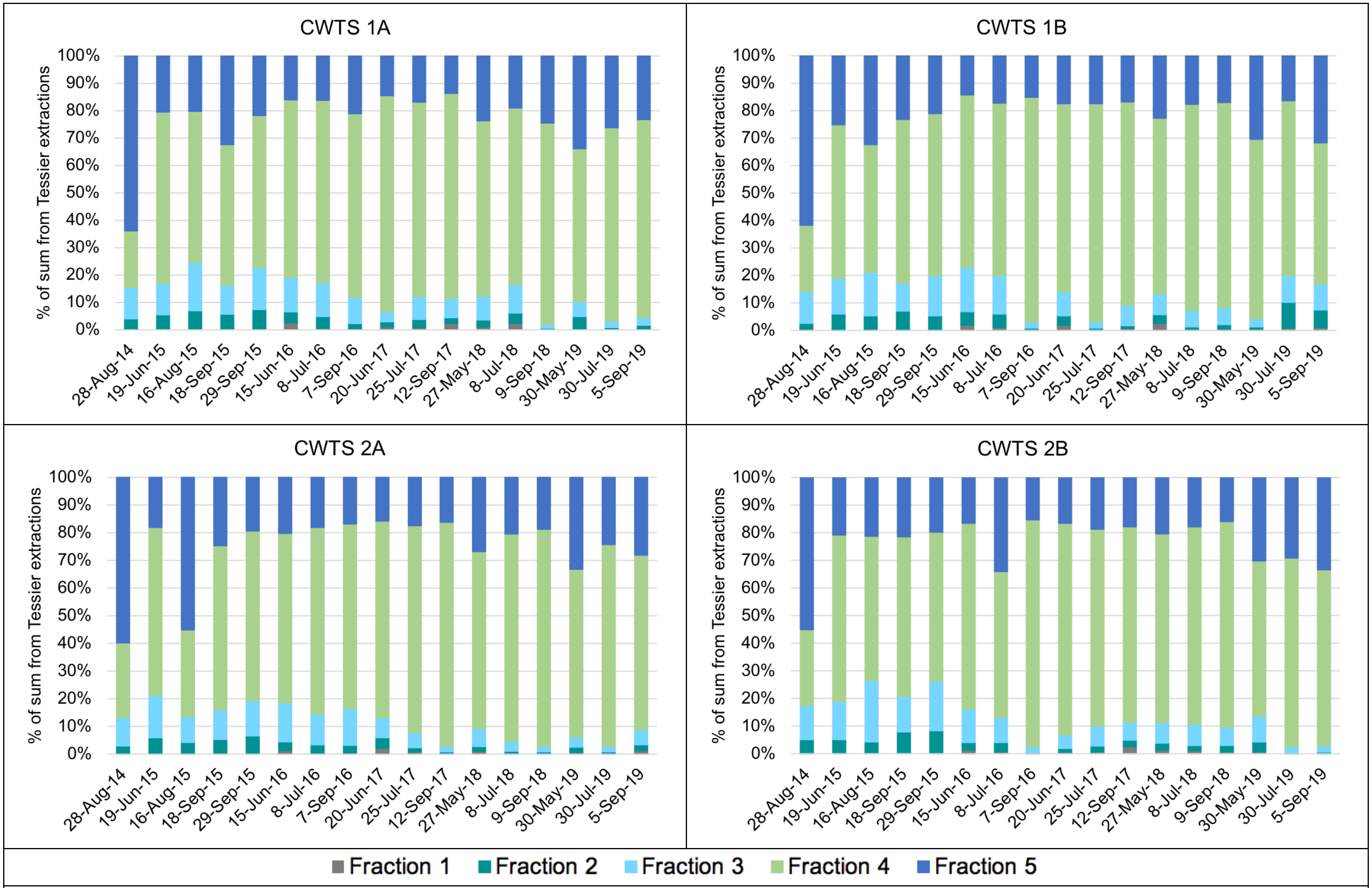


Figure B8 – Sequential leach fraction distribution of copper expressed as percent over time (2014-2019).
Fractions are defined in Table B3.

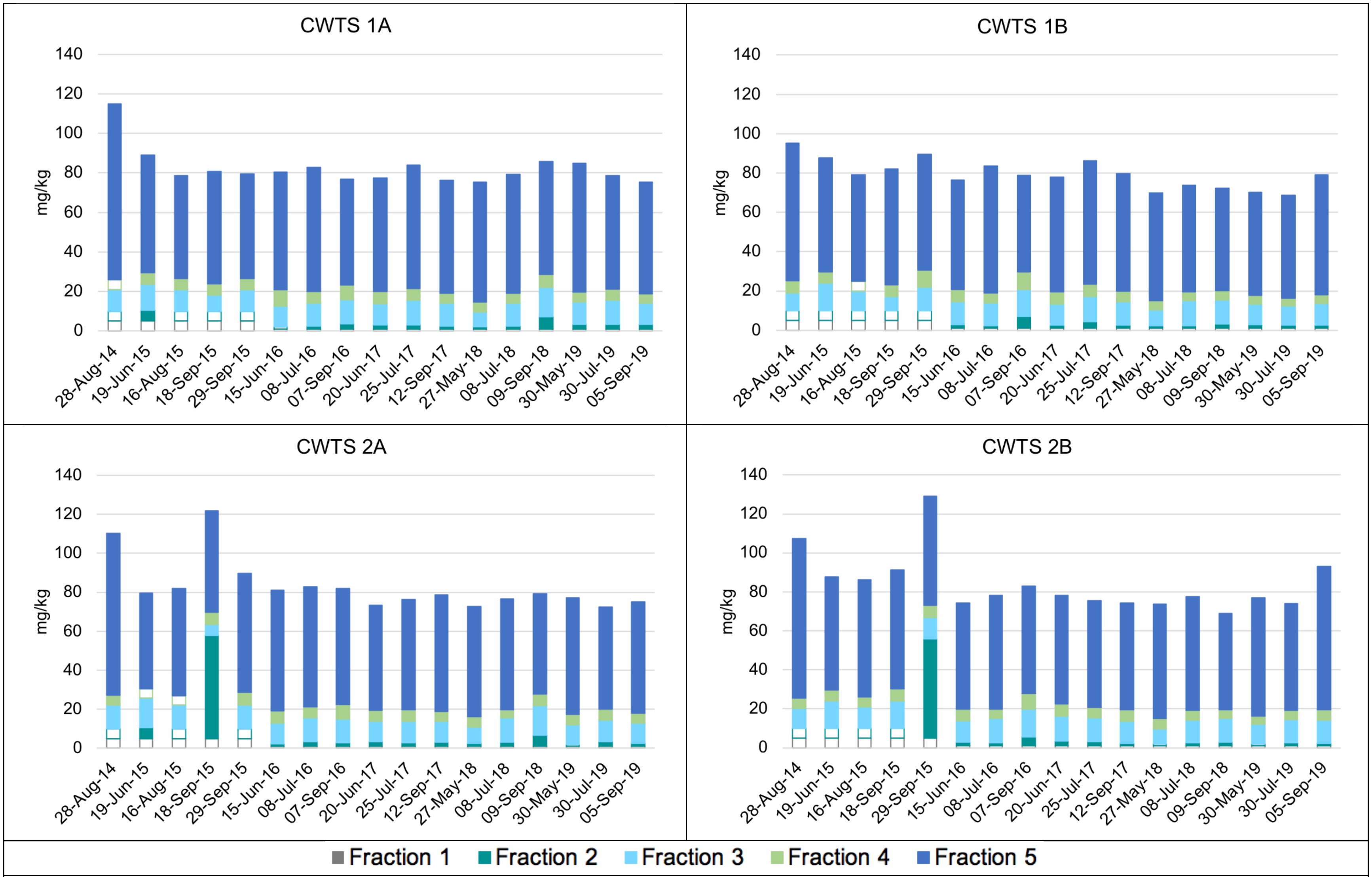


Figure B9 – Sequential leach fraction distribution of zinc in CWTS substrate over time (2014-2019).
Unfilled areas are values at or below detection limit. The detection limit for zinc is 1.0 mg/kg. Fractions are defined in Table B3.

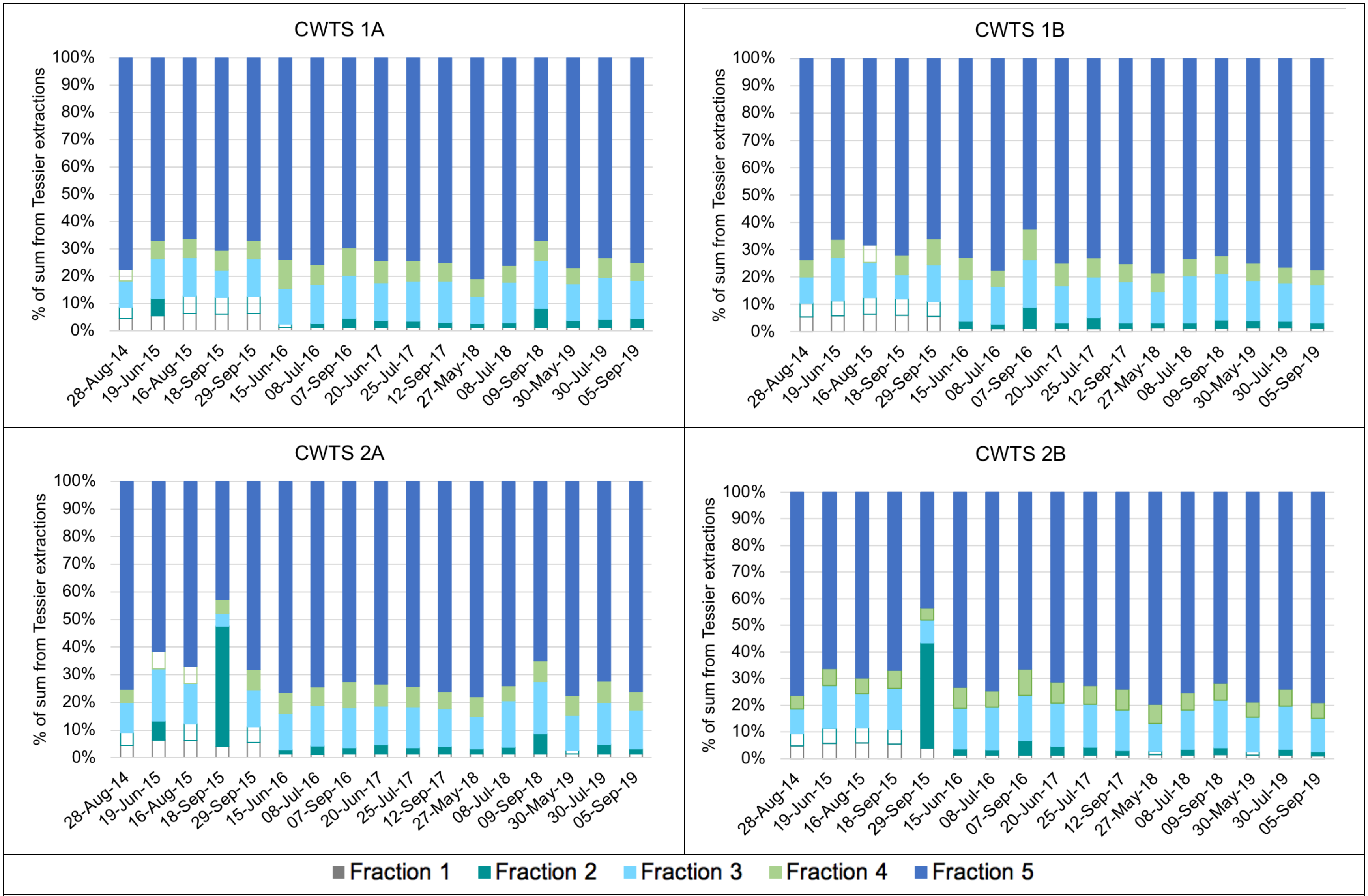


Figure B10 – Sequential leach fraction distribution of zinc expressed as percent over time (2014-2019).
Unfilled areas are values at or below detection limit. Fractions are defined in Table B3.

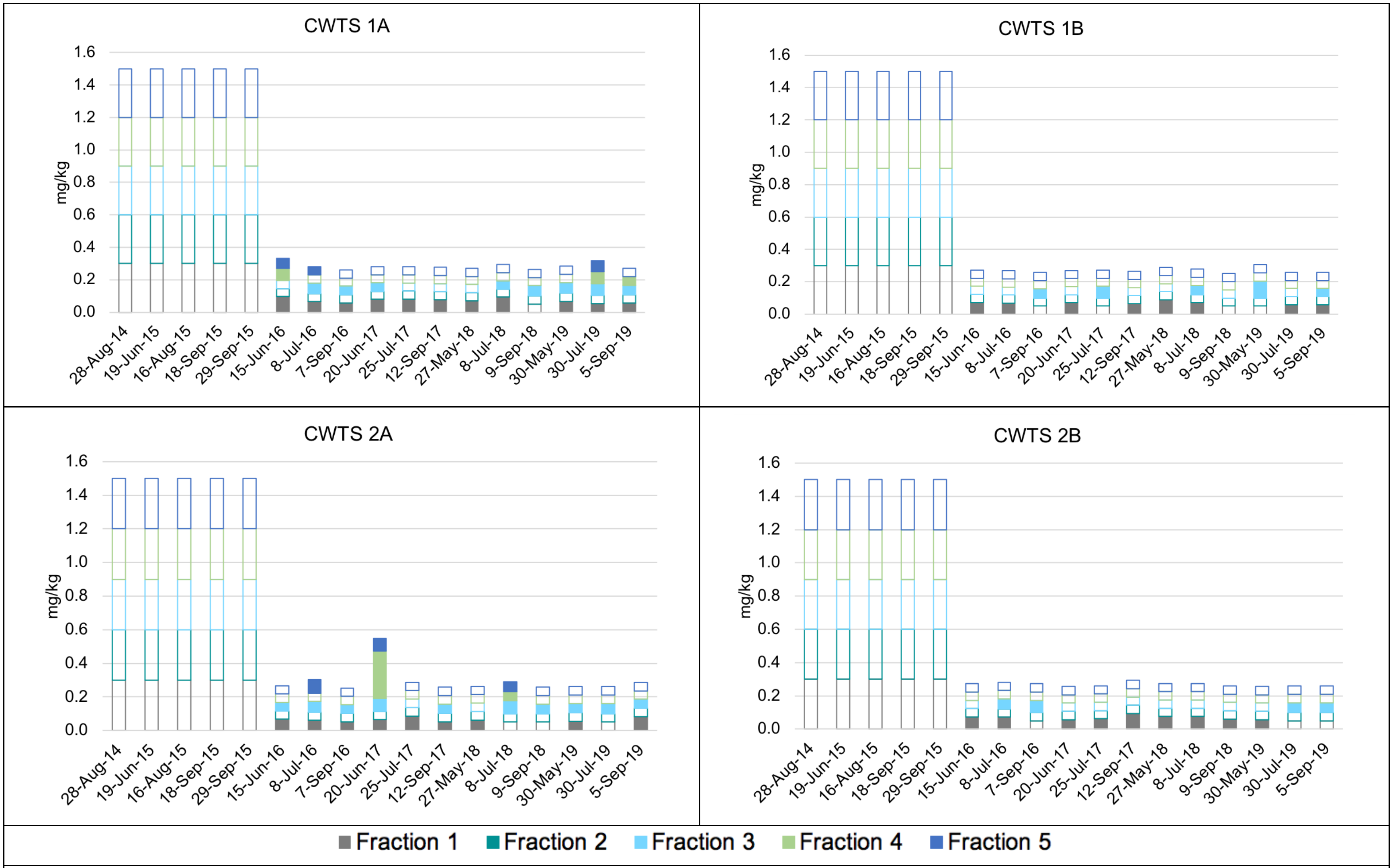


Figure B11 – Sequential leach fraction distribution of cadmium in CWTS substrate over time (2014-2019). Unfilled areas are values at or below detection limit. Detection limits changed after 2015, which is indicated by the smaller bars after 2015. The detection limit (DL) for cadmium in 2014 and 2015 was 0.30 mg/kg for all fractions. The DL for cadmium in 2016-2019 was 0.050 mg/kg for all fractions. Fractions are defined in Table B3. Graphs for the sequential leach fraction distribution expressed as percent over time was not included based on majority being less than the detection limit.

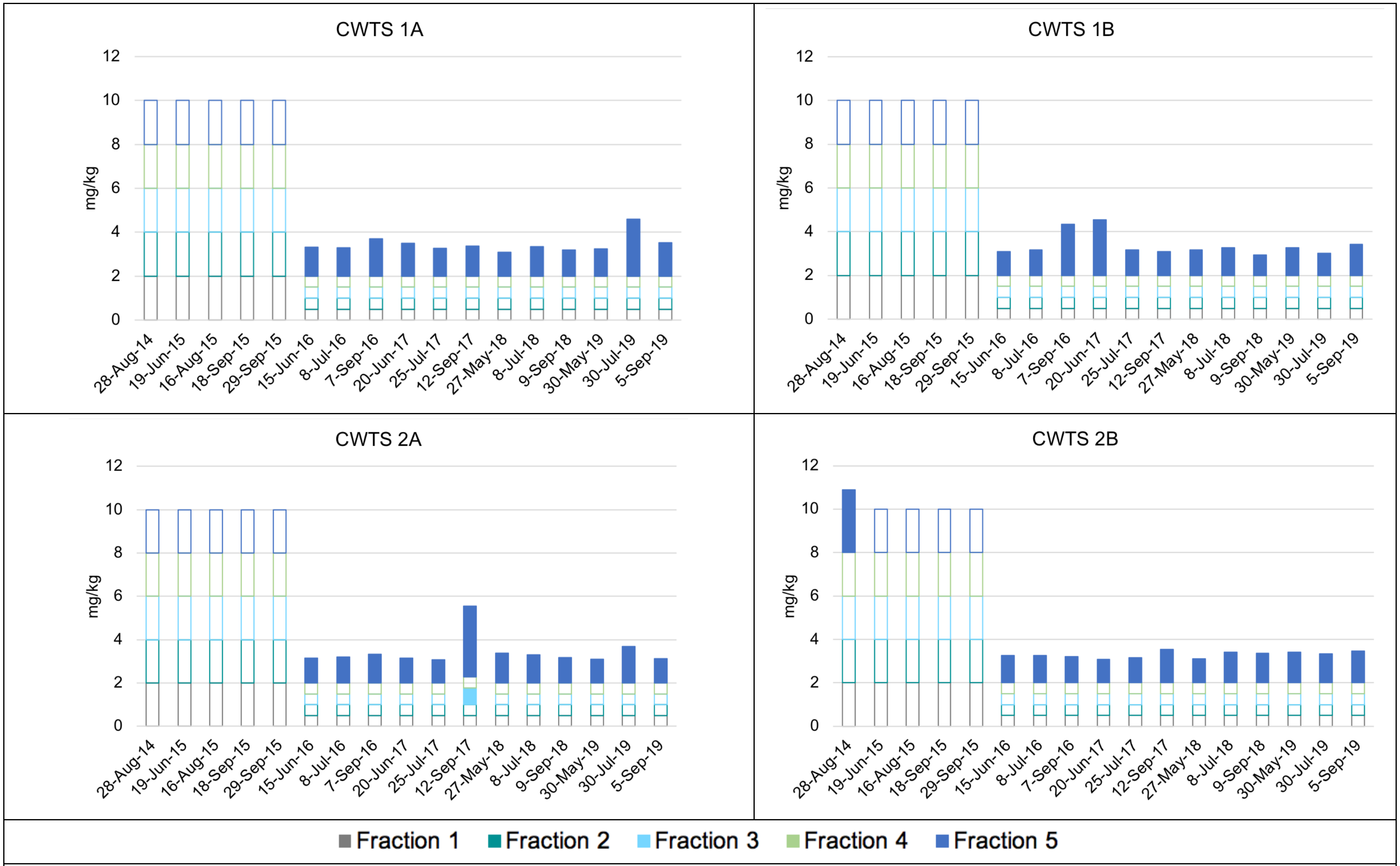


Figure B12 – Sequential leach fraction distribution of molybdenum in CWTS substrate over time (2014-2019).
Unfilled areas are values at or below detection limit. Detection limits changed after 2015, which is indicated by the smaller bars after 2015. The detection limit (DL) for molybdenum in 2014 and 2015 was 2.0 mg/kg for all fractions. The DL for molybdenum in 2016-2019 was 0.50 mg/kg for all fractions. Fractions are defined in Table B3. Graphs for the sequential leach fraction distribution expressed as percent over time was not included based on majority being less than the detection limit.

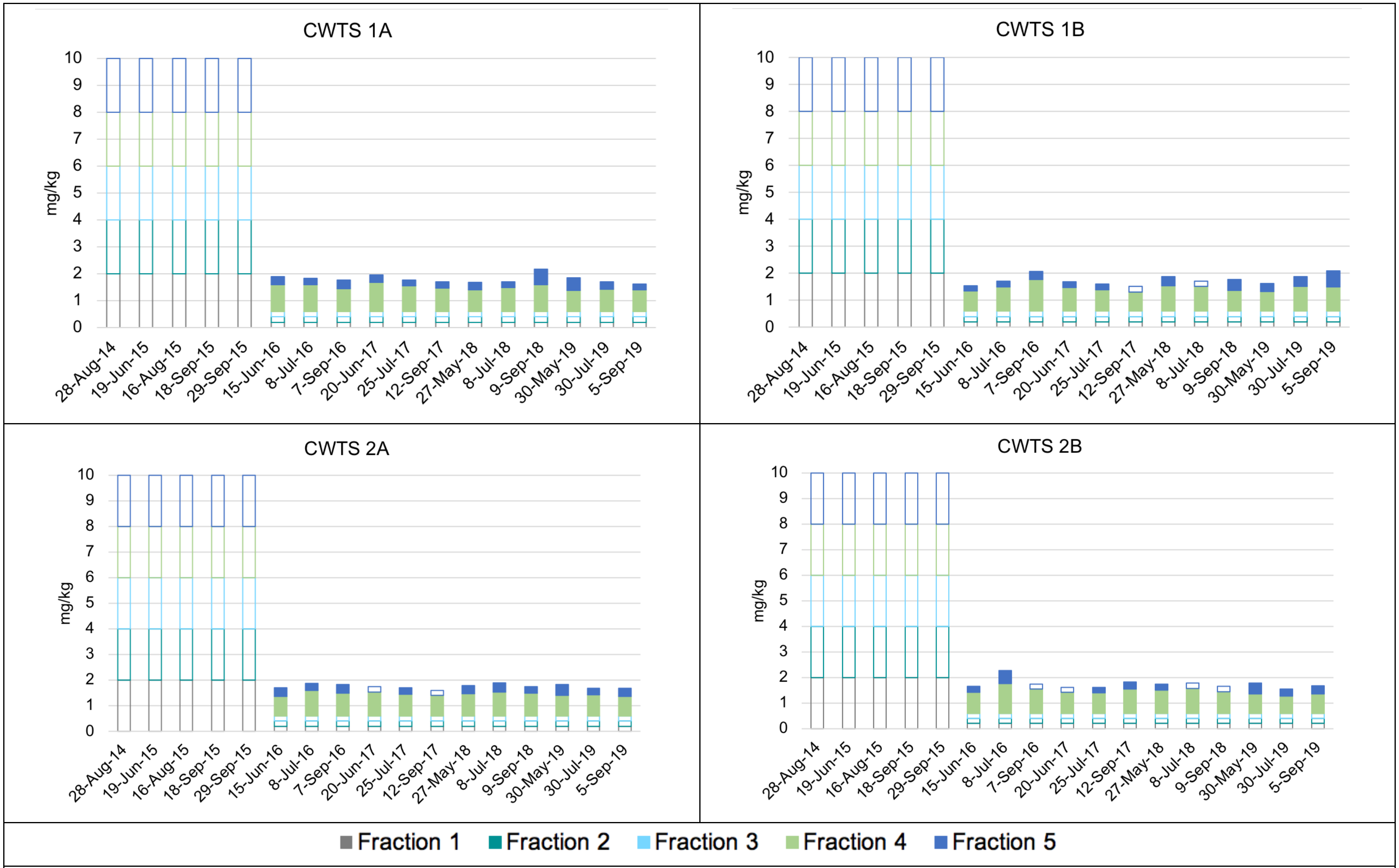


Figure B13 – Sequential leach fraction distribution of selenium in CWTS substrate over time (2014-2019).
Unfilled areas are values at or below detection limit. Detection limits changed after 2015, which is indicated by the smaller bars after 2015. The detection limit (DL) for selenium in 2014 and 2015 was 2.0 mg/kg for all fractions. The DL for selenium in 2016-2019 was 0.20 mg/kg for all fractions. Fractions are defined in Table B3.

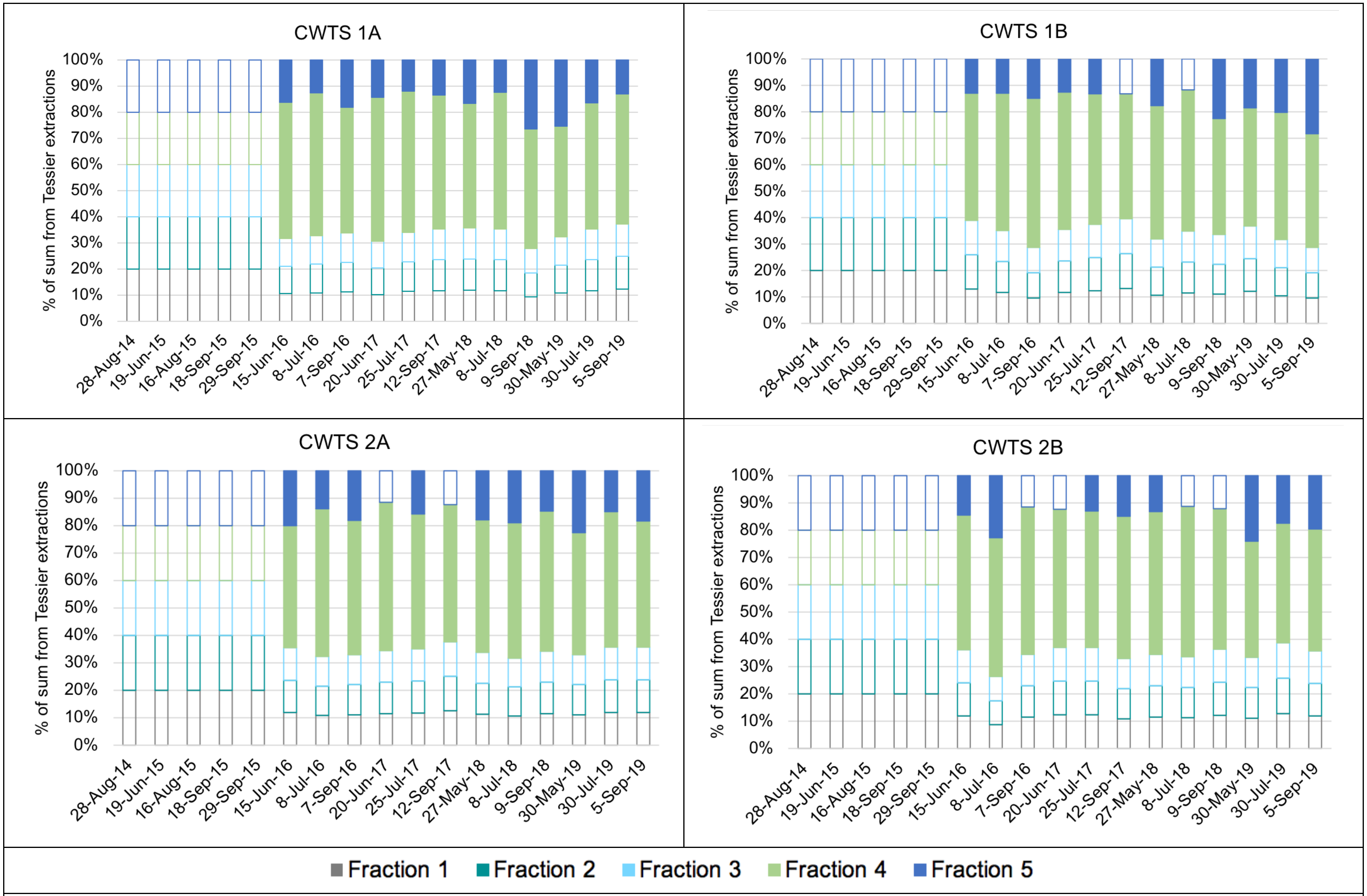


Figure B14 – Sequential leach fraction distribution of selenium expressed as percent over time (2014-2019).
Unfilled areas are values at or below detection limit. Fractions are defined in Table B3.

B3. Plant Results

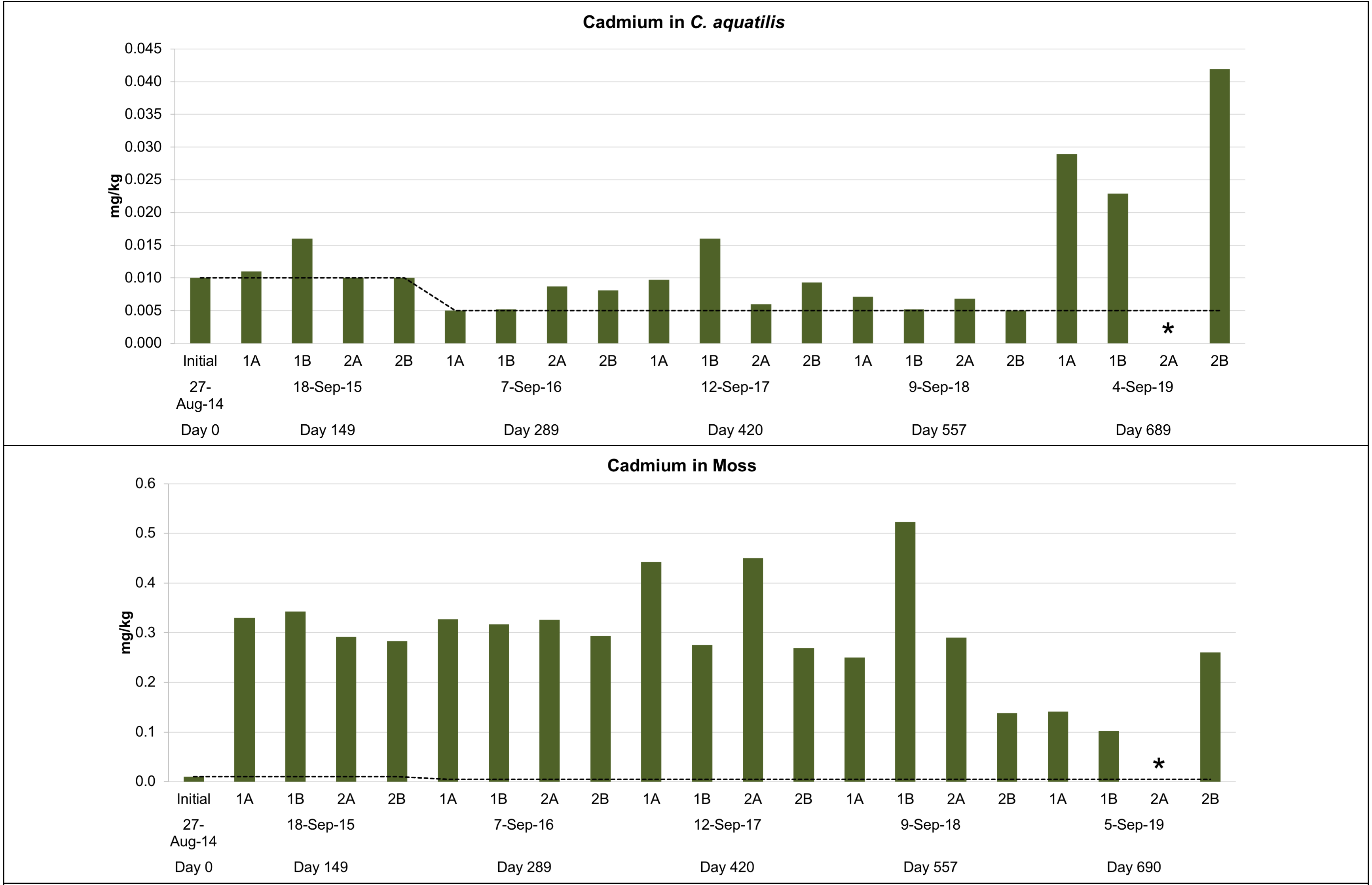


Figure B15 – Cadmium concentrations in plants.
The 2014 detection limit (DL; horizontal dotted line) for cadmium is 0.10 mg/kg, the 2015 DL is 0.010, and the 2016-2019 DL is 0.0050 mg/kg. The initial timepoint is the average of three C. aquatilis or three moss replicates at construction.

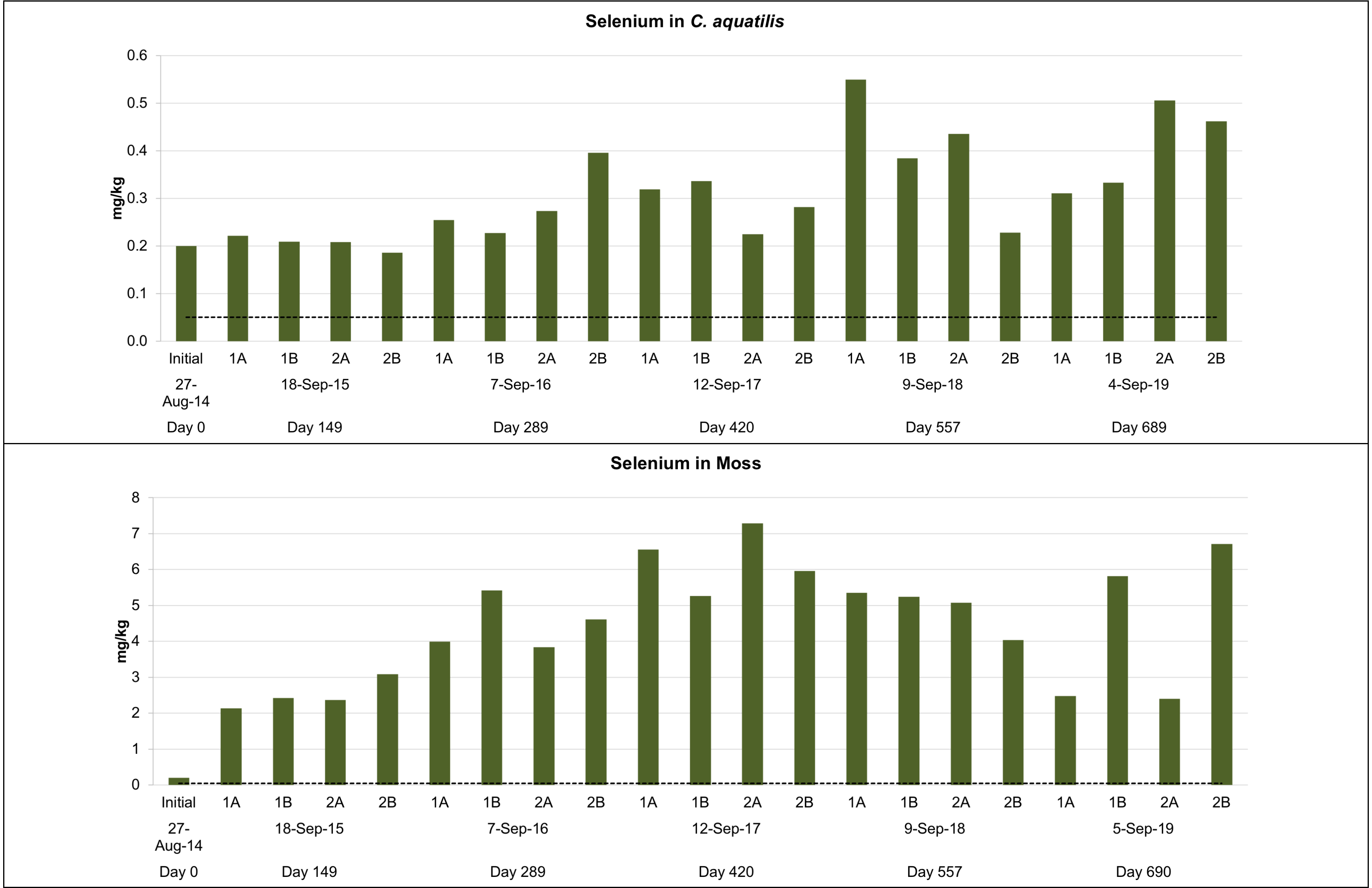
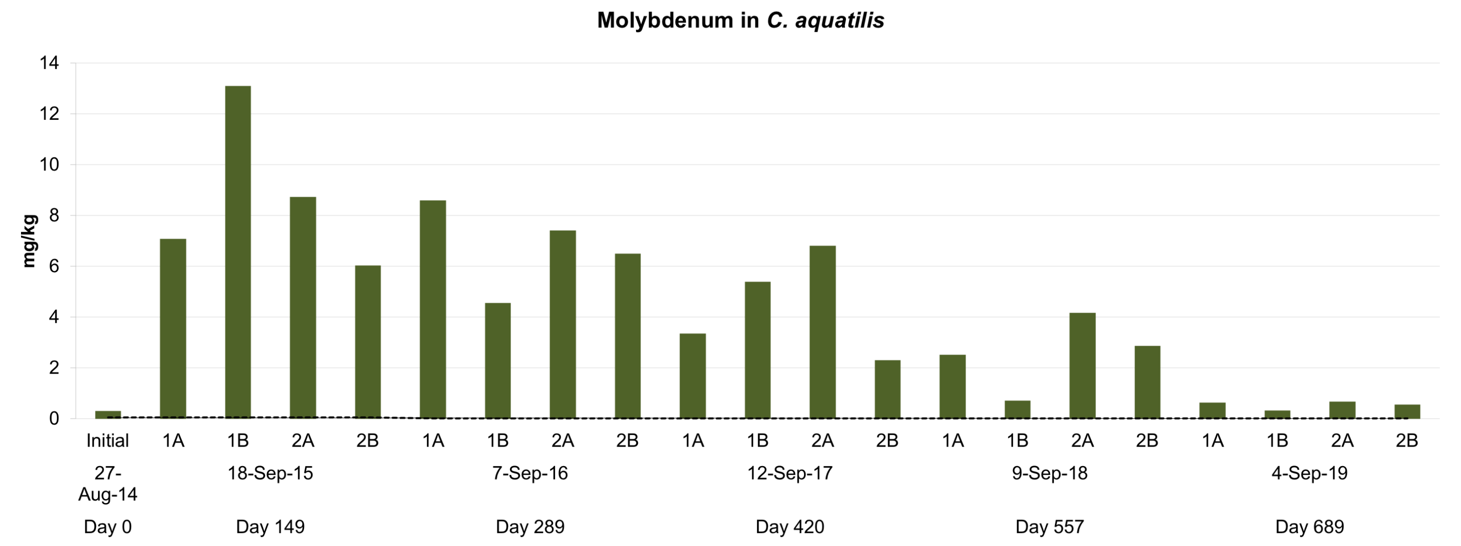


Figure B16 – Selenium concentrations in plants.
The detection limit (DL; horizontal dotted line) for all years for selenium is 0.05 mg/kg. The initial timepoint is the average of the three *C. aquatilis* or three moss replicates at constructions.



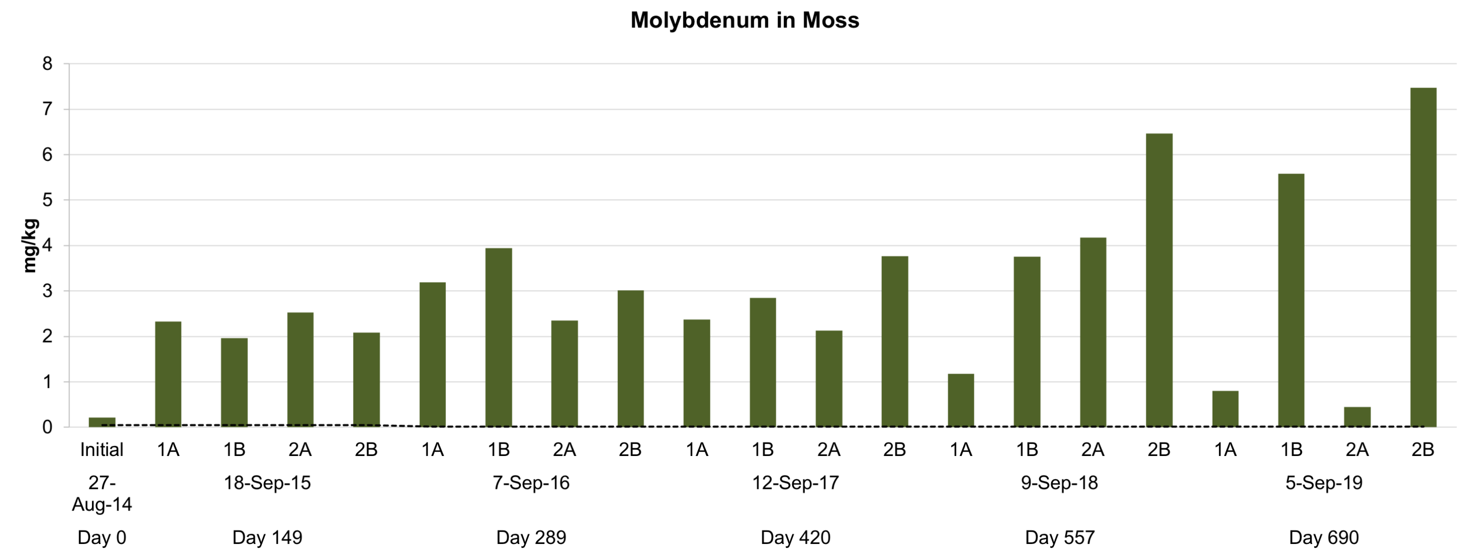
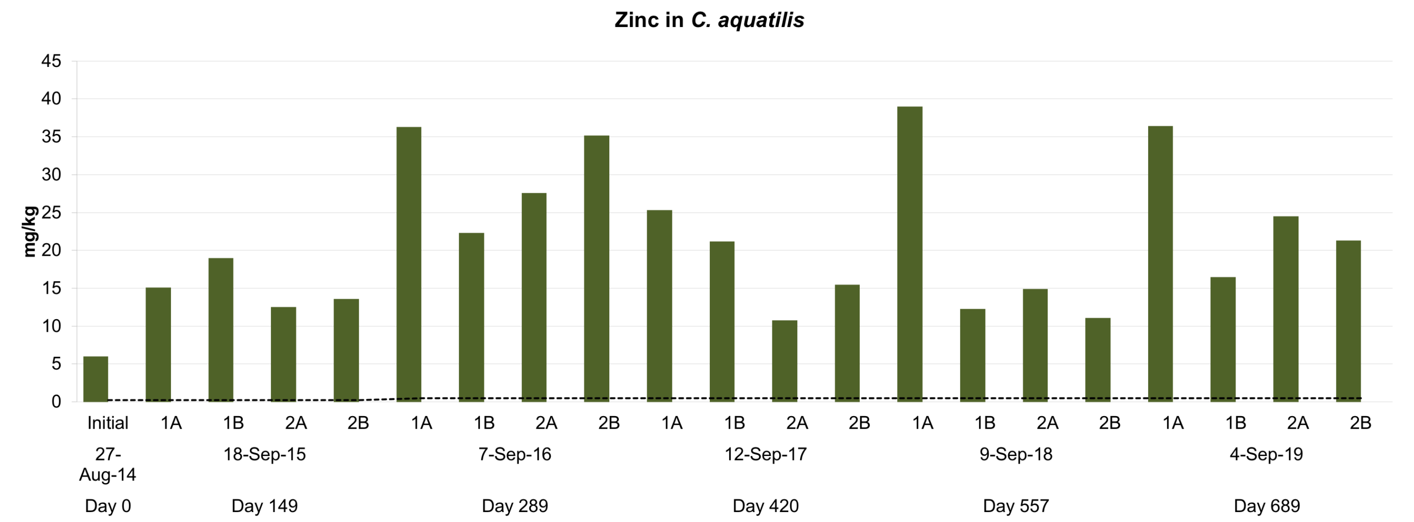


Figure B17 – Molybdenum concentrations in plants.
The 2014 and 2015 detection limit (DL; horizontal dotted line) for molybdenum is 0.05 mg/kg, and the 2016-2019 DL is 0.020 mg/kg. The initial timepoint is the average of the three *C. aquatilis* or three moss replicates at construction.



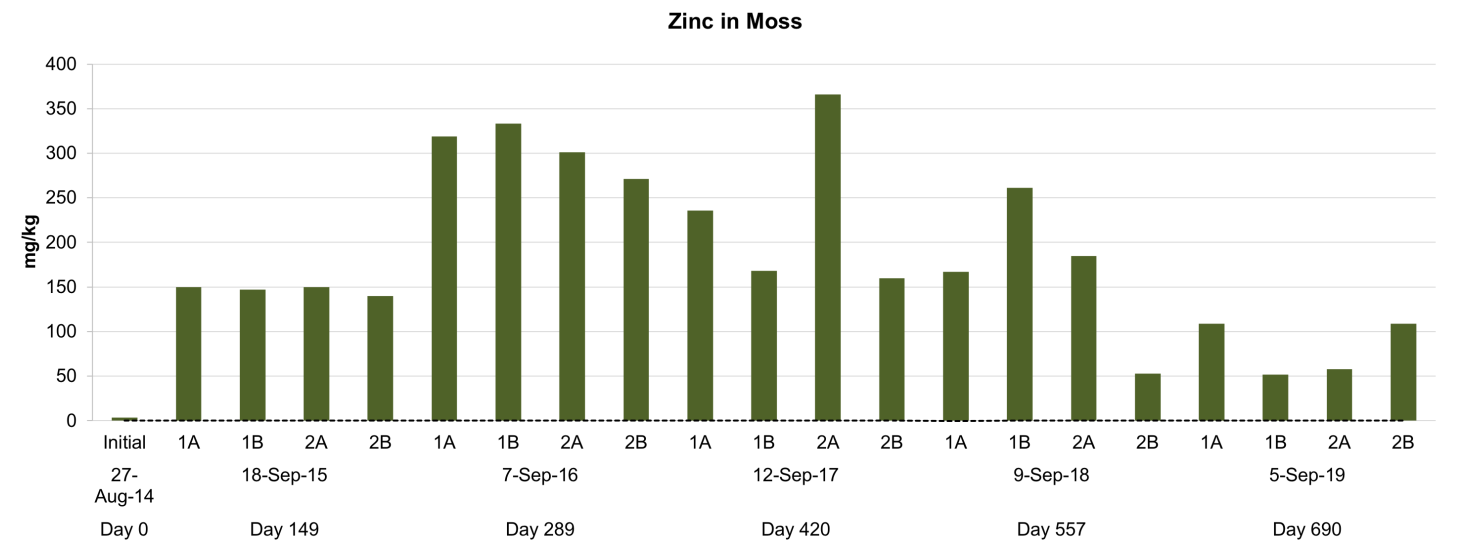


Figure B18 – Zinc concentrations in plants.
The 2014 and 2015 detection limit (DL; horizontal dotted line) for zinc is 0.20 mg/kg, and the 2016-2019 DL is 0.50 mg/kg. The initial timepoint is the average of three *C. aquatilis* or three moss replicates at construction.

B4. Microbiology Results

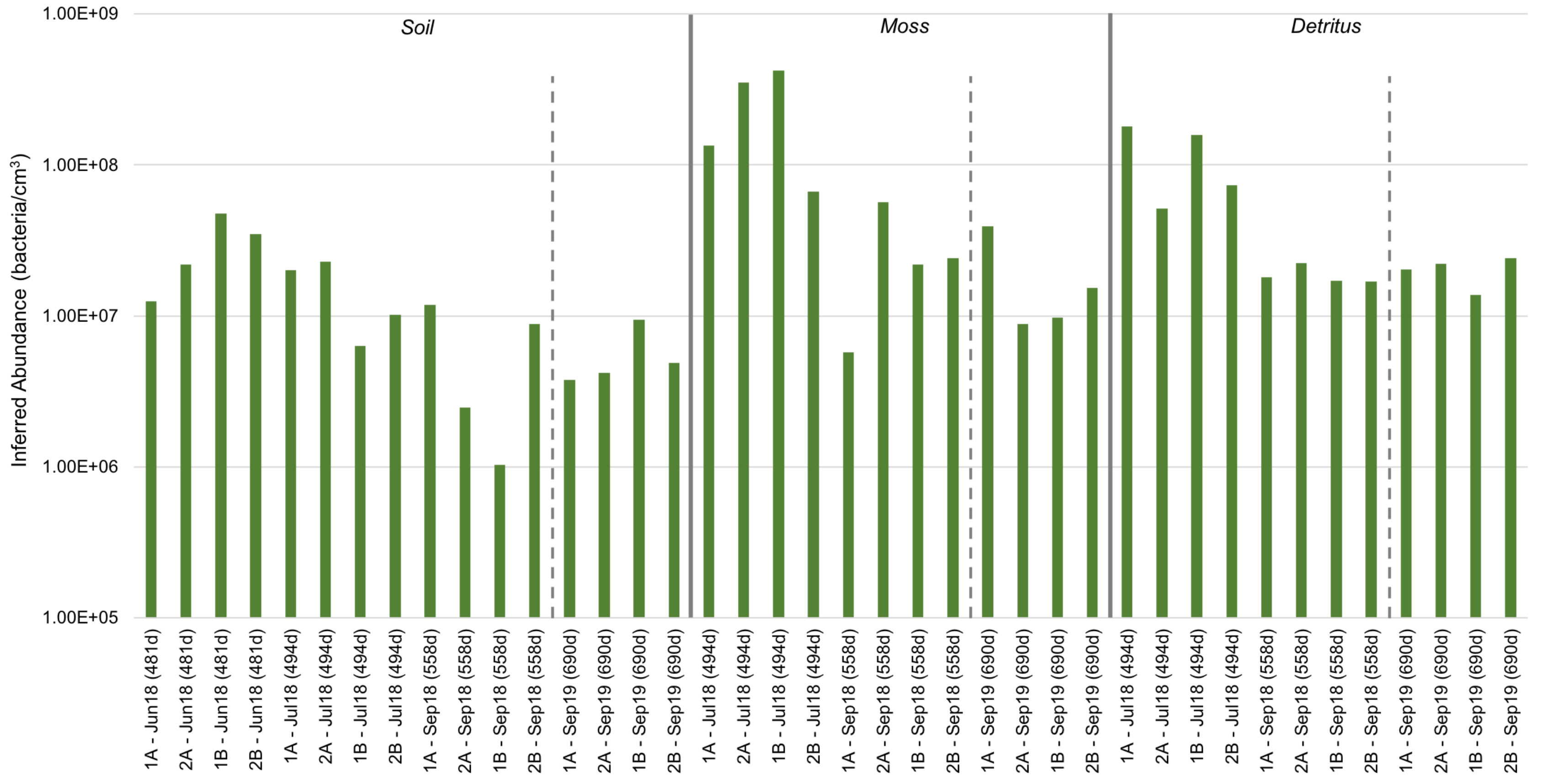


Figure B19 – Inferred abundance of denitrifying bacteria in soil, moss, and detritus in the demonstration-scale CWTS in 2018 and 2019.

Inferred abundance is calculated based on a combination of genetic and quantification data. Methods for quantification changed from growth-based analyses (most probable number) from 2014 to 2017 to quantitative polymerase chain reaction (qPCR) analyses in 2018 and 2019. As methods are not directly comparable (Appendix A, Section A7.5.1.), only results from 2018 and 2019 are shown here. Solid vertical lines separate the different sample types (soil, moss, detritus), while dashed vertical lines separate the year samples were collected (2018, 2019). Inferred abundance is not calculated for root samples.

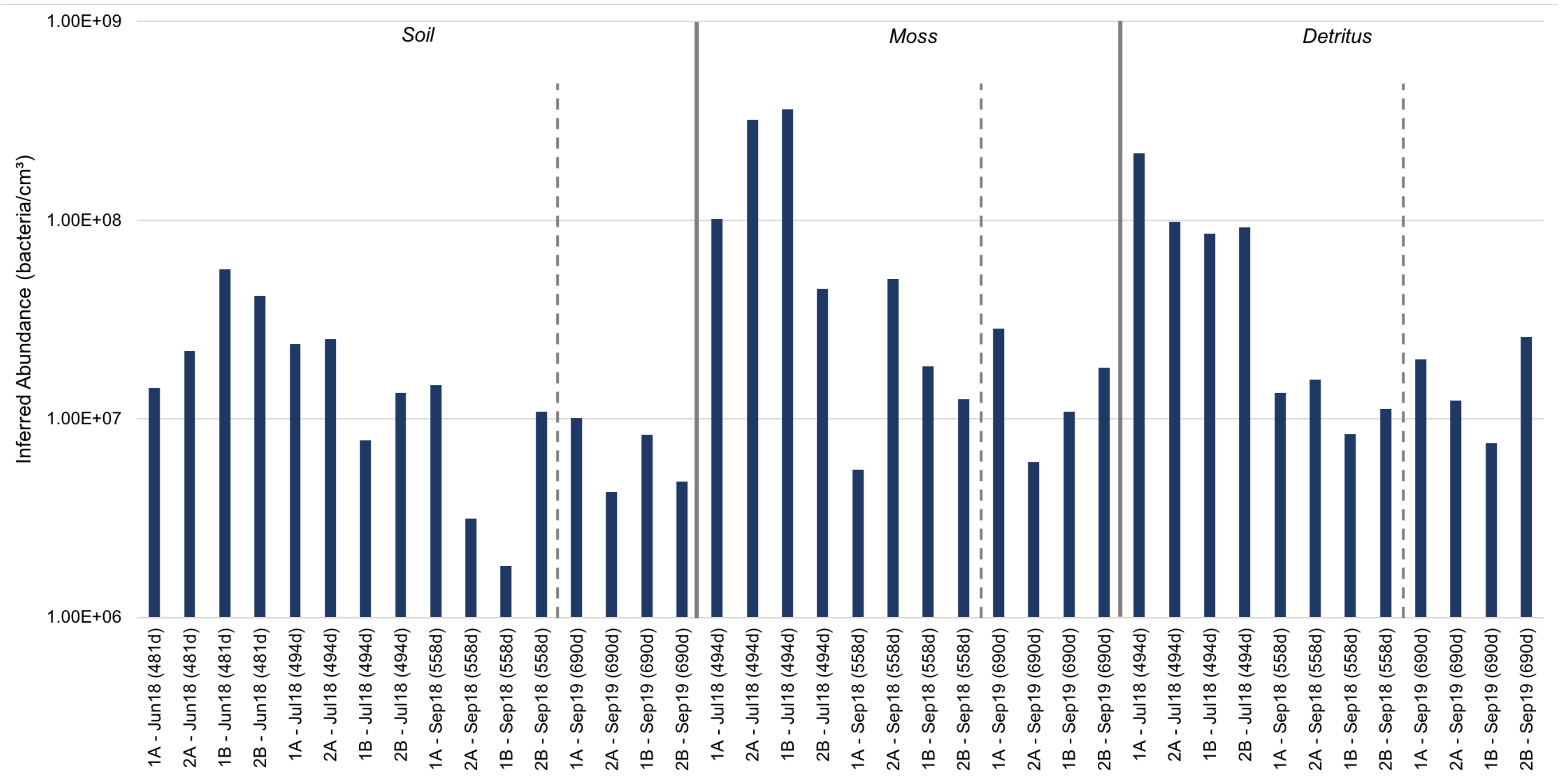


Figure B20 – Inferred abundance of selenium-reducing bacteria in soil, moss, and detritus in the demonstration-scale CWTS in 2018 and 2019.
Inferred abundance is calculated based on a combination of genetic and quantification data. Methods for quantification changed from growth-based analyses (most probable number) from 2014 to 2017 to quantitative polymerase chain reaction (qPCR) analyses in 2018 and 2019. As methods are not directly comparable (Appendix A, Section A7.5.1.), only results from 2018 and 2019 are shown here. Solid vertical lines separate the different sample types (soil, moss, detritus), while dashed vertical lines separate the year samples were collected (2018, 2019). Inferred abundance is not calculated for root samples.

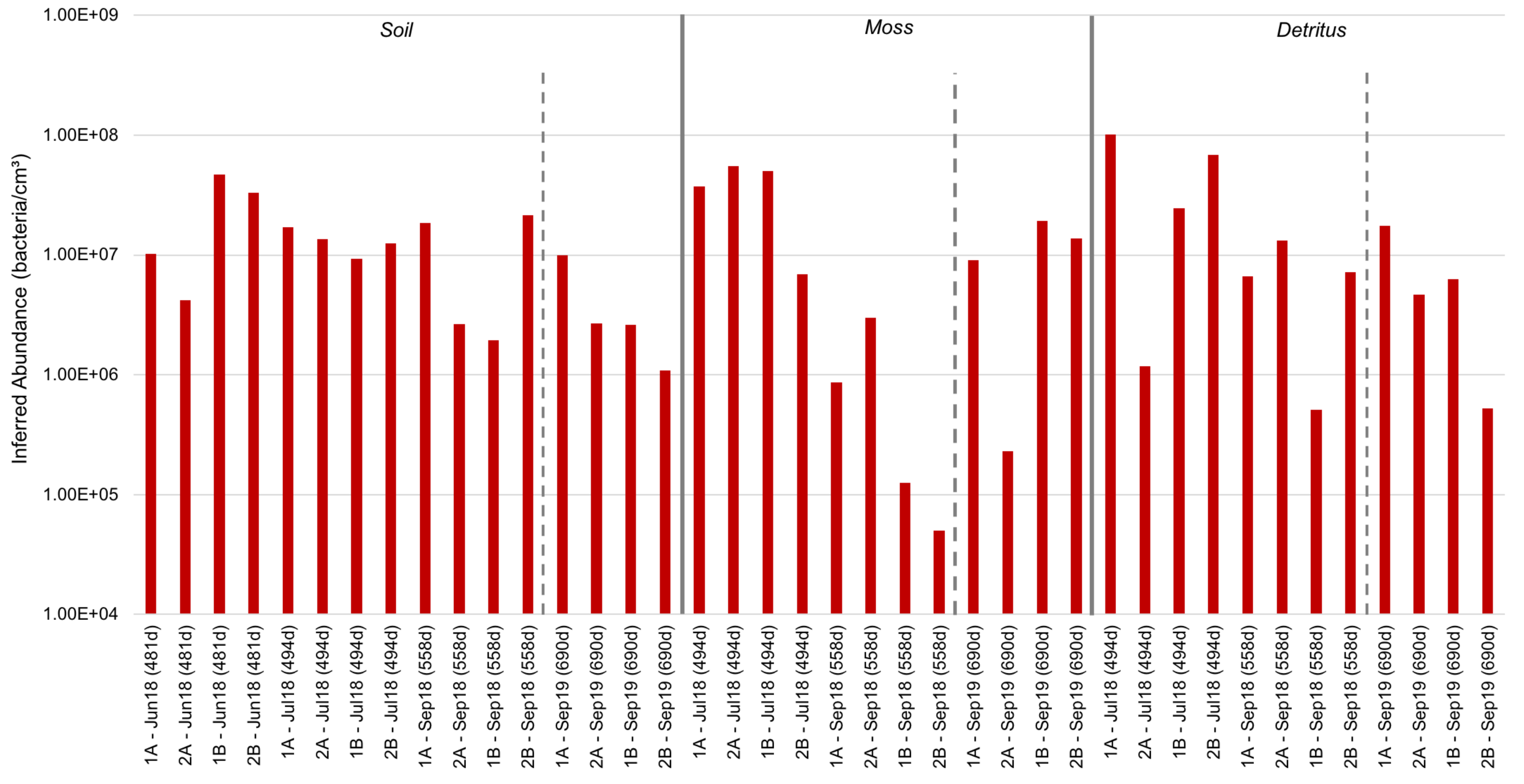


Figure B21 – Inferred abundance of sulphide-producing bacteria in soil, moss, and detritus in the demonstration-scale CWTS in 2018 and 2019.

Inferred abundance is calculated based on a combination of genetic and quantification data. Methods for quantification changed from growth-based analyses (most probable number) from 2014 to 2017 to quantitative polymerase chain reaction (qPCR) analyses in 2018 and 2019. As methods are not directly comparable (Appendix A, Section A7.5.1.), only results from 2018 and 2019 are shown here. Solid vertical lines separate the different sample types (soil, moss, detritus), while dashed vertical lines separate the year samples were collected (2018, 2019). Inferred abundance is not calculated for root samples.

Appendix C – Multi-year Workplan

Table C1 – Schedule of work and activities for demonstration-scale CWTS.

Item	Date	Activities	Actual
Construction	2014	Identify potential location for demonstration scale CWTS (Contango site visit – 1 scientist)	Completed June 2014
		Engineering and geotechnical (Minto)	Completed July 2014
		Construction (Minto)	Completed July 2014
		Planting and bringing system online (Contango site visit – 1 scientist, 1 technologist), coordinate for local students to assist	Completed August 2014 (no students available, brought 2 technologists)
Commissioning	2014	Acclimation and maturation at constant flow rate, ~20 hr HRT	Completed
		September - Contango site visit/checkup (1 technologist, 1 scientist)	Did not occur because construction was last week of August
	2015	Continued commissioning. Operation at constant flow rate, ~20 hr HRT	Completed (at shorter HRT)
		Spring – Contango site visit/checkup (1 technologist, 1 scientist), includes micro sampling	Completed
		Summer - Increase depth from 10 cm to 20 cm (1 technologist), includes micro sampling	Completed (scientist)
		Fall – Contango site visit/checkup (1 technologist), includes micro sampling	Completed (scientist)
	2016	Minto to add sandbags prior to first site visit and begin W15 creek monitoring	Completed May/June 2016
		Spring – Contango site visit (1 scientist, 1 technologist), includes microbial sampling and tasks outlined in Table 5 of report. HRT tracer study completed, outlined in section 7 of report.	Completed June 2016
		Summer - Contango site visit/checkup (1 scientist, 1 technologist), includes microbial sampling and tasks outlined in Table 5 of report.	Completed July 2016

Item	Date	Activities	Actual
		Evapotranspiration study completed as outlined in Section 9 of report. Organics were added to the CWTS as outlined in Section 5.1 of report.	
		Fall - Contango site visit/checkup (1 technologist), includes microbial sampling and tasks outlined in Table 5 of report	Completed September 2016
	2017	Continued commissioning operations at constant flow rate.	Completed May 2017
		Two evapotranspiration studies were completed	Completed May/June 2017
		Spring – Contango site visit (1 scientist, 1 technologist), includes microbial sampling and tasks outlined in Appendix A of report. Completed HRT tracer study. Sample for AVS to assess if the added organics are having the desired effect.	Completed June 2017
		Summer - Contango site visit/checkup (1 scientist), includes microbial sampling and tasks outlined in Appendix A of report.	Completed July 2017. Seasonal water sampling was not completed due to flow interruptions. Seasonal water sampling was completed by Minto in August.
Commissioning		Minto added sandbags to outflows of CWTS cells to increase water depth	Completed August 2017
		Commissioning completed and beginning of operational period	Completed August 2017
Operations		Fall – Contango site visit/checkup (1 scientist), includes microbial sampling and tasks outlined in Table 5 of report.	Completed by Minto, after being taught microbial sampling by Contango. No site visit needed by Contango.
		Monitor soil redox. Determine when it consistently reaches targeted range.	Completed throughout 2017
Performance monitoring	2018	Develop a sampling plan, and aphid control and monitoring plan for 2018	Completed March, 2018
Drought recovery		Start water flow to CWTS; add sandbags to end and along perimeter of each CWTS cell to increase	Completed May 2018

Item	Date	Activities	Actual
		water depth by 1 to 5 cm; aphid control using more powerful insecticide on a routine schedule	
		Assess recovery of CWTS from drought	Completed throughout 2018
		Summer – Contango site visit (1 scientist); conduct a vegetation plot harvest and assessment of biomass produced; collect one bag of *C. aquatilis* and one bag of polyester filter foam from each CWTS cell; replant *C. aquatilis* in areas with sparse vegetation	Completed July 2018
		Iron added to Series 1	Completed July 2018
		Two evapotranspiration studies were attempted (were not informative due to precipitation during trials)	Completed July/August 2018
Performance monitoring	2019	Fluctuate flow rates, based on expected amount of water for full-scale wetland (scaled to size). Evaluate performance of CWTS at different key periods. Fertilize plants (if necessary).	Completed throughout 2019. It was not necessary to fertilize plants.
Operations		Develop a flow rate schedule and sampling plan for 2019	Completed May 2019
		Provision of updated standard operating procedures for new staff responsible for monitoring and sampling CWTS	
		Start water flow to CWTS	Completed May 2019
		Continue aphid control using insecticide on a routine schedule	Completed May-September 2019
		Spring – Contango site visit; training of new staff responsible for monitoring and sampling CWTS, monitor for presence of aphids, add iron to Series 1, collect one bag of *C. aquatilis* and one bag of polyester filter foam from each CWTS cell	Completed May 2019. Iron addition to Series 1 was not completed due to prioritizing testing HRTs relevant to full-scale.

Item	Date	Activities	Actual
		Summer – Contango site visit; conduct a vegetation plot harvest and assessment of biomass produced; conduct evapotranspiration trial for warmer months	Completed July 2019. Vegetation plot harvest was not completed during the summer site visit as it was completed during the fall site visit. Evapotranspiration trial was not completed due to prioritizing testing HRTs relevant to full-scale.
		Fall – Contango site visit (if necessary), replanting if needed, soil harvesting for additional off-site stress tests, final sampling event.	Completed September 2019. Soil harvesting for additional off-site stress tests was not completed due to stress tests such as freezing occurring naturally each season. Replanting was not completed as it was not needed. Moss was added to the A cells during the spring site visit.
Maintenance and Operations	2020	Add tote to the inflow of the CWTS to simulate a forebay where a carbon source (straw) can be added. This will refine the full-scale design for early closure where higher nitrate loads may be present.	May 2020
		Test straw at the beginning and end of the operating season to evaluate depletion rates.	May 2020
		Develop a sampling plan for monthly monitoring of the CWTS performance through 2020.	April/May 2020
		Operate the CWTS at a hydraulic residence time (HRT) that mimics the full-scale system.	Throughout 2020
Reporting	Feb 2021	Memorandum to update on 2020 activities	On Schedule

Minto Mine Constructed Wetland Treatment Research Program – Demonstration-Scale 2019 Update Report

Document #011_0320_14B

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Executive Summary

The Minto Mine is an open pit and underground copper mine located 240 km northwest of Whitehorse in the Yukon Territory. As a result of mining activities, cadmium, copper, molybdenum, selenium, and zinc are slightly elevated in site drainage water beyond background concentrations and have been identified as constituents of concern (COC). As part of the Reclamation and Closure Plan for the Minto Mine, Contango, an AEG Company (Contango) was retained to evaluate the feasibility of a constructed wetland treatment system (CWTS) for passive water treatment at closure.

A phased approach is being followed to guide the site-specific design and implementation of a CWTS at closure for the Minto Mine. The phased approach was initiated with a site assessment in 2013 followed by pilot-scale testing to confirm and provide proof-of-concept before constructing the on-site demonstration-scale wetland.

The demonstration-scale CWTS was constructed at Minto in 2014, commissioned from 2015 through mid-2017 and transitioned into the operational period in August 2017. In 2018 the demonstration-scale CWTS was tested for its ability to recover and perform under the unintentionally imposed stresses of a winter/freshet drought and elevated nitrate concentrations in the inflow water. The CWTS demonstrated successful recovery and in 2019 the operational period had the primary objective of assessing performance under conditions that would be similar to the full-scale CWTS. This primary objective was developed as a response to lines of questioning in preliminary regulatory review of closure planning documents. Additional aspects that were evaluated include the fate and distribution of treated metals, detritus decomposition and accretion rates, carbon demand, and microbial community characterization. This report presents findings from all operational years of the demonstration-scale CWTS, with a focus on 2019 activities.

The flow rates in 2019 were higher than previous years to mimic shorter hydraulic retention times that are currently anticipated for the full-scale CWTS. The results from 2019 have highlighted that the demonstration-scale CWTS can operate under these shorter HRT conditions while successfully treating most COC and notably removing more load of COC than any previous year. Beneficial microbial populations in the CWTS remained stable, and COC have been treated with minimal uptake by plants. Removal rate coefficients have been developed throughout operations of the demonstration-scale CWTS which will be used to advance the design of a full-scale CWTS at the Mine.

The removal rate coefficients for cadmium, copper, and zinc in 2019 are similar or better to previous years, indicating they were unaffected by the shorter HRTs and less reducing conditions experienced in the CWTS. In contrast, molybdenum and selenium (somewhat) treatment was impacted by the decreased nitrate removal and correspondingly less reducing conditions in the CWTS. While nitrate is not a primary COC for CWTS treatment, removal is evaluated as nitrate can impact treatment of the primary COC. The demonstration-scale system was likely carbon limited due to higher nitrate loads going to the CWTS as a result of higher flow rates. As a result, the removal of molybdenum and selenium (somewhat) was impacted, with decreased removal rate coefficients for molybdenum (albeit similar to 2017)

and slightly lower rates for selenium. Outflow concentrations of molybdenum and selenium did not get as low and the percent removal was lower in 2019 than in previous years.

The testing in 2019 has therefore identified that when nitrate loads are high, the carbon demand for the CWTS may be greater than what is available through annual plant growth. The carbon demand for the full-scale CWTS will be evaluated in the context of expected nitrate loads in closure, where concentrations are expected to decrease over time and would be lower if there is any pre-treatment (e.g., pit lake treatment) before the CWTS. *In situ* pit lake treatment is also being evaluated in 2020 and 2021 with bench- and pilot-scale trials. Should higher nitrate loads be expected early in closure to the CWTS, a forebay could be used for periodic carbon supplementation. To further refine the full-scale CWTS design it is therefore recommended that in 2020 a forebay with organics be incorporated into the demonstration-scale CWTS to evaluate the amount and frequency of carbon addition that may be needed to manage high nitrate loads.

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Abbreviations and Definitions

Accretion – The process of growth or increase of sediments through deposition and accumulation of organic material deposited solids (such as minerals) within a wetland.

Acid volatile sulphide (AVS) – Sulphide complexed with Fe (FeS) where the sulphide can preferentially exchange Fe for heavy metals (Ni, Zn, Cd, Pb, Cu, Hg) which are then more stably bound.

Acidity – A measure of the capacity of water to neutralize base. Influences pH along with alkalinity.

Alkalinity (Alk) – A measure of the capacity of water to neutralize acids. Influences pH along with acidity.

Amendment – A chemical or organic material added to encourage specific conditions (e.g., aerobic/anaerobic, pH, ORP) or as a source of something that is needed for passive treatment (e.g., nutrients, alkalinity, binding sites, etc).

Biofilm(s) – A visible and often slimy-looking film (community) of bacteria (may contain other microbes).

Carbon source – A source of carbon (energy/electrons) for microbes (see **electron donors**). Examples include ethanol, methanol, acetate, sugar (glucose), molasses, wood chips, detritus (dead plant matter).

Carex aquatilis – A plant (emergent macrophyte) commonly known as water sedge.

CCME – Canadian Council of Minister of the Environment.

Constituent of Concern (COC) – Specific elements that have been identified for evaluation, including cadmium, copper, molybdenum, selenium, and zinc.

Constructed wetland treatment system (CWTS) – Wetlands that are designed and constructed to remove compounds from water, using natural processes to sequester them into the soils rendering them less bioavailable. They are different from wetlands that provide habitat for wildlife.

Denitrification – Where nitrate (NO_3^-) is reduced by microorganisms to form nitrite (NO_2^-), nitric oxide (NO), or nitrous oxide (N_2O), or nitrogen gas (N_2) (see **nitrate reduction**).

Dissimilatory metal(s) reduction – A process used by microbes to conserve energy through oxidizing organic or inorganic electron donors and reducing a metal or metalloid.

Dissolved organic carbon (DOC) – Organic (carbon based) molecules in water, that have passed through a filter of 0.45 µm.

Dissolved oxygen (DO) – Diatomic oxygen (O_2) dissolved in water; oxygen can dissolve in water by diffusion from surrounding air, as a product of photosynthesis, or through forced aeration.

Electron donor(s) – A chemical compound that donates electrons to another compound (see **carbon source**). An electron donor is a reducing agent, which that by virtue of it donating electrons, is itself oxidized (see **oxidation** and **reduction**).

Explanatory parameters – Quantifiable parameters that describe how water treatment reactions take place.

Evapotranspiration – The process by which water is transferred to the atmosphere by evaporation from the surface of water and by transpiration from plants.

ICP-MS – Inductively coupled plasma mass spectrometry.

Macrophytes – An aquatic plant, large enough to be seen by eye. Can be emergent, submergent, or floating.

Microbes – Microscopic organisms that cab be uni- or multi-cellular. This includes algae, bacteria, fungi, viruses, and yeast.

Molybdenum reduction – Microbially mediated reduction of soluble Mo(VI) to create Mo(IV) which can complex with sulphide compounds.

Nitrate reduction – Where microbes reduce nitrate (NO_3^-) to form nitrite (NO_2^-); the first step in denitrification (see **denitrification**).

Oxidation – The loss of electrons, or increase in valence state, by a molecule, atom, or ion. Can be driven by microbes. Process is complementary to chemical reduction.

Oxidation-reduction potential (ORP) – A measure of the tendency of a chemical species to acquire or donate electrons, thus becoming reduced or oxidized, respectively, measured in millivolts.

Redox – Oxidation-reduction potential (in sediment), a measure of the tendency of a chemical species acquire or donate electrons, thus becoming reduced or oxidized, measured in millivolts. This measurement is relative to the water ORP.

Reduction (chemical) – The gain of electrons, or a decrease in valence state, by a molecule, atom, or ion. Can be catalyzed by microbes. Process is complementary to chemical oxidation.

Selenium reduction – Microbially mediated reduction of soluble Se(VI) and Se(IV) to insoluble elemental selenium.

Simultaneously extracted metals (SEM) – amounts of heavy metals such as Ni, Zn, Cd, Pb, Cu, Hg in sediment, assessed in the context of AVS for excess sulphide. (also see acid volatile sulphide)

Sorption – The physical and/or chemical process by which one substance becomes attached to another substance.

Specific conductivity (SPC) – A measurement of electrical conductivity in water that is typically expressed in µs/cm, which has been adjusted for temperature (25°C).

Species (sp.) – One of the basic units of biological classification and a taxonomic rank. Rank in the classification of organisms below genus and above strain. Also can be used to refer to the oxidation state of a mineral (e.g., selenate and selenite are species of selenium).

Sulphide – An inorganic anion of sulphur that can form stable complexes with metals and make them insoluble in water (remove them from the water).

Sulphide producing bacteria (SPB) – Microbial reduction of sulphur compounds, such as sulphate, sulphite, thiosulphate, and sulphur, which produces sulphides and alkalinity. (see also **SRB**).

Sulphate reducing bacteria (SRB) – a form of sulphide producing bacteria that specifically uses sulphate for reduction (see **sulphide producing bacteria**).

Sulphide production – Microbial reduction of sulphur compounds, such as sulphate, sulphite, thiosulphate, and sulphur, which produces sulphides and alkalinity.

Total dissolved solids (TDS) – A measure of the combined organic and inorganic salts dissolved in water.

Total kjeldahl nitrogen (TKN) – The sum of organic nitrogen, ammonia (NH_3), and ammonium (NH_4^+) in water (or soil). To calculate the total nitrogen, the concentrations of nitrate as N (NO_3^-N) and nitrite (NO_2^-N) are added to TKN.

Total organic carbon (TOC) – A measurement of the total organic carbons present in water.

Total suspended solids (TSS) – A measurement of all particles in water that are larger than 2 µm (anything smaller than 2 µm considered a dissolved solid).

Transfer – Processes that treat water by transferring a constituent to another location without changing its form. For example: absorption, adsorption, dilution, dispersion, filtration, precipitation (aqueous to solid), and volatilization.

Transform – Processes that change the chemical form or state of a constituent. For example: biodegradation, biotransformation, hydrolysis, ionization, oxidation, photolysis, and reduction.

1. Introduction

The Minto Mine (the "Mine"), owned and operated by Minto Explorations (previously Capstone Mining Corp), is a combination open pit/underground copper mine located 240 km northwest of Whitehorse on the west side of the Yukon River. Mining began in October 2007 and the deposits being mined were copper sulphide mineral deposits. In October 2018, the Mine was placed into temporary care and maintenance due to unfavourable equity market conditions (Capstone, 2018). In June 2019 the Mine was purchased by Minto Explorations and underground mining activities resumed in late 2019. Surface and ground water quality is a key consideration in the evaluation of potential effects of mining and mineral development projects. The resultant changes to water quality parameters have the potential to affect aquatic and human use of water resources.

A Reclamation and Closure Plan (RCP) is required for the Minto Mine under both the Water Use License and the Quartz Mining License. The RCP is intended to address the long-term physical and chemical stability of the site and closure of the proposed features and disturbances associated with the Mine. As a part of the RCP, the Mine has retained Contango Strategies, an AEG company (Contango), to complete an evaluation of the feasibility of a Constructed Wetland Treatment System (CWTS) for water treatment at closure. This assessment includes a phased approach approved during the Minto Phase V/VI Expansion Project (Yukon Online Registry Project Number 2013-0100). The CWTS phased approach will design, evaluate, and optimize water treatment of constituents of concern (COC; cadmium, copper, molybdenum, selenium, and zinc) for closure in a site-specific manner. CWTS are desirable for closure water treatment because once established, they can become self-sustaining ecosystems with the plants providing yearly renewal of carbon to fuel microbial activity. As such, they possess the desirable potential to remediate contaminated mine drainage for as long as it is generated.

Through the RCP, a demonstration-scale CWTS (Phase 4) was constructed at the Minto Mine in 2014, based on the design that was evaluated through pilot-scale testing (Contango, 2014b). Two series were constructed in parallel, each with two cells planted with local *Carex aquatilis* and moss. The demonstration-scale CWTS was commissioned from 2015-2017, and then underwent performance testing from 2017-2019. This report focuses on activities and results of the 2019 operational testing period. Background information on previous phases of work is summarized in Section 3. Background information on construction, commissioning, and operations of the demonstration-scale CWTS leading up to and including 2019 can be found in previous annual reports and is summarized in Section 4. Treatment processes are outlined in Section 5, and results from the demonstration-scale CWTS operations (2017-2019) presented in Section 6. Health and establishment of CWTS vegetation and treatment mechanisms are outlined in Section 7 and 8 respectively, and a summary is presented in Section 9 with recommendations and next steps for 2020 outlined in Section 10.

2. Objectives

The overriding objective of the Minto Mine demonstration-scale CWTS program is to advance proof of concept and ultimately site design of a full-scale CWTS for the Minto Mine. The primary objective in 2019 was to assess performance under a wide range of conditions that mimic the full-scale CWTS. Additional sampling occurred at the end of the 2019 season to evaluate the fate and distribution of COC within the CWTS. Other ongoing activities that have been reported on in previous years and continued in 2019 included:

- Evaluating CWTS performance and determining lowest achievable COC concentrations (performance limits) to provide information for full-scale treatment performance;
- Refining site-specific removal rate coefficients (RRCs) to provide information for full-scale CWTS sizing;
- Monitoring metals leaching from the mineralized soils used in construction to inform treatment extent;
- Assessing the mineral forms of COC sequestered into the soils and production of acid volatile sulphides (AVS) to inform on stability of COC in soils;
- Monitoring for the presence of aphids in the CWTS, and implementing a routine insect pest control plan (for aphids) to maintain plant health during the testing season;
- Determining the amount of vegetation growth and the rate and extent of detritus decomposition (*Carex aquatilis* leaves) in the CWTS over time to evaluate organic carbon production in a mature wetland; and
- Assessing treatment mechanisms (including microbes present) to confirm targeted biogeochemical processes and advance proof of concept.

3. Background

The phased approach for CWTS development at the Mine is summarized in Table 1 along with the objective of each phase. Phases that have been completed and reported elsewhere are also summarized.

Table 1 – Five phased approach for CWTS design and implementation.

Phase	Objective	Status	Document Number
Phase 1	Site assessment and information gathering	Complete	Contango, 2014a
Phase 2	Technology selection and conceptual design	Complete	
Phase 3	Off-site pilot-scale testing and optimization (at Contango)	Complete	Contango, 2014b
Phase 4	**On-site demonstration-scale testing and optimization (at the Mine)**	**In progress**	011_0315_01A 011_0316_03B 011_0217_05B 011_1117_10C 011_0119_13B **This report**
Phase 5	Full-scale implementation	Future scope	Future scope

3.1 Site Assessment and Pilot-Scale Testing

The site assessment (Phase 1) was conducted in 2013 to evaluate feasibility of a CWTS, and to identify possible CWTS locations and borrow sources for substrates and plants. During the site assessment, water, soil, plant, and microbiological samples from the natural wetland and a creek area between the W10 to W15 monitoring stations were collected and assessed. The site assessment revealed borrow sources for the CWTS substrate and vegetation, as well as probable locations for a CWTS (Contango, 2014a). Additionally the geochemical data collected indicated that substantial treatment of seepage water was occurring on site within the natural wetland validating the concept that a CWTS with optimized performance could be designed to function in the long-term closure conditions at the Mine. All the sites sampled were host to a wide diversity of microbes with known capability of performing favourable biogeochemical reactions, which will contribute to water treatment in a CWTS.

Findings from the site assessment supported progression to Phase 2 to select the technology and conceptually design the CWTS (Phase 2). An anaerobic CWTS technology was identified and conceptually designed based on the COC requiring treatment (copper and selenium) and site-specific considerations. The conceptual CWTS design was tested off-site at pilot-scale

(Phase 3) to refine the design for passive treatment during closure. The pilot-scale CWTS tested three anaerobic designs: planted with (i) *C. aquatilis,* (ii) *C. aquatilis* and moss, or (iii) *C. aquatilis,* moss, and with biochar amendment (hybrid bioreactor-CWTS). The three designs were tested in duplicate with synthetic water designed to mimic the predicted worst-case post-closure water chemistry during early and long-term closure (i.e., high and low nitrogen, respectively). Through pilot-scale testing the recommended CWTS design for long-term passive treatment of copper and selenium at the Mine was identified as a combination of *C. aquatilis* and moss planted in a sand substrate supplemented with 2-7% by volume as organic material (e.g., woodchips and peat). This recommendation was used to guide the design and implementation of the demonstration-scale CWTS (Phase 4) at the Mine.

4. Demonstration-Scale CWTS Construction, Commissioning, and Operations (2014-2019)

4.1 Overview of Demonstration-Scale History

Construction of the demonstration-scale CWTS and details of CWTS design, vegetation, and substrate borrow sources are reported in Contango, 2015. A potential borrow source was tested and selected prior to construction as soils in a mining area are likely mineralized. However, a different borrow source (organic peat) was used to construct the demonstration-scale CWTS, and analyses received after construction indicated an elevated concentration of leachable copper (described in Appendix A, Contango, 2017b).

The commissioning period is the time period between the construction of the CWTS and establishment of plants and microbial populations which result in achievement of expected treatment performance. The commissioning period of the demonstration-scale CWTS at the Minto Mine had two stages between September 19, 2014 and August 18, 2017 (Table 2). CWTS plant establishment occurred during the first stage (Commissioning-A; Table 2). Organics (straw and wood chips) were added to the CWTS at the start of the second stage (Commissioning-B; Table 2) to further aid in treatment of the leachable copper in the soils used in construction and to transition copper into sulphide mineral forms. The commissioning period was longer than typical for a CWTS based on the high leachable copper in the soils used for construction. Once sufficient reducing conditions were established at the end of the 2017 commissioning-B period, copper leaching subsided and treatment occurred at a faster rate than leaching (Contango, 2017b). Copper leaching has been discussed extensively in previous reports, with details of the two commissioning periods and criteria marking the end of commissioning outlined in Contango 2016a, 2017a, and 2017b.

The demonstration-scale CWTS was operated from mid-August 2017 to September 2019 (Table 2). In spring 2018, the CWTS was unintentionally exposed to a double stress test which included drying out the CWTS and exposing the wetland soils to air, as well as elevated nitrate concentrations in the water. Following the double stress test, the two mitigation strategies tested to return the CWTS to an operational status showed variable recovery periods for treatment of each COC (Table 2; Contango, 2019). Increased monitoring was implemented through the 2018/2019 winter and early spring season to ensure the CWTS remained flooded prior to beginning flow to the CWTS in 2019. This scenario of spring freshet drought is not expected to occur during full-scale operations as water will be flowing into the wetland by gravity as spring melt occurs and will not rely on pumps with seasonal constraints to supply water to the CWTS. The beginning of the 2019 operational period was marked by the start of continuous flow through the CWTS on May 15, 2019 (Table 2).

Table 2 – Summary of demonstration-scale CWTS timeline.

Period	Year	Days of Operation	Date	
			Start	End
Commissioning-A	**2014**	0 - 23	Aug 27	Sep 19
	2015	24 - 160	May 16	Sep 29
	2016	161 - 248	May 2	Jul 28
Commissioning-B	**2016**	249 - 311	Jul 29	Sep 30
	2017	312 - 394	May 27	Aug 17
Operational Period	**2017**	395 - 430[1]	Aug 18	Sep 22
Double Stress Test Period - Series 1	**2018**	439 - 494	May 15	Jul 8
Double Stress Test Period - Series 2	**2018**	439 - 533	May 15	Aug 16
Operational Period	**2018**	534 - 557[2]	Aug 17	Sep 9
Operational Period[3]	**2019**	577 - 690	May 15	Sep 5

[1] Flow was continued past the operational period until September 30, 2017 (day 438).
[2] Flow was continued past the operational period until September 28, 2018 (day 576).
[3] The operational period of 2019 consisted of multiple targeted HRT periods as shown in Figure 2.

4.2 Operational Adjustments in 2019

Operational adjustments were made to the demonstration-scale CWTS in 2019 to assist with addressing the objective of assessing performance under conditions that mimic the full-scale CWTS. These adjustment are discussed in Sections 4.2.1 and 4.2.2 below.

4.2.1 Increasing Water Depth

The water depth in each CWTS cell was raised in 2019 to mimic the water depths in the full-scale design and to further promote reducing conditions. Sandbags were added to the end and along the perimeter of each CWTS cell between May 5, 2019 and July 17, 2019 to increase the water depth and minimize short circuiting, respectively. Sandbags were added gradually as the stabilized water depth was confirmed. The water depths were increased by 17 to 23 cm in the four cells, to target 30 to 40 cm (Table 3). It is noted that at full-scale, short circuiting would be mitigated using rip rap armouring around the edges of the wetland.

Table 3 – Demonstration-scale CWTS water depths.

CWTS Cell	Average Water Depth 2017 (cm)	Average Water Depth 2018 (cm)	Maximum Water Depth 2019 (cm)[1]
1A	15.2	20.2	37.5
1B	16.0	20.3	40.5
2A	15.9	18.6	36.5
2B	14.4	15.6	38.5

[1] In 2019, the depth was gradually increased from May 5 to July 17, 2019.

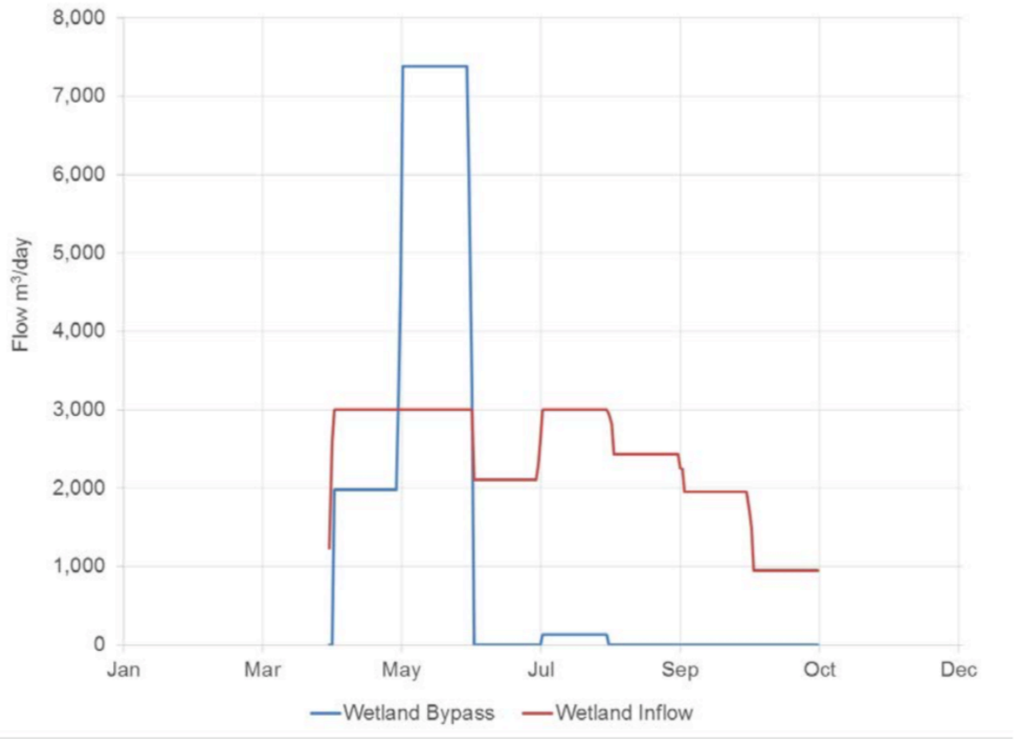
4.2.2 Flow Rates and HRT

Preliminary full-scale design specifications have the flow rate to the CWTS ranging from 1000 to 3000 m^3/day (Figure 1; 2018 Water and Load Balance Model Report; Contango, 2016b; SRK, 2016; SRK, 2018). The maximum flow rate through the full-scale CWTS is designed to be capped at 3000 m^3/day, with water from higher flows directed through the high flow bypass channel. The flow rates of 3000, 2000, and 1000 m^3/day would correspond to approximately 0.8, 1.2, and 2.5 day HRTs in the preliminary full-scale CWTS design, respectively. Thus, these HRTs were selected for testing on the demonstration-scale system in 2019 to mimic the full-scale CWTS.

In addition to the targeted 0.8, 1.2, and 2.5 day HRTs tested in 2019, a longer HRT of 5 days was also tested for comparison to previous years (Figure 2). The targeted HRTs in 2019 resulted in a greater amount of water entering the demonstration-scale CWTS daily compared to previous years, therefore resulting in higher loads of COC entering the CWTS compared to any other year (Table 4). The targeted nominal HRT was calculated using the actual water depth in each series prior to starting the HRT scenario (as the depth gradually increased as sandbags were added until target depths were reached), plus the correction factor obtained from the 2017 tracer study. Actual flow rates are represented along with targeted flow rates and corresponding HRTs in Figure 2.

The influence of evapotranspiration on performance was also evaluated to understand the amount of water lost, which in turn concentrates elements measured at the outflow and influences the constituent load to the receiving environment. Total evapotranspiration from the system is the combined effects of open water evaporation and plant transpiration and is further described in previous reports (Beebe et al., 2014; Contango, 2017b). Therefore, the future models for assimilative capacity in the downstream receiving environment should take into account not only the predicted outflow concentrations from the CWTS using removal rate coefficients (as discussed below), but also the load accounting for evapotranspiration.

The evapotranspiration rate of 5.4 L/m^2/day water loss was applied to the 2019 load removal data to determine the influence of evapotranspiration on outflow loads of COC from the demonstration-scale CWTS (Contango, 2017b). There was minimal influence from evapotranspiration on the load of COC removed in 2019 based on the high volumes of water reporting to the CWTS which were much greater than the volume lost through evapotranspiration (for example, only 1-2% of water is lost at the 0.8-1.2 day HRT).



Z:\01_SITES\Minto\!020_Site_Wide_Data\Water_and_Load_Balance_Files\01_Project_Phases\12_Phase_VII_Files\Model Results\Model_Results_Text_Graphs_REV00_knk

Figure 1 – CWTS and high-flow bypass typical monthly flows (SRK, 2018).
Figure 5-2, as shown on page 36 of the 2018 Water and Load Balance Model Report shows the expected inflow to the full-scale wetland, which is capped to a maximum of 3000 m^3/day as water from higher flows will be directed through the high flow bypass channel.

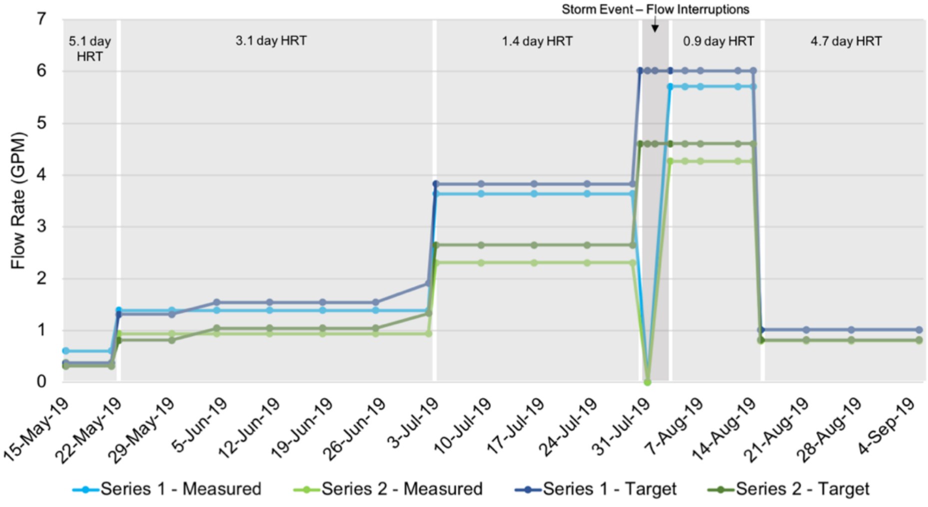


Figure 2 – Flow rates and HRT schedule for Minto demonstration-scale CWTS for Series 1 and 2 over 2019.
Targeted and measured flow rates for Series 1 and 2 are plotted. Grey shading corresponds to different HRT scenarios tested in 2019 with the average HRT of Series 1 and 2 identified.

Table 4 – Volume of water treated per day in the demonstration-scale CWTS.

Year	Actual HRT (days)	m^3/day
2017	6.3	1.8
2018	7.3	1.7
2019	4.8	4.4
	3.1	6.3
	1.4	16.2
	0.9	27.2

5. Treatment Process

The CWTS test work has been designed to treat COCs that are poorly soluble under sulphate reducing conditions, specifically cadmium, copper, molybdenum, selenium, and zinc. Nitrate is also being evaluated as it impacts treatment rates of other COCs (Contango, 2014b). The pilot-scale and demonstration-scale CWTS were designed to stimulate microbes that are naturally in the water, soil, and on the plants in the system. These bacteria oxidize a reduced carbon “food” source (e.g., organics such as decaying *C. aquatilis*) and transfer the electrons released to a terminal electron acceptor (TEA). The TEAs are generally used in the order of which is most energetically favorable by microbes. Therefore, their concentrations can be used to determine the amount of reduced carbon that is necessary to reach sulphate-reducing conditions. Of the major TEAs typically present in mine-impacted surface waters, dissolved oxygen (DO) is used first, followed by nitrate (NO_3), selenium (VI), manganese(IV), iron(III), and then sulphate (SO_4), creating a “redox ladder” as shown in Figure 3. This order of TEA consumption is not absolute, and is used to guide treatment design and performance evaluation. The TEA consumption can be influenced by numerous factors including the overall concentrations of reduced and oxidized TEA species, spatial distribution of organic electron donors and TEAs, presence of constituents that may form complexes with TEAs, and the abundance and diversity of TEA-metabolizing microbial populations present.

In the Minto CWTS, the two TEAs that would have the largest effect on carbon needed to reach sulphate-reducing conditions are oxygen and nitrate. Oxygen concentrations are primarily driven by water temperature and source water conditions. Nitrate concentrations on the other hand are expected to decrease as the nitrogen-bearing residues of explosives used during mining are flushed from waste rock storage areas. Similarly, nitrate loads would be generally lower if there is any pre-treatment (e.g., pit lake treatment) before the CWTS.

While nitrate is not a primary COC for CWTS treatment at the Mine, treatment performance is evaluated in the demonstration-scale CWTS as removal is needed in order to subsequently achieve treatment of other constituents such as selenium and metals through sulphide production. Nitrate can be removed from water through denitrification by different types of microbes, including nitrate reducing bacteria which can reduce nitrate (NO_3) to nitrite (NO_2), and also denitrifying organisms that are capable of fully reducing nitrate to nitric oxide (NO), nitrous oxide (N_2O), and dinitrogen gas (N_2, which is the most abundant gas in air).

The targeted selenium treatment pathways in the CWTS include direct reduction in the water column of selenate (Se(VI)) to selenite (Se(IV)) and sorption to moss, detritus, and substrates, and subsequent microbial reduction of soluble (sorbed) selenite (Se(IV)) to insoluble elemental selenium (Se (0)). This reductive process can also be achieved directly in the water column alone but is more effective when associated with mosses and biofilms due to their sorptive properties that bring the selenium in contact with beneficial selenium-reducing bacteria (SeRB). Selenium reduction biogeochemical processes are achieved within the same range of soil redox conditions that are targeted for sulphate-reduction.

Sulphate-reducing conditions are encountered when the TEAs above sulphate on the redox ladder have either been consumed or their residual products are less energetically favourable to reduce than sulphate. Under sulphate-reducing conditions, sulphate or sulphur-containing compounds are reduced by sulphide-producing bacteria (SPB) to form sulphide, which may then react with chalcophile COC to form insoluble mineral sulphides. Insoluble sulphide minerals then precipitate from the water column and are deposited in the soils. These SPBs thrive in anaerobic conditions with soil redox ranges between -100 and -250 mV (Mitsch and Gosselink, 2007).

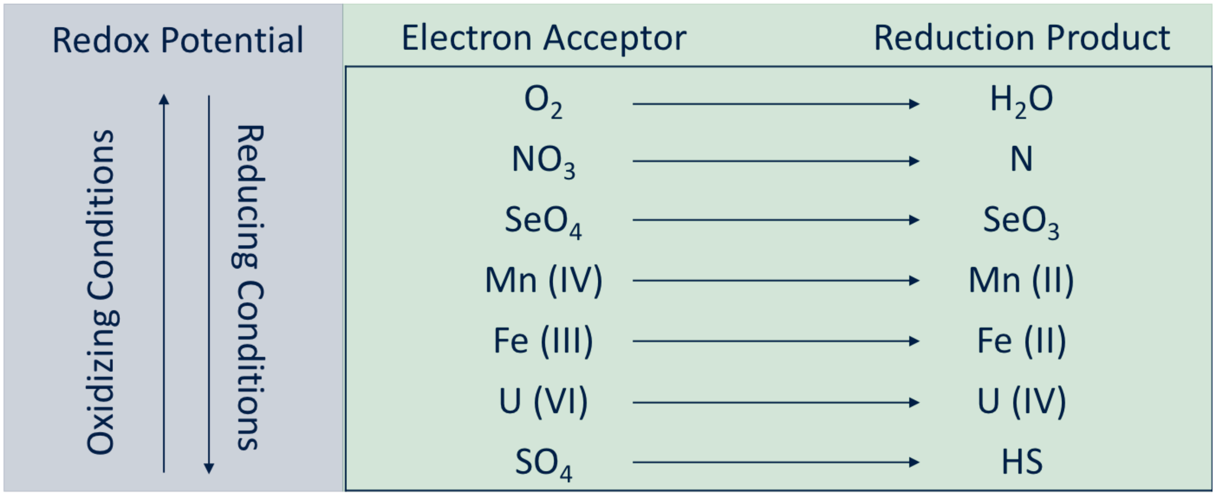


Figure 3 – Redox potential and terminal electron acceptors (TEAs).

6. Operational Period Results (2017-2019)

6.1 Monitoring Explanatory Parameters

In the demonstration-scale CWTS, reducing conditions are targeted to promote the reduction of nitrate, selenium, and sulphate and the subsequent precipitation of COC as metal sulphides. *In situ* measurements for temperature, conductivity, pH, dissolved oxygen (DO), and oxidation-reduction potential (ORP) are taken in the CWTS using a YSI ProPlus handheld unit to provide insight into the treatment mechanisms and conditions within the water (Table 5). Reducing conditions are characterised as DO concentrations less than 2 mg/L and ORP less than +50 mV (as measured with the YSI unit).

In 2019, the average ORP and DO was lower than in previous years (Table 5). While ORP and DO measurements decreased through the commissioning period, indicating that reducing conditions were being established, there was a subsequent increase through the operational periods in 2017 and 2018. Based on other explanatory parameters over this time period, it was determined that the increased measurements were likely as a result of the placement of the YSI unit as the CWTS matured and dense mats of vegetation began to interfere with measurements being taken at the base of the CWTS where treatment was occurring. In 2019 YSI measurement procedures were revisited and ensured measurements were recorded in the bottom portion of the CWTS water column. This placement of the YSI unit and the increased water depth in 2019 resulted in decreased ORP and DO measurements to levels commonly associated with reducing systems (Table 5). The average water temperature and conductivity measured in the demonstration-scale CWTS in 2019 was similar to previous years and as expected, pH remained circumneutral (Table 5).

The DO and ORP were also measured at various locations and water depths in 2019 to evaluate conditions through the CWTS. As expected, the DO was lower at the bottom of the wetland water column compared to the surface. Similarly, the outflow measurements were lower than the inflow and midpoint of each CWTS cell. Measurements have historically been taken from the outflow of each cell at the base of the wetland and it is recommended this location be maintained for future measurements of the demonstration-scale CWTS. The ORP measurements throughout the wetland did not present any notable trends or differences.

The soil redox in all demonstration-scale CWTS cells has remained stable within the targeted range (-100 and -250 mV; Contango, 2014b) since the 2017 Commissioning-B period (Figure B5 in Appendix B). In 2018, the average soil redox in Series 1 was unaffected by the CWTS drying out in early spring/freshet, while Series 2 was above -100 mV on May 14, 2018 but rapidly recovered by May 27, 2018 without additional carbon amendments. The average soil redox in Series 1 and 2 remained in the targeted range throughout the double stress test and operational periods in 2018 and shorter HRTs tested in 2019 (Contango, 2019; Table 5, Figure B5 in Appendix B). The stable soil redox indicates a matured CWTS.

In addition to *in situ* measurements, the concentration and trends of redox-active constituents and their relative position in the redox ladder was also evaluated (Figure 3). The low DO in the demonstration-scale CWTS in 2019 (Section 6.1) indicated that the first step on the redox ladder had been achieved (i.e., consumption of dissolved oxygen). In addition to the persistence of elevated nitrate concentrations, no increases in dissolved manganese or iron were observed in the 2019 dataset (aside from a short-lived peak between June 25 and July 2, 2019), which would be suggestive of more reducing conditions (i.e., manganese- and iron-reducing conditions, respectively). As such, it appears that denitrification was the most reducing stage achieved in the CWTS in 2019 based on the outflow chemistry, with no strong evidence for the development of more reducing manganese-, iron-, or sulphate-reducing conditions.

Table 5 – Average *in situ* measurements from the demonstration-scale CWTS.

Period		Water					Soil
		Temp (°C)	DO (mg/L)	Specific Conductivity (µS/cm)	pH	ORP (mV)	Redox (mV)
2015		12.9	10	817.9	8.11	147.9	-52
2016	Commissioning-A	10.2	15.9	890.9	7.79	143.7	-85
	Commissioning-B		8.4	1020	7.59	157.6	-89
2017	Commissioning-B	15.8	4.3	795.9	7.43	18.7	-162
	Operational period	9.7	5.3	879.7	7.36	124.9	-152
2018	Double stress test period	13.5	6.1	978.8	7.55	143.3	-176
	Operational period	9.8	7.9	990.1	7.45	143.1	-178
2019	5 Day HRT scenario	9.7	4.8	1093.7	7.24	122.7	-180
	2.5 Day HRT scenario	13.1	2.5	1052.0	7.18	87.4	-175
	1.2 Day HRT scenario	12.7	1.8	1083.6	7.34	-32.1	-153
	0.8 Day HRT scenario	10.6	2.7	1068.1	7.18	30.7	-159

DO – dissolved oxygen; ORP – oxidation-reduction potential.

6.2 Carbon Demand and Decomposition

6.2.1 Detritus Study

The detritus study initiated in 2017 was continued through 2019 to assess decomposition rates of *C. aquatilis* in the CWTS over time (Chimney and Pietro, 2006; Hammerly et al., 1989). Carbon cycles through a wetland by accumulation into the plants during photosynthesis, and release through plant decomposition (U.S. EPA, 2008). The rate of decomposition and nutrient release is dependent on many factors, such as plant type, HRT, and environmental conditions (U.S. EPA, 2008), and is therefore assessed through site-specific testing. The rate of decomposition is important in a CWTS to determine the amount of organic matter that will be broken down and become available as organic carbon, and the amount that will contribute to accretion. Accretion is the gradual accumulation of additional layers of organic matter, which aids in building new soils in the CWTS from undecomposed plant tissues. It is an important process in the CWTS as it buries treated minerals making them more stable and maintains low overall concentrations of metals.

The study began on June 21, 2017 when bags filled with oven dried *C. aquatilis* or polyester filter fiber material were submerged into each CWTS cell (Figure 4). Bags with both material were removed from each CWTS cell on specific sampling events up until July 2019 when the study was completed. This resulted in four replicate bags that were dried and weighed for each sampling date. Additional details describing the methods can be found in Appendix A.

In previous reports (Contango, 2017b; Contango, 2019) the amount of *C. aquatilis* decomposition was adjusted for the weighed amount of algae growth on the polyester filter fiber material. However, this adjustment was revisited in 2019 based on measurements of the polyester filter fiber material inferring that all plant material had decomposed, while visible plant material was still present in the bags. As such, results provided in this report for all years were not adjusted based on polyester filter fiber material weights (Figure 4, Figure 5, Appendix A).

The trials show that decomposition occurs quickly after *C. aquatilis* is submerged into the CWTS, with 38% decomposition occurring after 34 days. After 82 days, 48% of *C. aquatilis* had decomposed which represents decomposition that would be expected after one operational season of the CWTS (i.e., from spring to fall). After the first year, decomposition rates begin to plateau around 55% (average of last three time points) indicating that approximately 55% of plant material in the CWTS will decompose over 2 years. The plant material that decomposes provides organic carbon for microbes in the CWTS, while the plant matter that does not readily decompose (~45%) will contribute to accretion.

Figure 4 – Detritus study bags.
Left are mesh bags filled with *C. aquatilis* and polyester fiber fill stuffing in 2017, prior to submersion in the CWTS (June 21, 2017). Middle is a closed mesh bag, and right is an open mesh bag with decomposed *C. aquatilis* (left bag) and polyester fiber fill stuffing (right bag) on July 29, 2019 from cell 1A.

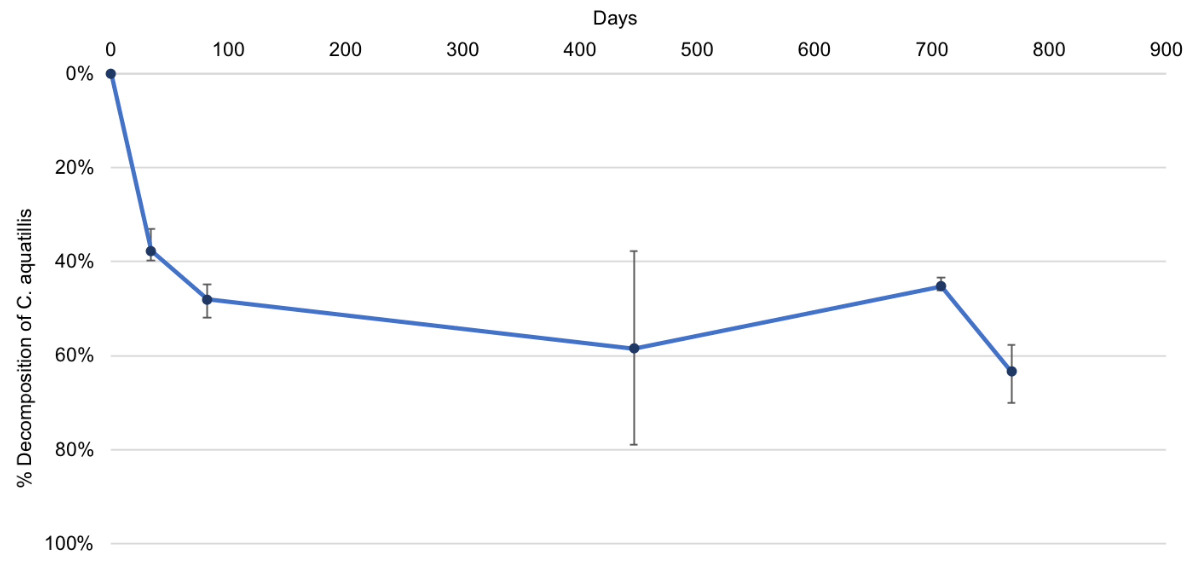


Figure 5 – *C. aquatilis* decomposition over time in the CWTS.
Decomposition was measured by the decrease in dry weight over time of the *C. aquatilis* samples compared to the initial weight. Error bars indicate the variation in results for each time point from multiple cells.

6.2.2 Available organic carbon

A 1 m^2 plot of above water *C. aquatilis* was harvested in 2018 and 2019 (Contango 2019, Appendix A, Section A7.7) to determine the amount of organic matter that is input into the wetland each year. The tests indicated that on average approximately 0.67 kg of dry weight above water *C. aquatilis* biomass is produced per year per square meter in the CWTS (0.80 and 0.54 kg/m^2 in 2018 and 2019, respectively). It is anticipated that annual *C. aquatilis* growth in the demonstration-scale CWTS will be similar to growth in a full-scale CWTS that is exposed to the same site conditions. This information is used in conjunction with the detritus study results to determine the amount of annual *C. aquatilis* biomass that will contribute to accretion and to available organic carbon.

While considering the multiple factors that can impact organic matter decomposition (Section 6.2.1), approximate carbon load into the CWTS was estimated for 2019 based on information available to date. The measured amount of total organic carbon in *C. aquatilis* is approximately 40%*,* meaning 40% of the dry weight is organic carbon. Additionally, the amount of decomposition in one operational season was approximately 48% (Section 6.2.1). Considering the load of oxygen, nitrate, and COC (cadmium, copper, molybdenum, selenium, and zinc) in the feed water requiring treatment over 2019, the amount of organic carbon needed to fuel treatment in Series 1 and 2 looks to be greater than what was supplied with yearly plant growth. The majority of this carbon demand is based on the nitrate load going to the CWTS at the higher flow rates through 2019.

Other sources of carbon in the wetland include straw that was added at the start of the commissioning period B in July 2016. Elevated dissolved organic carbon (DOC) concentrations were measured in the water after straw was added to the wetland, and have gradually decreased over time towards baseline DOC concentrations by the end of 2018. Measurements throughout 2019 were also at baseline DOC concentrations, indicating no excess carbon was available in the wetland. This is likely due to a combination of depleted available carbon in the straw from commissioning over time, as well as a higher carbon demand based on nitrate load going to the CWTS in 2019 with higher flow rates. In other words, the testing in 2019 has identified that the carbon demand for the CWTS may be greater than what is available through annual *C. aquatilis* growth when nitrate loads are high.

The carbon demand for the full-scale CWTS will be evaluated based on the expected nitrate load over time in closure, where nitrate concentrations are expected to decrease as the nitrogen-bearing residues of explosives used during mining are flushed from waste rock storage areas. Similarly, nitrate loads would be generally lower if there is any pre-treatment (e.g., pit lake treatment) before the CWTS. If additional carbon is needed in early phases of closure to accommodate higher nitrate loads, the full-scale CWTS could be supplemented with additional carbon through a forebay.

To further refine the full-scale CWTS design, it is recommended that in 2020 a forebay with organics be incorporated into the demonstration-scale CWTS to provide additional carbon for higher nitrate load removal. This testing will refine the amount and frequency of carbon addition that is required to reduce nitrate loads that may be encountered in the full-scale CWTS, and will refine the full-scale CWTS design. It is planned that the flow rate will remain constant in 2020, and a forebay system in the form of a tote with a carbon source will be incorporated upstream of the demonstration-scale CWTS. Bench- and pilot-scale *in situ* pit lake treatment testing is also planned for 2020 and 2021 and the results of these tests will contribute to the full-scale CWTS design.

6.3 Water

6.3.1 Summary of Performance During 2019 Operational Period

As discussed in Section 4.2.2, the flow rates in 2019 were faster than previous years to mimic HRTs expected for the full-scale CWTS. The higher flow rates in 2019 did not result in elevated levels of total concentrations at the outflow or erosion, except for cadmium. While total cadmium concentrations periodically were elevated during the fastest HRT, they remained an order of magnitude below the CCME guideline. Treatment performance was evaluated at different HRT scenarios by the decrease in COC concentration between the inflow and the outflow of each Series, the load of COC removed per day, and the percent removal of COC (Table 6). Treatment performance of nitrate is discussed in Section 6.3.1.1, copper, cadmium, and zinc are discussed in Section 6.3.1.2, and molybdenum and selenium are discussed in Section 6.3.1.3.

Another important factor for CWTS design is the rate of treatment, also known as the removal rate coefficient (RRC; k). The RRC is based on the treatability of a specific compound and the HRT of the CWTS, both of which are site-specific based on water chemistry, CWTS designs, and characteristics of the CWTS. The RRC is developed through site-specific testing and is used to refine future sizing and performance estimations of a full-scale CWTS. Information regarding calculation of RRCs can be found in previous reports (Contango, 2017b).

A RRC was calculated for all COC during the 2019 operational period (May 15 to September 4, 2019). Although nitrate is not a COC, a RRC was developed to evaluate full-scale CWTS sizing that would be required to remove nitrate before treatment of other COC would occur. There are two orders for a RRC: zero-order and first-order. Treatment with a zero-order removal rate is linear and is independent of concentration, whereas treatment with a first-order removal rate is exponential and proportional to concentration (a half-life type of reaction). Cadmium, copper, selenium, zinc, and nitrate were reported here with first-order RRC based on historical treatment kinetics (Contango, 2019). However, copper, selenium and nitrate did appear to follow a zero-order reaction kinetic at several instances in 2019, possibly due to increased flow rates and/or different treatment mechanisms ongoing in the CWTS (e.g., precipitation as metal (hydr)oxides, sorption, nutrient uptake). During higher flow periods (HRT >1.2 days) cadmium and zinc looked as though it was being removed through a zero-order reaction kinetic, likely due to the increased flow rates, and returned to the expected first-order reaction kinetic at HRTs <1.2 days. The zero-order RRC were therefore also calculated (not presented here) and can be used alongside RRC calculated through various operational testing periods of the demonstration-scale CWTS (Table 7) to evaluate different potential scenarios in the wetland (e.g., high nitrate load with or without carbon supplementation). The RRC for molybdenum has followed a zero-order kinetic throughout the operational period of the demonstration-scale CWTS.

Through subsequent sections, RRCs in the 2019 operational period for each COC and nitrate are discussed alongside other treatment performance metrics. RRCs were also compared to the average RRCs calculated from another pilot-scale copper study completed in the Yukon and were generally similar or better for cadmium, copper, and zinc (Table 7). RRCs developed from the Minto pilot-scale study are also presented in Table 7, however, they were developed using total concentrations of COC in a low nitrate scenario (0.86 mg/L nitrate as N) and are therefore not directly comparable to the RRCs developed from the demonstration-scale studies.

The performance limit (referred to as thermodynamic minimum in previous reports; Contango 2017b) was also evaluated and is the lowest concentration consistently achievable for a given treatment design and water chemistry. Once the performance limit is reached, making the CWTS bigger will not result in further decrease of outflow concentration. In 2019 the performance limit was met for cadmium only. In previous years, the performance limit for cadmium, copper (series 2 only), zinc, and nitrate (series 2 only), had also been achieved at a longer HRT of ~3.5 days. These results indicate that the full-scale CWTS could be larger if there is available space, to increase the HRT and treatment of COC.

Table 6 – Average inflow and outflow concentrations, percent and load removal of COC during the demonstration-scale CWTS operational periods.

COC (µg/L) (Dissolved)		2017	2018		2019							
		6.3 Day HRT	7.3 Day HRT		4.8 Day HRT		3.1 Day HRT		1.4 Day HRT		0.9 Day HRT	
		Avg Series 1 & 2	Series 1	Series 2	Series 1	Series 2	Series 1	Series 2	Series 1	Series 2	Series 1	Series 2
Cd	In	0.0261	0.0264	0.0264	0.0174	0.0174	0.0207	0.0207	0.0157	0.0157	0.0170	0.0170
	Out	0.0092	0.0050	0.0050	0.0050	0.0069	0.0070	0.0058	0.0067	0.0050	0.0099	0.0067
	% removal[1]	**66**	**81**	**81**	**71**	**61**	**66**	**72**	**58**	**68**	**42**	**61**
	Load removal (mg/day)	0.0332	0.0410	0.0310	0.0547	0.0337	0.103	0.0742	0.179	0.134	0.222	0.241
Cu	In	49.1	65.8	65.8	48.1	48.1	56.2	56.2	46.1	46.1	39.8	39.8
	Out	17.3	12.5	16.1	15.5	13.3	23.8	20.4	17.6	15.8	19.5	16.3
	% removal[2]	**65**	**81**	**76**	**68**	**72**	**58**	**64**	**62**	**66**	**51**	**59**
	Load removal (mg/day)	59.7	102	72	161	129	245	183	566	381	634	547
Mo[3]	In	6.3	10.5	10.5	7.56	7.56	7.16	7.16	6.27	6.27	7.37	7.37
	Out	2.7	2.38	3.48	6.36	7.01	6.71	7.09	5.66	5.94	6.50	6.79
	% removal	**57**	**77**	**67**	**21**	**12**	**6**	**5**	**10**	**6**	**12**	**8**
	Load removal (mg/day)	6.73	15.5	10.2	8.35	3.70	3.43	1.71	12.0	4.65	27.2	13.4
Se[4]	In	4.0	3.68	3.68	3.03	3.03	2.56	2.56	2.20	2.20	2.80	2.80
	Out	0.5	0.53	0.47	1.66	1.41	1.81	1.37	1.61	1.45	2.15	2.12
	% removal	**87**	**86**	**87**	**45**	**53**	**29**	**46**	**27**	**34**	**24**	**24**
	Load removal (mg/day)	6.36	6.00	4.63	6.91	6.13	5.64	6.07	11.7	9.36	20.8	15.8
Zn	In	49.2	17.3	17.3	11.2	11.2	20.3	20.3	13.0	13.0	7.43	7.43
	Out	1.9	1.23	1.15	2.85	1.75	1.77	1.30	3.30	1.38	2.87	2.40
	% removal[1]	**96**	**93**	**93**	**74**	**84**	**91**	**94**	**75**	**89**	**61**	**68**
	Load removal (mg/day)	85.3	30.6	23.3	32.4	27.1	140	96.8	193	146	142	117
NO_3 (mg/L)[5]	In	6.98	8.99	8.99	8.17	8.17	7.26	7.26	6.49	6.49	7.20	7.20
	Out	0.17	0.05	0.01	1.84	1.79	3.48	2.23	3.80	3.15	5.32	5.10
	% removal	**98**	**99**	**100**	**77**	**78**	**52**	**69**	**41**	**51**	**26**	**29**
	Load removal (mg/day)	12,549	17,096	12,993	30,961	23,509	28,565	26,021	53,421	41,887	57,870	48,836

% removal – percent load removal

[1] Percent load removal for Cd and Zn are artificially low in 2018 and 2019 due to several outflow concentrations below the detection limit.

[2] Extent of copper removal was influenced by higher copper concentrations in the soils.

[3] Mo concentration at outflow of B cell was typically within 20% method error of inflow in 2019. Percent and load removal have been estimated here, with instances of no treatment included in average as 0.

[4] Total Se concentrations were used in 2019 instead of dissolved Se as described in Appendix A. Instances of no treatment were included as 0 in average for % and load removal.

[5] Nitrate is not a COC, however removal is evaluated as it impacts treatment of other COC as described in Section 5.

Table 7 – Removal rate coefficients (k*day^{-1}) for dissolved COC during the 2017-2019 demonstration-scale CWTS operational periods compared to pilots-scale CWTS.

COC	Minto Pilot[1]	Other Yukon Cu Pilot	2017 Demonstration	2018 Demonstration		2019 Demonstration	
	Total COC		Avg Series 1&2	Series 1	Series 2	Series 1	Series 2
First order removal rate coefficients unless noted otherwise							
Cd	1.14	0.50	>0.52[2]	>0.42[2]	>0.41[2]	0.54	0.66
Cu	1.17	0.50	>0.31[3]	>0.22[3]	>0.35[3]	0.52	0.57
Mo (Zero)	0.101 (First)	N/A	0.0006	0.0011	0.0010	0.0005[6]	0.0003[6]
Se	0.0018 (Zero)	0.46	0.32	-[4]	0.29	0.20[5]	0.23[5]
Zn[7]	1.14	0.48	>0.51[2]	0.57	0.45	1.04	1.08
Nitrate[8]	0.56	N/A	0.59	-[4]	0.57	0.33	0.41

RRC – removal rate coefficient; N/A – RRC is not available.

[1] Values calculated from total concentration data in Contango, 2014b for *C. aquatilis* + moss design with low nitrogen scenario (0.86 mg/L nitrate as N). These RRC are therefore included for reference purposes only and are not directly comparable to other RRC reported here.

[2] Data for Cd or Zn had most sample points at the detection limit in 2017/2018, resulting in insufficient resolution and artificially low RRC for cadmium and zinc in 2017 and cadmium in 2018.

[3] RRCs for copper in demonstration-scale CWTS are artificially low due to copper leaching from soils used in construction of the system.

[4] RRC was not calculated for NO_3 and Se in Series 1 as described in Contango, 2019.

[5] RRC for selenium based on total concentrations instead of dissolved in 2019 as described in Appendix A.

[6] Mo concentration at outflow of B cell was typically within 20% method error of inflow in 2019. RRC have been estimated here, with instances of no treatment included as 0.

[7] Dissolved Zn concentrations used for RRC calculations in 2019 do not include data of low feed concentrations from August 21-September 5, 2019 as treatment is difficult to observe when feed concentrations are so low.

[8] Nitrate is not a COC, however removal is evaluated as it impacts treatment of other COC as described in Section 5.

6.3.1.1 Nitrate

Although nitrate is not a COC, removal is evaluated as it impacts treatment of other COC as described in Section 5. The concentration of nitrate in the feed to the demonstration-scale CWTS has remained relatively stable through the operational periods in 2017-2019 (~6.5-10.0 mg/L as N), other than a short lived spike up to ~20 mg/L as N in early 2018. The extent of treatment, percent removal, and RRC of nitrate in 2019 were lower than previous years (Table 6 andTable 7), likely due to insufficient carbon in the wetland to remove the high nitrate load in 2019 (Section 6.2). The demonstration-scale CWTS removed between 26-78% of nitrate in 2019, compared to 98-100% removal in previous operational years. However, despite insufficient carbon to remove the entire nitrate load in 2019, the demonstration-scale CWTS still removed 2-3 times more nitrate load per day (mg/day) than any previous operational year (Figure 6, Table 6).

The forebay testing with organics in 2020 will provide information on the extent of nitrate load removal that can be achieved with carbon supplementation. This information will be used to refine the design for the full-scale CWTS in closure based on nitrate treatment needs (Section 6.2.2).

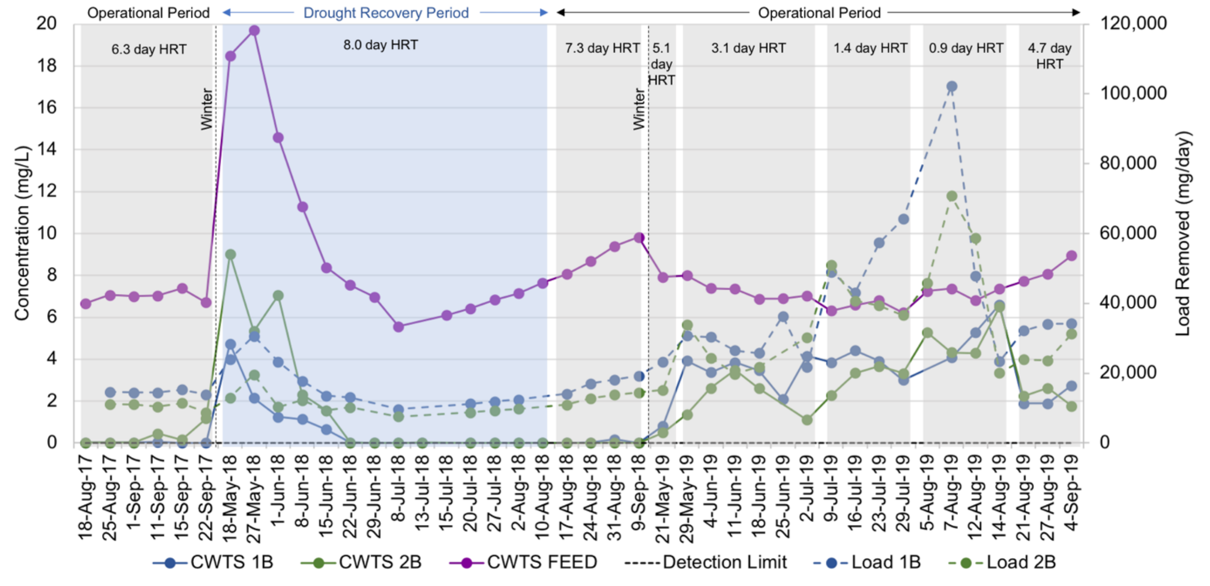


Figure 6 – Nitrate concentrations and load removed per day over the 2017 – 2019 operational periods.
Dissolved water concentrations are on the primary y-axis (solid lines) while load removed are on the secondary y-axis (dotted lines). Concentrations and load removed are based on outflow concentrations from each CWTS series. Operational periods are identified from 2017 through 2018 according to average HRT of Series 1 and 2. Blue shading corresponds to the drought recovery period of 2018. The ALS detection limit (DL; black dotted line on primary y-axis) for dissolved nitrate is 0.005 mg/L.

6.3.1.2 *Treatment of copper, cadmium, and zinc*

The concentrations of cadmium and copper going to the demonstration-scale CWTS has remained relatively stable through the operational periods in 2017-2019 (0.0157-0.0264 and 39.8-65.8 µg/L, respectively; Table 6). The concentration of zinc has gradually decreased over time from 49.2 µg/L in 2017 to 6.5 µg/L at the end of 2019. The outflow concentrations of cadmium, copper, and zinc have remained similar throughout the 2017-2019 operational periods (0.0050-0.0099, 12.5-23.8, 1.15-3.30 µg/L respectively) despite being operated at a range of HRTs (7.3 days to 0.9 days). The results from 2019 have highlighted that the demonstration-scale CWTS can consistently remove these COC at shorter HRTs (Table 6).

In 2019 the demonstration-scale CWTS removed higher loads per day (mg/day) of cadmium, copper, and zinc compared to any previous operational year (up to 0.241, 634, and 193 mg/day in 2019, respectively; Table 6; Figure 7-Figure 9). The percent removal of cadmium, copper, and zinc at HRTs > 0.9 days were comparable to percent removal in 2017 and 2018 (61-81, 62-81, and 74-96% removal respectively; Table 6). At the fastest HRT of 0.9 days, which represents the maximum flow rate through the currently proposed full-scale CWTS, the average percent removal was slightly lower than other HRT periods, however the overall load removed at this HRT remained higher than any other operational year. As the percent removal does not take into account the HRT of the system, a more holistic approach to characterizing treatment is the removal rate coefficients (RRC) which takes into account not only inflow and outflow concentrations but also HRT.

RRCs for cadmium, copper, and zinc in 2019 are similar or better to previous years, indicating they were unaffected by the shorter HRTs and less reducing conditions in the CWTS (>0.41-0.66, >0.31-0.57, and 0.45-1.08 per day, respectively; Table 7). It is noted, however, that RRCs for copper in the demonstration-scale CWTS in previous years were artificially low due to copper leaching from soils used in construction of the system (Contango, 2016a, 2017a, and 2017b; Section 6.4.1). Therefore, the treatment of copper occurring within the CWTS in commissioning and early operations was far greater than what was being observed by simply measuring the inflow and outflow points of the CWTS cells. Copper leaching from soils was confirmed to have subsided in 2019 based on no increases of copper in the water through the system from the feed to the outflow of the B cells (Figure 10; Section 6.4.1). Leaching of cadmium and zinc has also been monitored from 2015-2019 with no substantial leaching observed (Figures B1 to B4).

Similarly, RRCs for cadmium and zinc in 2017 and 2018 were artificially low as these COC were often treated to levels below the detection limit. At these low concentrations the effects of natural metal attenuation and release processes (i.e., sorption/desorption) are also more noticeable, in addition to decreased analytical precision at these low concentrations. RRCs for cadmium and zinc in the 2019 demonstration-scale CWTS had better resolution as higher flow rates resulted in measurable concentrations in the A cell outflow. There was however, a period of time from August 21 to the end of 2019 where the RRC for zinc could not be evaluated as zinc concentrations in the feed water were low.

The lowest consistently achievable concentrations (performance limit) was achieved only for cadmium in 2019. The performance limit for dissolved cadmium looked to be achieved after

1.5 days. This was determined by the concentration of dissolved cadmium having no statistical difference (as determined by a t-test and described in Appendix A of Contango 2017b) between the outflow of the A cell and the outflow of the B cell at a CWTS HRT of 3 days.

Given the lack of evidence for strongly reducing conditions within the CWTS in 2019 (Section 6.1), the removal of copper, cadmium, and zinc is likely through precipitation of metal (hydr)oxides and/or sorption, instead of the targeted treatment mechanism of sulphate-reduction. Should copper, cadmium, and/or zinc have sorbed on iron and/or manganese (oxyhdr)oxides within the CWTS, the development of more reducing conditions may result in their transient release as the host phases are dissolved under manganese- and iron-reducing conditions. However, they are not expected to be remobilized to a significant degree as the subsequent development of sulphate-reducing conditions would re-precipitate these metals as stable sulphide minerals within the CWTS. Furthermore, leaching of cadmium, copper, or zinc from soils was not promoted in less reducing conditions in 2019 suggesting these COC are stable in the soils. Thus, results in 2019 continued to demonstrate treatment performance when less reducing conditions were present due to insufficient carbon.

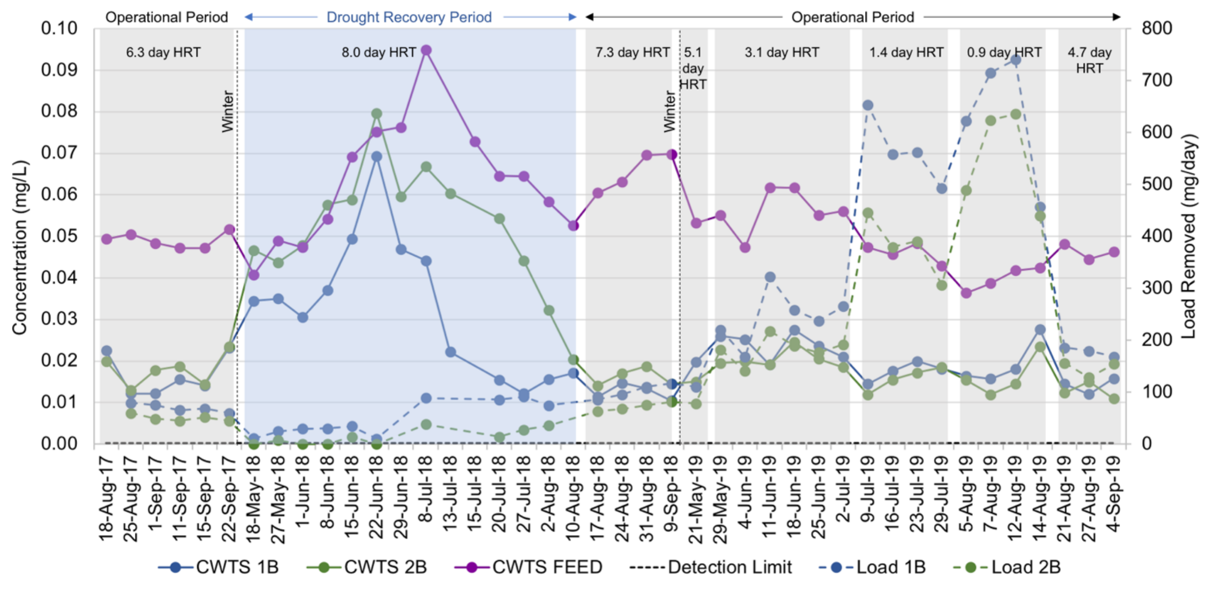


Figure 7 – Dissolved copper concentrations and load removed per day over the 2017 – 2019 operational periods.
Dissolved water concentrations are on the primary y-axis (solid line) while load removed are on the secondary y-axis (dotted lines). Concentrations and load removed are based on outflow concentrations from each CWTS series. Grey shading corresponds to operational periods in 2017, 2018, and 2019, with average of Series 1 and 2 HRT noted. Blue shading corresponds to the drought recovery period of 2018. The ALS detection limit (DL; black dotted line on primary y-axis) for dissolved copper is 0.0002 mg/L.

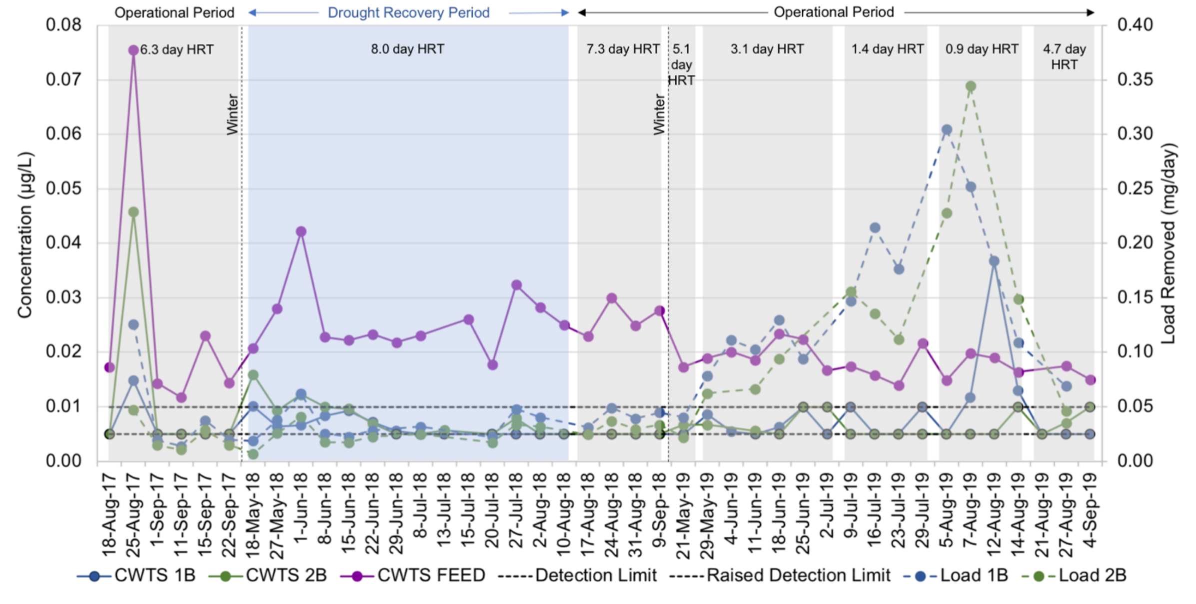


Figure 8 – Dissolved cadmium concentrations and load removed per day over the 2017 – 2019 operational periods.

Dissolved water concentrations are on the primary y-axis (solid lines) while load removed are on the secondary y-axis (dotted lines). Concentrations and load removed are based on outflow concentrations from each CWTS series. Operational periods are identified from 2017 through 2018 according to average HRT of Series 1 and 2. Blue shading corresponds to the drought recovery period of 2018. The ALS detection limit (DL; black dotted line on primary y-axis) for dissolved cadmium is 0.005 µg/L and on occasion was raised up to 0.01 µg/L. Elevated dissolved cadmium concentrations at the 1B location on August 12, 2019 also had elevated total concentrations and may have resulted from sampling.

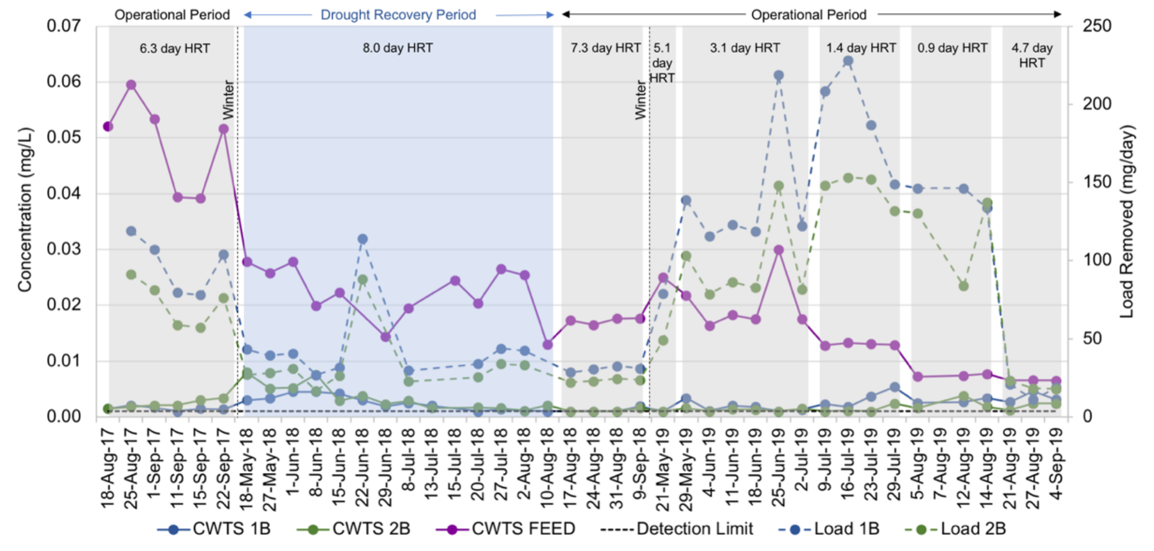


Figure 9 – Dissolved zinc concentrations and load removed per day over the 2017 – 2019 operational periods.

Dissolved water concentrations are on the primary y-axis (solid lines) while load removed are on the secondary y-axis (dotted lines). Concentrations and load removed are based on outflow concentrations from each CWTS series. Operational periods are identified from 2017 through 2018 according to average HRT of Series 1 and 2. Blue shading corresponds to the drought recovery period of 2018. The ALS detection limit (DL; black dotted line on primary y-axis) for dissolved zinc is 0.001 mg/L.

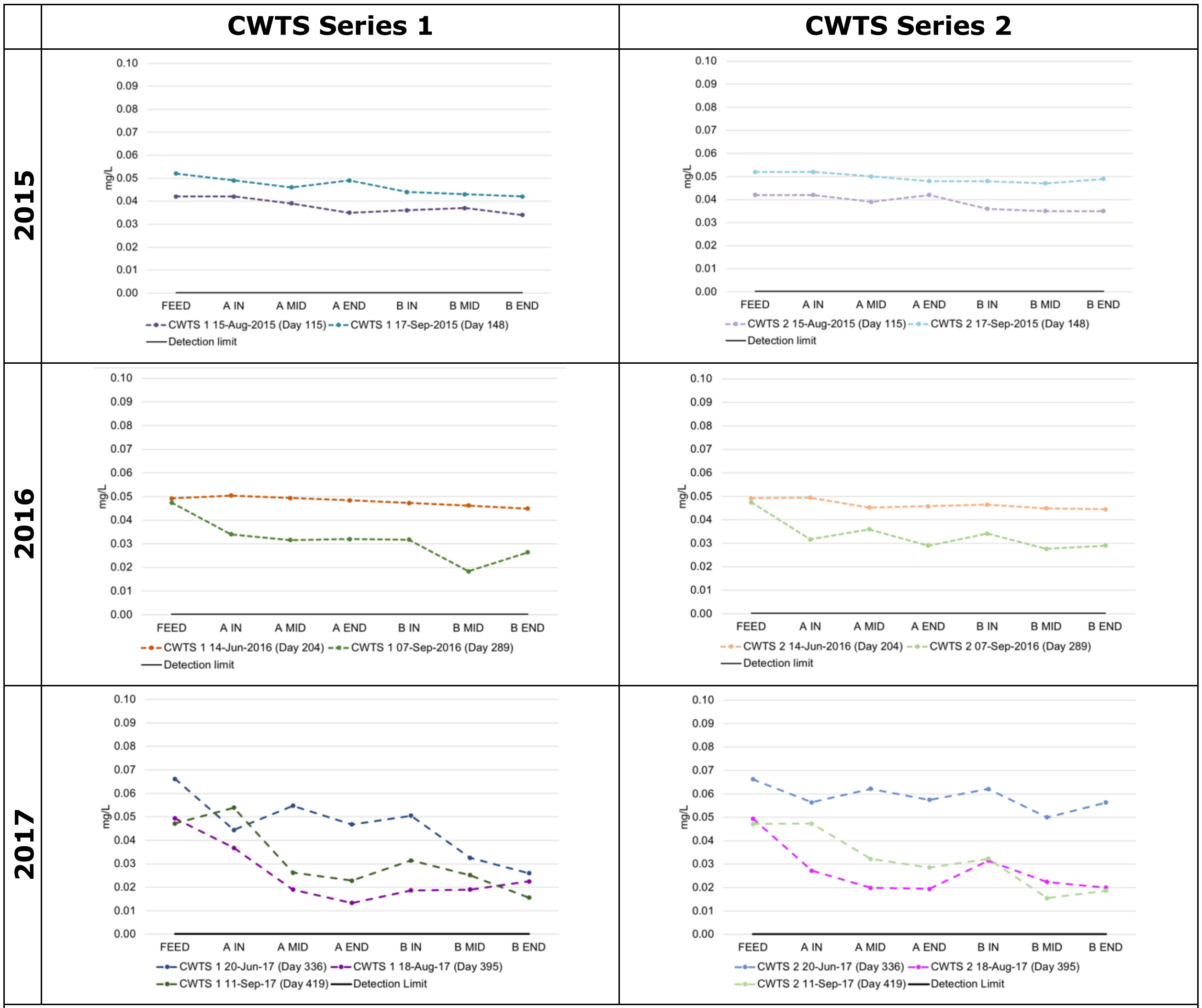


Figure 10 – Copper concentrations in water through the demonstration-scale CWTS.

Dissolved copper concentrations in water along the length of the CWTS in 2015 through 2019. The Maxxam (2015 results) and ALS (2016–2019 results) detection limit (DL; black line) for copper is 0.0002 mg/L. The HRT at end of the B cell varies with date in 2019 based on different HRT scenarios that were tested.

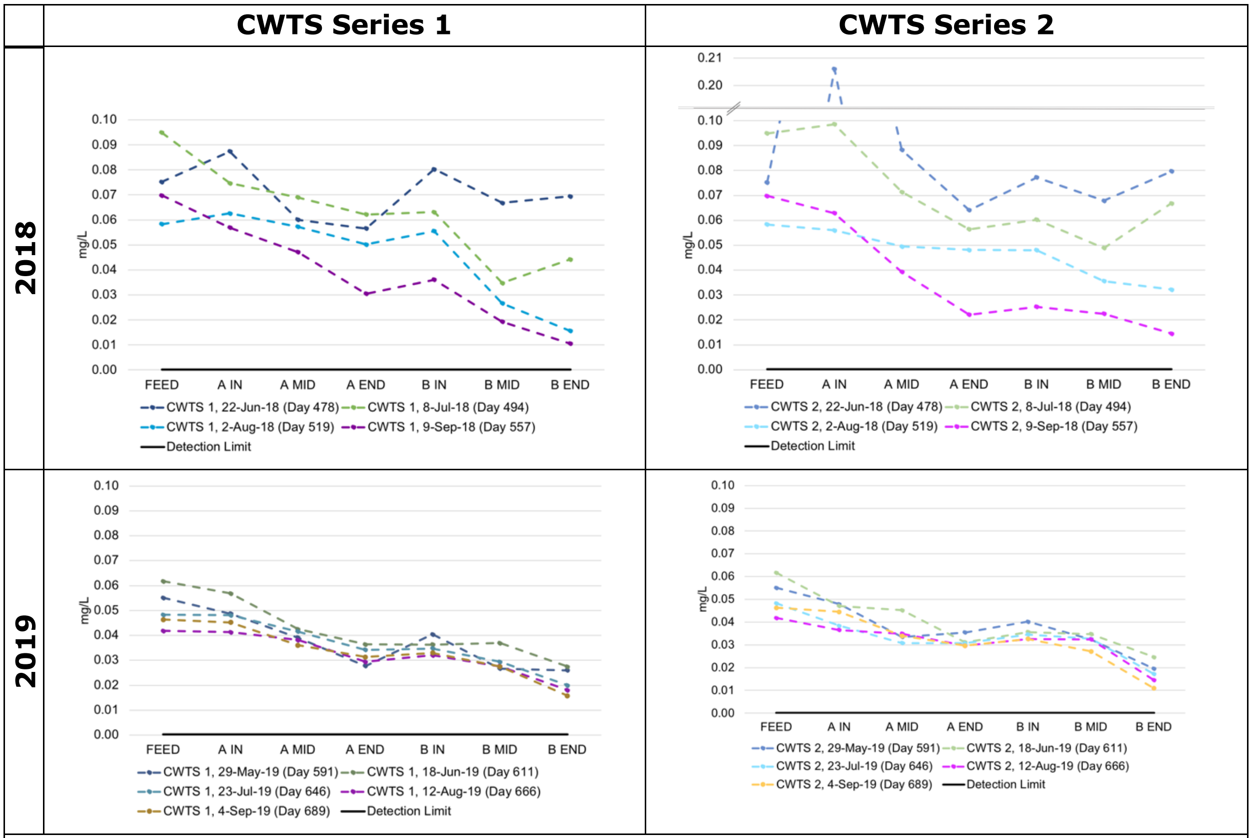


Figure 10 continued – Copper concentrations through the demonstration-scale CWTS.

Dissolved copper concentrations along the length of the CWTS in 2015 through 2019. The Maxxam (2015 results) and ALS (2016–2019 results) detection limit (DL; black line) for copper is 0.0002 mg/L. The HRT at end of the B cell varies with date in 2019 based on different HRT scenarios that were tested.

6.3.1.3 Treatment of molybdenum and selenium

The concentrations of molybdenum and selenium going to the demonstration-scale CWTS have remained relatively stable through the operational periods in 2017-2019 at 6.27-10.5 and 2.2-4.0 µg/L (Table 6). As noted in Section 6.3.1.1, the demonstration-scale system was likely carbon limited due to higher nitrate loads going to the CWTS. As a result, nitrate removal was impacted and since nitrate can interfere with treatment of molybdenum and selenium, the outflow concentrations of these COC did not get as low and the percent removal was lower in 2019 (5-21 and 24-53% removal, respectively) than in previous years (57-77 and 86-87% removal, respectively; Table 6, Figure 11, Figure 12). Despite being carbon limited, however, the overall load removed per day of molybdenum and selenium was higher than previous years (up to 27.2 and 20.8 load removed per day in 2019, respectively).

As discussed in Section 6.1 the most reducing stage likely achieved in 2019 was denitrification. Studies have shown that nitrate and selenate (oxidized selenium) can be co-reduced through a variety of mechanisms (selenate: Madhaiyan et al., 2009; Oremland et al., 1999; selenite: DeMoll-Decker & Macy, 1993). It is therefore possible that selenium treatment in 2019 was through sorption to mosses/detritus and potentially co-reduction with nitrate. Treatment of selenium is expected to improve with lower nitrate concentrations in the influent and/or sufficient carbon to remove the higher nitrate loads. Treatment of molybdenum is expected to improve in sulphate-reducing conditions as molybdenum is first reduced to Mo(IV) in sulphate-reducing conditions and then treated through dissimilatory sulphate reduction and co-precipitation with iron-sulphides

Treatment performance assessed by the RRC showed a decreased RRC for molybdenum compared to 2018 (0.0004 vs. 0.0010 per day, respectively), but was similar to the RRC developed for molybdenum in 2017 (0.0006 per day). Despite the lower percent removal of selenium in 2019 compared to 2018, the RRC for selenium only had a small decrease in 2019 (0.22 per day) from previous operational years (0.27-0.32 per day; Table 7). Although the RRC was calculated for selenium using a first-order reaction kinetic, a zero-order reaction kinetic could be applied to full-scale sizing calculations to determine the extent of removal (concentration (mg/L) achieved at the outflow of the CWTS) possible under less reducing conditions.

The lowest consistently achievable concentrations (performance limits) were not achieved for molybdenum or selenium in 2019, nor have they been achieved in previous operational years. The addition of carbon in 2020 will provide insight on the influence of carbon limitation on achieving a performance limit for these COC.

A forebay could act as a mitigation strategy during early closure, when nitrate concentrations are expected to increase the carbon demand required to reach sulphate reducing conditions (Section 6.2.2). The RRCs applied here are intended to be conservative estimates for conceptual sizing purposes and will need to be refined through information gathered from the demonstration-scale CWTS in 2020.

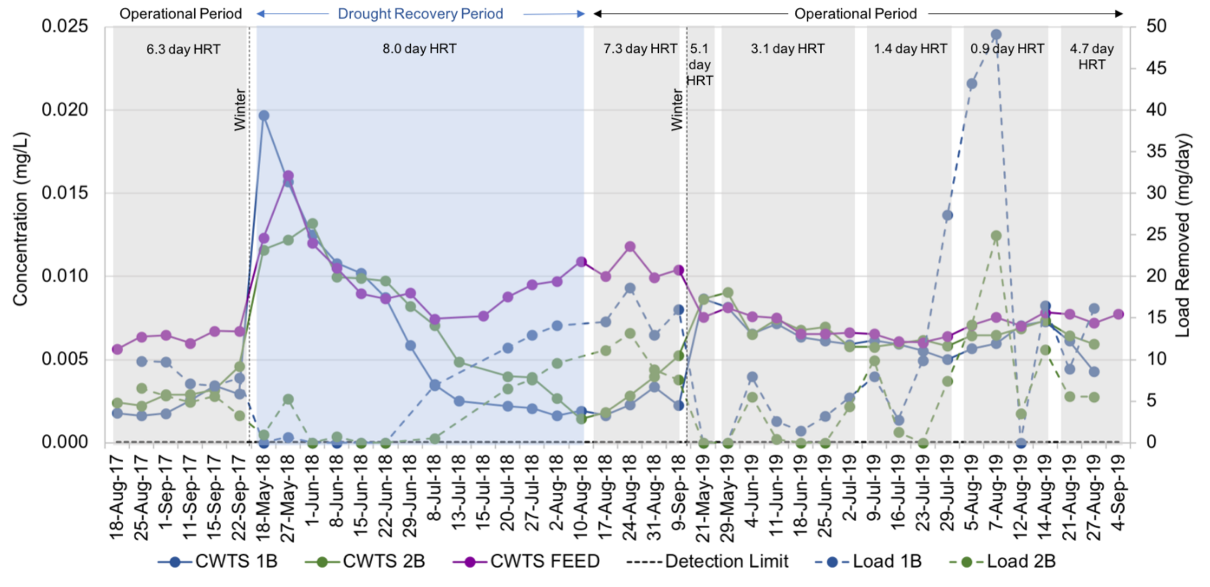


Figure 11 – Dissolved molybdenum concentrations and load removed per day over the 2017 – 2019 operational periods.

Dissolved water concentrations are on the primary y-axis (solid lines) while load removed are on the secondary y-axis (dotted lines). Concentrations and load removed are based on outflow concentrations from each CWTS series. Operational periods are identified from 2017 through 2018 according to average HRT of Series 1 and 2. Blue shading corresponds to the drought recovery period of 2018. The ALS detection limit (DL; black dotted line on primary y-axis) for dissolved molybdenum is 0.00005 mg/L.

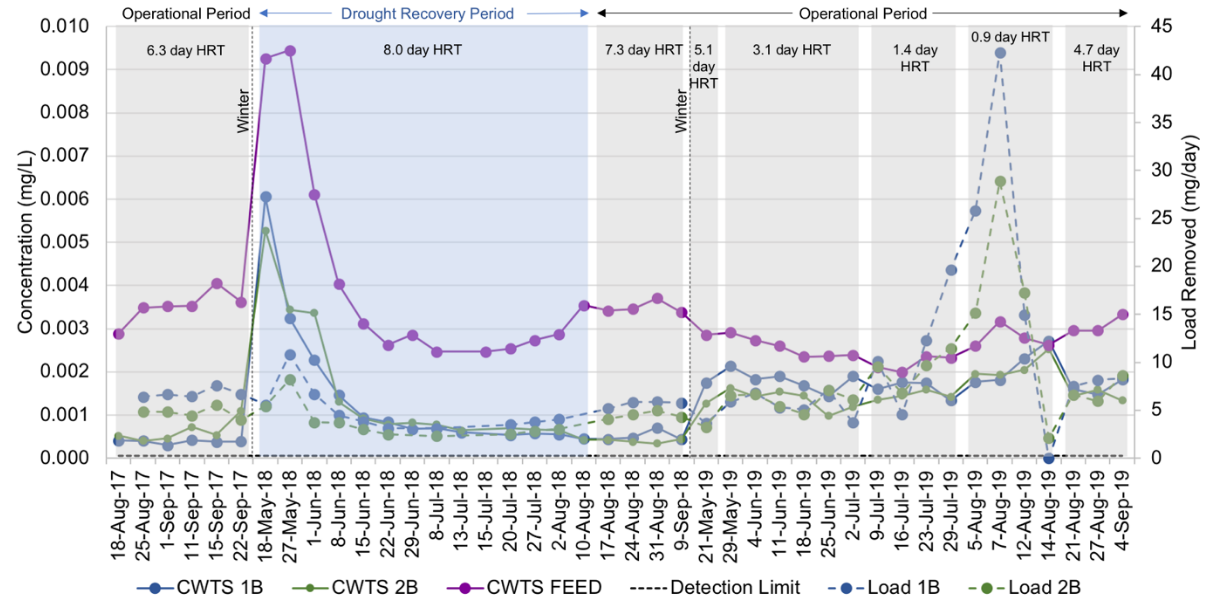


Figure 12 – Total selenium concentrations and load removed per day over the 2017 – 2019 operational periods.

Total water concentrations are on the primary y-axis (solid lines) while load removed are on the secondary y-axis (dotted lines). Concentrations and load removed are based on outflow concentrations from each CWTS series. Operational periods are identified from 2017 through 2018 according to average HRT of Series 1 and 2. Blue shading corresponds to the drought recovery period of 2018. The ALS detection limit (DL; black dotted line on primary y-axis) for total selenium is 0.00005 mg/L.

6.4 Fate and Distribution

6.4.1 Copper leaching from soils

Although unintentional, the high initial leachable copper concentrations in the CWTS soils allowed for additional testing to be carried out on the CWTS (Table B1, and B2, in Appendix B). When compared to 2016 and 2017 results, leachable copper concentrations in the substrate decreased in the CWTS through 2018 and remained low in 2019 (Contango, 2017a, 2017b, 2019), despite slightly less reducing conditions in 2019. Total copper concentrations in the soils remained within ranges previously measured. Additional soil sampling locations were tested in 2019 (near the inflow and mid-way of each cell) to confirm that copper leaching from the soils has stopped. Leachable copper was negligible at the mid-point and outflow of each cell and slightly higher but still low at the inflow of the CWTS. The full-scale system will be built with soil that will have low leachable copper. Additionally, iron could be supplemented in the soils during construction to promote excess acid volatile sulphides (AVS) which provides an additional treatment capacity and redox-buffer during low microbial sulphide production through exchangeable iron sulphide reserve (Section 6.4.3).

6.4.2 Mass balance

Mass balances were calculated for each CWTS series to assess the fate and distribution of COC removed from the water during the commissioning and operation of the demonstration-scale CWTS. Load of a COC retained in the system (difference between concentrations of COC entering and exiting the CWTS) and the concentrations of COC in moss, *C. aquatilis* leaves, and soil at the end of 2019 were evaluated (Appendix A). The percent of each COC load that was removed and retained in the plant and moss was calculated, and the percentage that was not retained in the plants is assumed to be within the soils, plant roots, detritus, and biofilms. The stability of COC in the soils was also assessed through sequential extraction analysis, with definitions of extractable fractions in Appendix B, Table B3 (Tessier et al., 1979). While the concentrations of COC in the top 10 cm of soil were measured in 2019, the load of COC removed by each series is less than the method error of the soils analysis due to the high initial COC concentrations in the soils used for construction. For example, the concentration of zinc in the initial soils for Series 1 is 67.8 mg/kg, which has a greater method error (+/- ~13 mg/kg) than the amount of zinc retained in the series.

The majority of copper entering the demonstration-scale CWTS during the operational period was treated and retained as desired. Sequential extraction analysis shows that despite elevated initial leachable copper concentrations, the soils have become more stable (less leachable) over time in the CWTS as the soils have aged, shifting from oxidized to reduced mineral forms (Contango, 2019; Appendix B, Figures B6, B7, and B8). This beneficial aging of soils to a less soluble mineralized sulphide form is expected for this type of anaerobic CWTS design (Contango, 2017b) and the distribution of copper in mineralized sulphide remained stable in the slightly less reducing conditions in 2019.

The other chalcophile COC (cadmium and zinc) entering the demonstration-scale CWTS were also treated and retained within the CWTS as desired. Cadmium concentrations in the CWTS soils are at or near detection limits for all fractions (Appendix B, Figures B11). Zinc mineral forms have been unchanged over time, with most of the constituent found in the reduced or mineral form (fraction 4 and 5; Appendix B, Figures B9 and B10). Selenium was at or near the detection limit for all fractions at the end of 2019 (Appendix B, Figures B13 and B14). Molybdenum was in the most stable residual mineral fraction 5, which contained around 40% of the total molybdenum in the samples (Appendix B, Figures B12).

Over time, constituents sorbed to mosses will form reduced minerals, rendering them less bioavailable. Mosses have long been known as metal accumulating organisms useful in remediation. Aquatic mosses are particularly useful to CWTS design as they have a high sorption capacity and contribute to both sulphide-producing conditions and accretion of soils. In contrast to macrophytes (e.g., *C. aquatilis*), mosses tend to trap large amounts of elements, both through sorption and filtration (Aldrich & Feng, 2000; Gstoettner & Fisher, 1997), and are a relatively benign sink for these elements. Subsequent to these transfer processes, the minerals can be transformed to stable insoluble minerals through reductive processes. Mosses also contribute significantly to CWTS substrate accretion and are conducive to the development of reducing conditions by serving as a carbon source. It should be noted that mosses are not generally a food source for invertebrates or higher animals and as such do not contribute greatly to bioaccumulation (Haines & Renwick, 2009; Longton, 1997; Suren & Winterbourn, 1991).

The fate and distribution of treated copper in the CWTS is difficult to assess due to the challenge of quantifying the amount of copper that leached from the soils which has contributed to the load of copper removed by the CWTS. Therefore the concentration of copper in *C. aquatilis* and moss were compared to previous years, and to the load of copper removed in 2019. Copper concentrations in *C. aquatilis* in 2019 were higher than 2018 concentrations, but within the range of concentrations reported in 2017 (Figure 13). The load of copper removed in 2019 by the CWTS was higher than any previous year, and ~2.5% of the load removed was taken up by *C. aquatilis.* Similarly, copper concentrations in moss were lower in 2019 than any previous year in Series 1 (265-396 mg/kg) and Cell 2A (166 mg/kg). Concentrations were higher in moss in Cell 2B (1800 mg/kg) at the end of 2019, however, these concentrations are within the range observed through previous years (Figure 13).

Cadmium concentrations entering and retained within the wetland throughout the demonstration-scale CWTS have been low. As such, the fate and distribution of retained cadmium could not be measured, with concentrations in *C. aquatilis* and moss continuing to be low in 2019 (0.023-0.043 mg/kg and 0.10-0.26 mg/kg, respectively; Figure B15, in Appendix B).

Uptake of molybdenum, selenium, and zinc by *C. aquatilis* and moss over the duration of the demonstration-scale CWTS was evaluated based on the overall load of each COC retained in the wetland over time compared to the concentration that was present in *C. aquatilis* and moss at the end of 2019. The uptake of these COC was low (< 2%) suggesting that these COC retained within the demonstration-scale CWTS are non-bioavailable as intended (Table 8).

In 2019 zinc concentrations in moss were lower than previous operational years (Figure B18, in Appendix B). Zinc concentrations in *C. aquatilis* in Series 1 remained similar to 2018 concentrations, while Series 2 experienced an increase in 2019 although was within trends from previous years despite the elevated load of COC removed by the CWTS in 2019 (Figure 13, Figure B18, in Appendix B). Selenium concentrations in *C. aquatilis* were generally similar in 2019 compared to 2018 (Figure B16, in Appendix B). In contrast, molybdenum concentrations in *C. aquatilis* decreased in 2019 compared to all previous years (Figure B17 in Appendix B). Lower selenium and molybdenum concentrations in moss were observed in the A cells in 2019 (Figure B16, B17, in Appendix B) and may be due to newly growing moss in cells 1A and 2A, while the concentrations have gradually increased in the B cells since constructing the demonstration scale CWTS in 2014.

Table 8 – Uptake of COC into *C. aquatilis* and moss throughout commissioning and operations.

COC	% Uptake into *C. aquatilis*		% Uptake into moss	
	Series 1	Series 2	Series 1	Series 2
Mo	0.55%	1.25%	0.88%	1.62%
Se	0.23%	0.55%	0.59%	0.90%
Zn	0.74%	0.73%	0.14%	0.37%

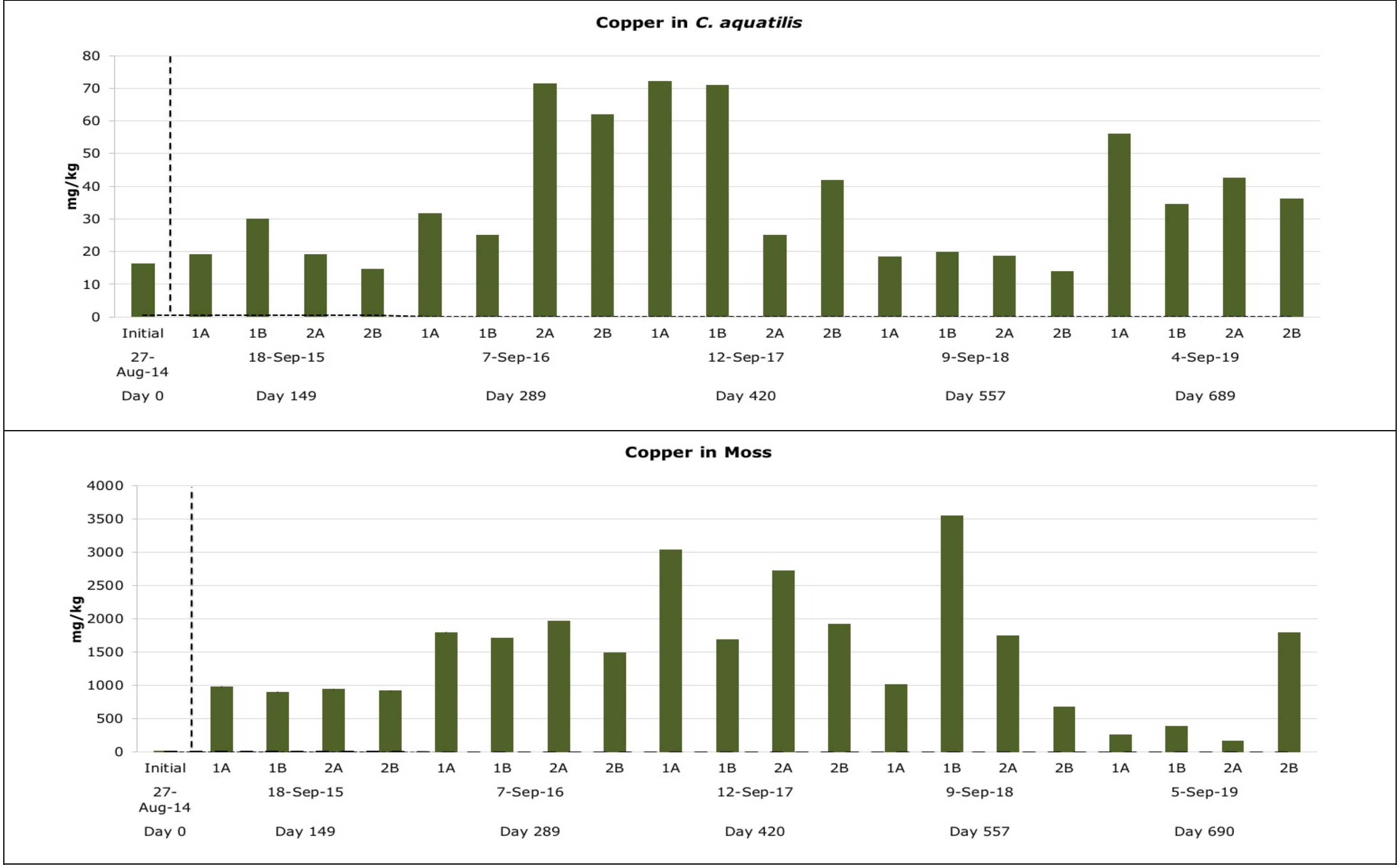


Figure 13 – Copper concentrations in plants.

The 2014 detection limit (DL; horizontal dotted line) for copper is 0.5 mg/kg, the 2015 DL is 0.050 mg/kg, and the 2016-2019 DL is 0.010 mg/kg. The initial timepoint is the average of the three *C. aquatilis* replicates at construction. The vertical dashed line separates the initial timepoint (following CWTS construction) and remaining timepoints that were harvested from the demonstration-scale CWTS.

6.4.3 Acid Volatile Sulphides

Additional treatment capacity can be stored in a CWTS through creation of a reserve of AVS (newly formed amorphous iron sulphides; Contango, 2017b). A strong AVS pool will provide redox buffering and continued metals treatment during periods with insufficient carbon or slower microbial activity (during the shoulder seasons). AVS can also serve as a buffer to oxidation should the soils of a reducing (sulphide producing) CWTS be exposed to oxygen (e.g., briefly drying out), thereby making sequestered metals less likely to re-solubilize. In the case of Minto, where the soils used in construction had excess copper, the appearance of measurable AVS would also indicate that the copper in the soils is nearing an endpoint of transformation to sulphide forms.

AVS has not been measured in desired concentrations in the demonstration-scale CWTS (small amounts measured in 2017 for the first time, as well as in 2018 and 2019; Contango, 2017b, Contango, 2019) as much of it was used to sequester total copper in the copper-rich soils. While small amounts of AVS were measured in 2019, the ratio of simultaneously extractable metals to AVS (ΣSEM:AVS) in all cells were greater than one, indicating there is no excess AVS present in the soil. This is not surprising as there were higher treatment demands in 2019 which resulted in insufficient carbon available to reach sulphide-producing conditions and subsequent formation of AVS. Addition of iron had also been initially planned in 2019 to improve AVS concentrations, however, based on priorities for testing the addition was delayed in order to focus on testing the CWTS at higher HRTs. The addition of iron will therefore be evaluated in 2020.

7. Health and Establishment of CWTS Vegetation

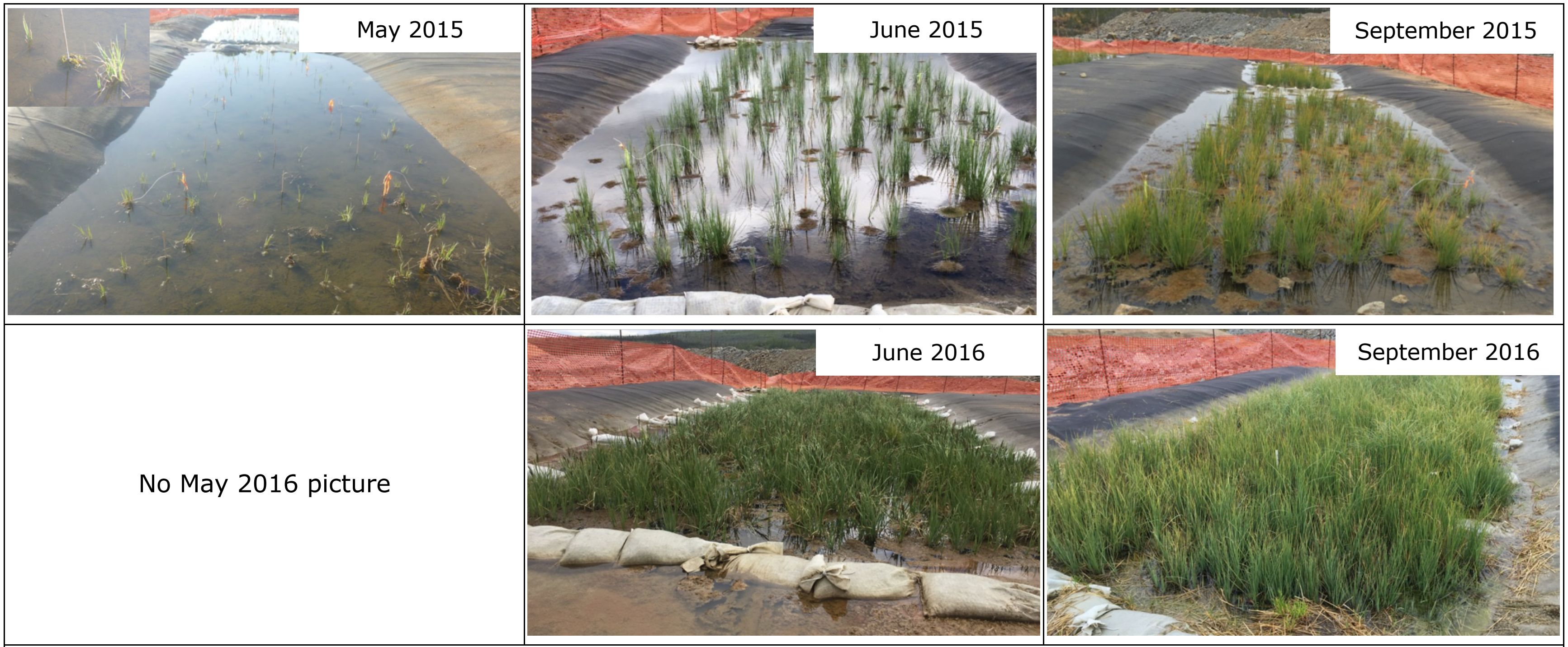
7.1 *Carex aquatilis*

Plants establish and mature over time, with density expected to increase over the commissioning period. From planting in 2014 up to July 2017, *C. aquatilis* thrived in the CWTS creating a dense emergent macrophyte monoculture, alongside aquatic mosses (Figure 14). However, an aphid infestation of the CWTS occurred in 2016 and 2017. Since the demonstration-scale CWTS is constructed of an emergent macrophyte monoculture of *C. aquatilis* in a relatively isolated area on the waste rock dump (i.e., located 50 m away from other vegetation and potential sources of insects), it is more susceptible to infestation by pests such as aphids (Dixon, 1971; Riley et al., 1995; Foottit and Maw, 1997; Contango, 2017b). Additionally, due to its isolated location the CWTS it is unlikely to attract predatory insects such as ladybugs, lacewings, and parasitic wasps to control aphid populations (Flint, 2001; Russel and Diaz, 2015; Finnamore, 1997; Contango, 2017b). While the demonstration-scale CWTS has experienced aphid infestations, this is not expected to occur in the full-scale CWTS and minimal insect control is expected to be needed (Rodgers et al., 2002). The full-scale CWTS will be built in an area with surrounding vegetation, thereby providing habitat for natural predators of aphids.

In July 2017, the aphid infestation affected the above water biomass of *C. aquatilis* (September 2017 and May 2018 photos in Figure 14; Contango, 2017b). While efforts were made in 2017 to control the population through application of pesticide (insecticidal soap), the ongoing spraying regimen was not maintained, and aphids remained. However, the plants continued to send out new shoots therefore suggesting that despite impacted vegetation, the *C. aquatilis* were resilient to the infestation. In 2018, *C. aquatilis* were replanted where vegetation was sparse. Additionally, stronger insecticidal soap (i.e. Trounce, End-All, or Bug-B-Gone) was applied biweekly or weekly to prevent or control aphid populations on *C. aquatilis* in 2018 (Contango, 2019). The CWTS was sprayed with pesticide every two weeks from May 14, 2018 to August 24, 2018 to prevent reoccurrence of the aphid infestation. The application was successful except for a small aphid population that appeared in cell 2A later in 2018, which was targeted with pesticide in August and September 2018. Bug-B-Gone was applied weekly or biweekly in 2019 and was effective at controlling aphid populations. Small isolated areas of aphid populations were observed in 1A and 2A on July 26 and August 27, 2019, respectively. However, these populations were quickly contained and/or eradicated with pesticide application. Routine pesticide application in 2020 is recommended on an as needed basis.

In 2018, the plants re-established in monoculture, and matured to densities visually similar to natural wetlands in the area (Figure 14; Figure 15), with the exception of cell 1A which was still recovering in 2018. The pre-existing mature plants in the CWTS re-established and matured in 2019 to densities similar to early 2017 (pre aphid infestation). However, some areas in the CWTS were still sparse in sections that were replanted in 2018 with plants slowly establishing. Aphid populations were controlled through 2019 with early and routine pesticide application (Table A1 in Appendix A).

Generally, the *C. aquatilis* has been successful in creating the desired conditions for water treatment, and the water chemistry and performance results of the 2019 operations (Section 6) confirm that *C. aquatilis* is a good candidate for use in the full-scale CWTS at Minto.



May 2015

June 2015

September 2015

No May 2016 picture

June 2016

September 2016

Figure 14 – Maturation of the CWTS from construction in August, 2014 and through operations (2017-2019).
2015 pictures show cell 2A. 2016 pictures show cell 1B.

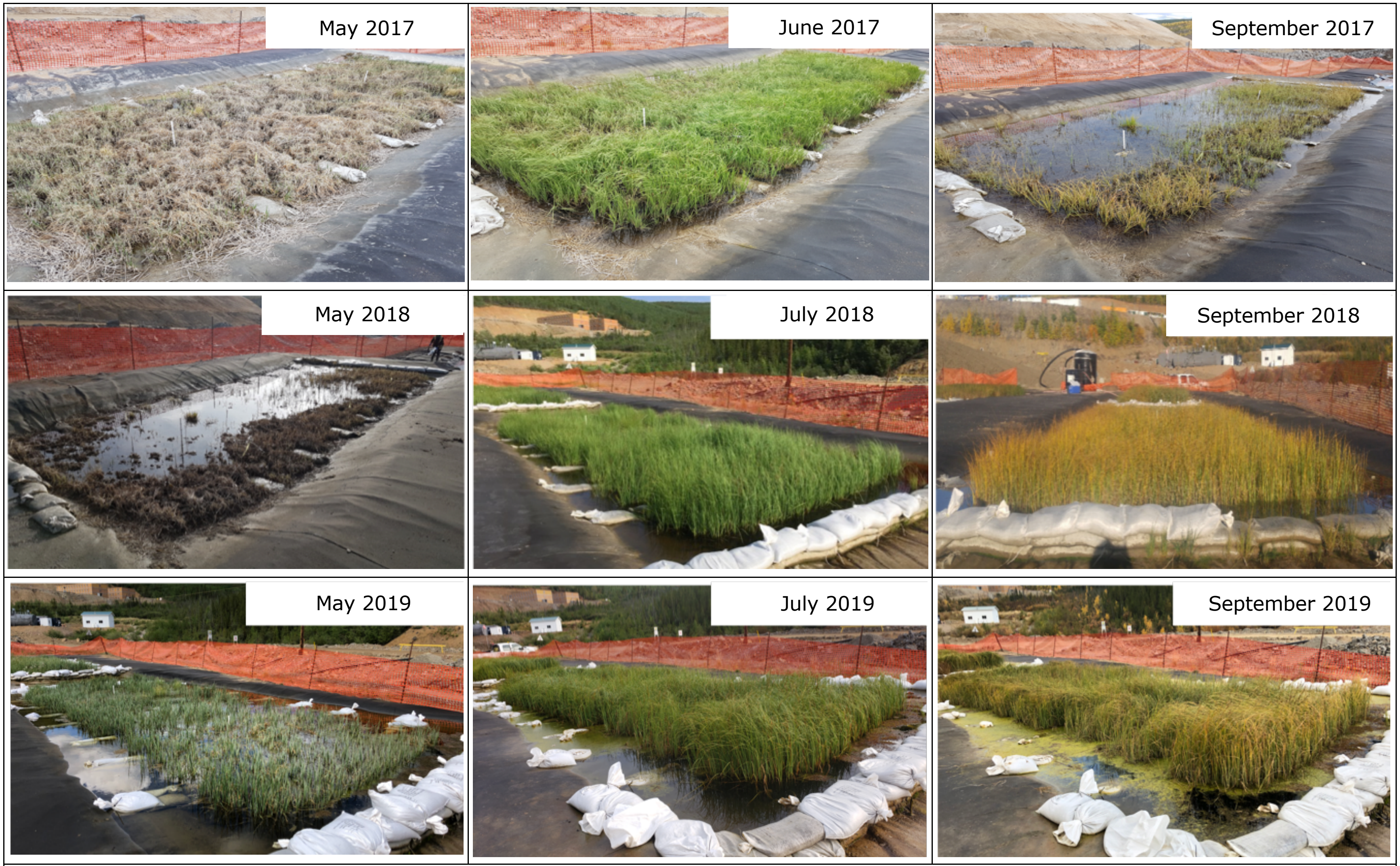

May 2017
June 2017
September 2017
May 2018
July 2018
September 2018
May 2019
July 2019
September 2019

Figure 15 – Maturation of the CWTS from construction through operations.
Pictures show cell 1B. September 12, 2017 shows increased yellowing and die off due to aphid infestation.

7.1 Moss

Aquatic mosses have continued to mature and grow from 2014 through 2019 (Contango, 2019). Lower abundance of moss in cell 1A was noted in 2018, and it was recommended that additional moss be added to the A cells in 2019. The lower amount of moss in the A cells may have been due to the addition of straw to the perimeter of the cells in 2016. The straw addition may have inhibited the growth of some of the moss in the A cells as double the amount of straw was added to the A cells compared to the B cells. Thus, moss was transplanted from W10 to cells 1A and 2A on May 30, 2019 in patches where moss was sparse. It was noted during the large September 2019 sampling event that moss within the A cells was still less abundant compared to the B cells, indicating time is needed for establishment. The mature mosses showed signs of successful transfer (sorption, filtration) and transformation (mineralization, reduction) processes such as new green biomass at the top of the moss and black decomposition at the bottom of the moss. The demonstration-scale testing has therefore continued to refine the process for full-scale implementation (which is the intent of the program), where straw would be added to a forebay rather than to an established CWTS cell, if additional carbon is needed. Thus, it is not expected that moss will need to be re-planted into a full-scale mature wetland, as straw would be added to a forebay.

8. Treatment Mechanisms

Specific types of bacteria have been evaluated in the soil, plant, roots, and detritus in the CWTS to inform treatment mechanisms that are occurring. Background information on the targeted treatment mechanisms and bacteria involved in these biogeochemical reactions is provided in Section 5. DNA testing can be used to identify all bacteria in a sample, along with their relative abundance as a percentage of the community, and diversity. The quantity of bacteria can be determined through growth-based testing. This type of community profiling allows for inferences to be made regarding community structures, functions, relatedness, and biodiversity of organisms in an environment, and helps in the understanding of how they change in response to environmental factors. Diversity in beneficial microbes is favourable and can be regarded as a measure of robustness to conduct a given biogeochemical function, as multiple different bacteria will be able to carry out the beneficial reaction under a wider range of conditions than a small diversity of bacteria could.

8.1.1 Denitrifying Bacteria

Nitrate is not a COC however it is being evaluated as described in Section 5.

As observed in previous years, denitrifying organisms were found associated with all sample types in the demonstration-scale CWTS (Figure B19 in Appendix B). There were slightly higher quantities of denitrifying bacteria associated with moss and detritus in the CWTS compared to the soil. Quantities have remained relatively similar from September 2018 to September 2019 (Figure B19 in Appendix B). The denitrifying bacterial population in the CWTS has demonstrated the capacity to remove higher nitrate loads through 2019. Denitrifying bacteria will be monitored at the end of 2020 for one of the CWTS series and compared with performance testing.

8.1.2 Selenium-reducing Bacteria

The targeted selenium treatment pathways in the Minto CWTS is described in Section 5.

As observed in previous years, selenium-reducing bacteria (SeRB) were found associated with all sample types in the demonstration-scale CWTS (Figure B20 in Appendix B). There were similar quantities of SeRB associated with soil, moss, and detritus in the CWTS in 2019. Inferred quantities have also remained stable from September 2018 to September 2019 (Appendix B), further supporting that the demonstration-scale CWTS has a beneficial bacterial population that is robust to changes in conditions.

8.1.3 Sulphide-producing Bacteria

Sulphide production is a key biogeochemical mechanism for water treatment as described in Section 5.

The inferred abundance of SPB in soils in 2019 remained stable and were within ranges observed in 2018 for detritus and soil, with an increase observed with moss samples (Figure B21 in Appendix B). The SPB populations therefore demonstrated resilience through the less reducing conditions observed in 2019 when the system was carbon limited. Diversity of SPB in all sample types (soil, roots, moss, and detritus) was also similar to 2018 (Table 9).

Table 9 – Number of different types of sulphide-producing bacteria in the demonstration-scale CWTS over time.

Sample Type	2014 & 2015	2016	2017	2018	2019
Detritus	NT	10	17	16	14
Moss	11	12	15	14	14
Root	11	14	14	15	16
Soil	12	17	18	17	14

NT – not tested. The average number of different types is based on the number of operational taxonomic units (clustered at 97% identity) that are classified as known sulphide-producing bacteria. Organism classifications and data analysis methods were updated based on available information in databases in 2018 (Contango, 2019).

The percentage of SPB in the populations associated with root and detritus were generally similar to 2018 (Figure 16 and Figure 17). The percentage of SPB with the soil and moss samples had some changes in 2019, where the B cells decreased slightly in the soil but increased with moss (Figure 18 and Figure 19). The types of SPB also continue to differ across sample types, with the soil having more *Clostridium* while roots, detritus, and moss have other types of SPB. This diversity across sample types provides robustness to the system as conditions change in the CWTS, as different types of bacteria have environmental preferences that drive their growth. An example of this robustness was observed with the SPB associated with *C. aquatilis* roots. In 2018, the percentage of SPB associated with *C. aquatilis* roots were initially lower potentially due to the initial drying out of the CWTS in the early spring/freshet; however, populations recovered by September of 2018 and have remained stable, indicating that the drying out of the CWTS did not have a long-term impact on SPB populations associated with *C. aquatilis* roots. However, there was a slight shift in the types of SPB that were associated with *C. aquatilis* roots in 2019. *Sulfurospirillum* has generally been the dominant SPB associated with roots in previous years, and this bacteria can grow in the presence of oxygen (facultative anaerobe or microaerophile). In 2019, *Sulfurospirillum* decreased and the SPB shifted to more anaerobic bacteria. This indicates that while less reducing conditions were experienced in the CWTS in 2019, there were still zones in the wetland that were reducing and could support sulphide-producing conditions should sufficient carbon be available to fuel the reaction.

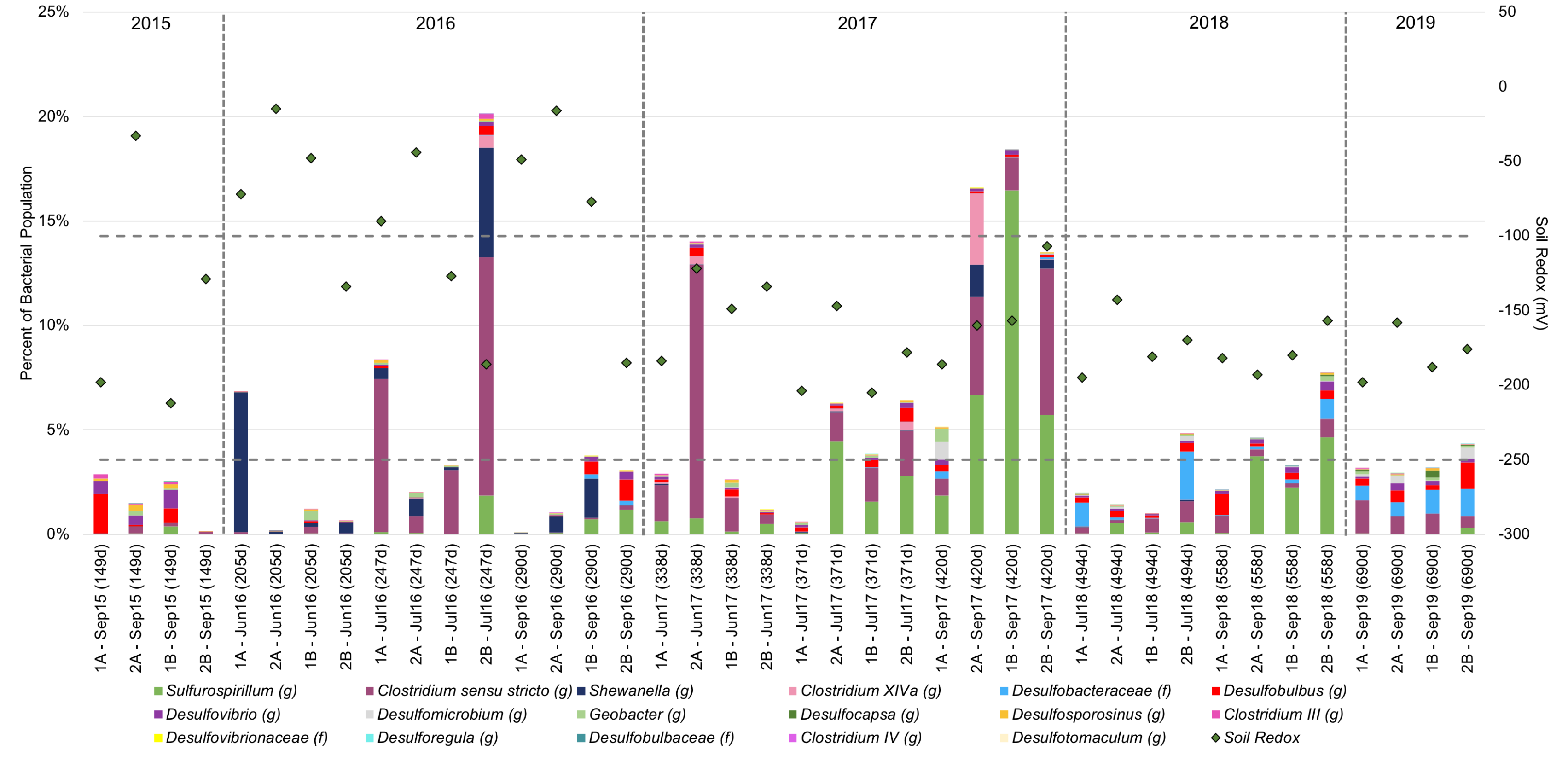


Figure 16 – Sulphide-producing bacteria associated with root alongside CWTS soil redox measurements. The primary y-axis provides the percentage of the bacterial population (relative abundance) that corresponds to sulphide-producing bacteria through the reduction of sulphate, sulphite, thiosulphate, and sulphur. The y-axis for root is different from other sample types as the percentage of sulphide-producing bacteria were much higher in many root samples. The secondary y-axis provides the soil redox measurements that were closest to the microbiology sampling date. Horizontal dashed lines indicate the targeted soil redox range. Percentage of bacteria is based on identification via genetic sequencing. Organisms are either classified to the genus (g) or family level (f).

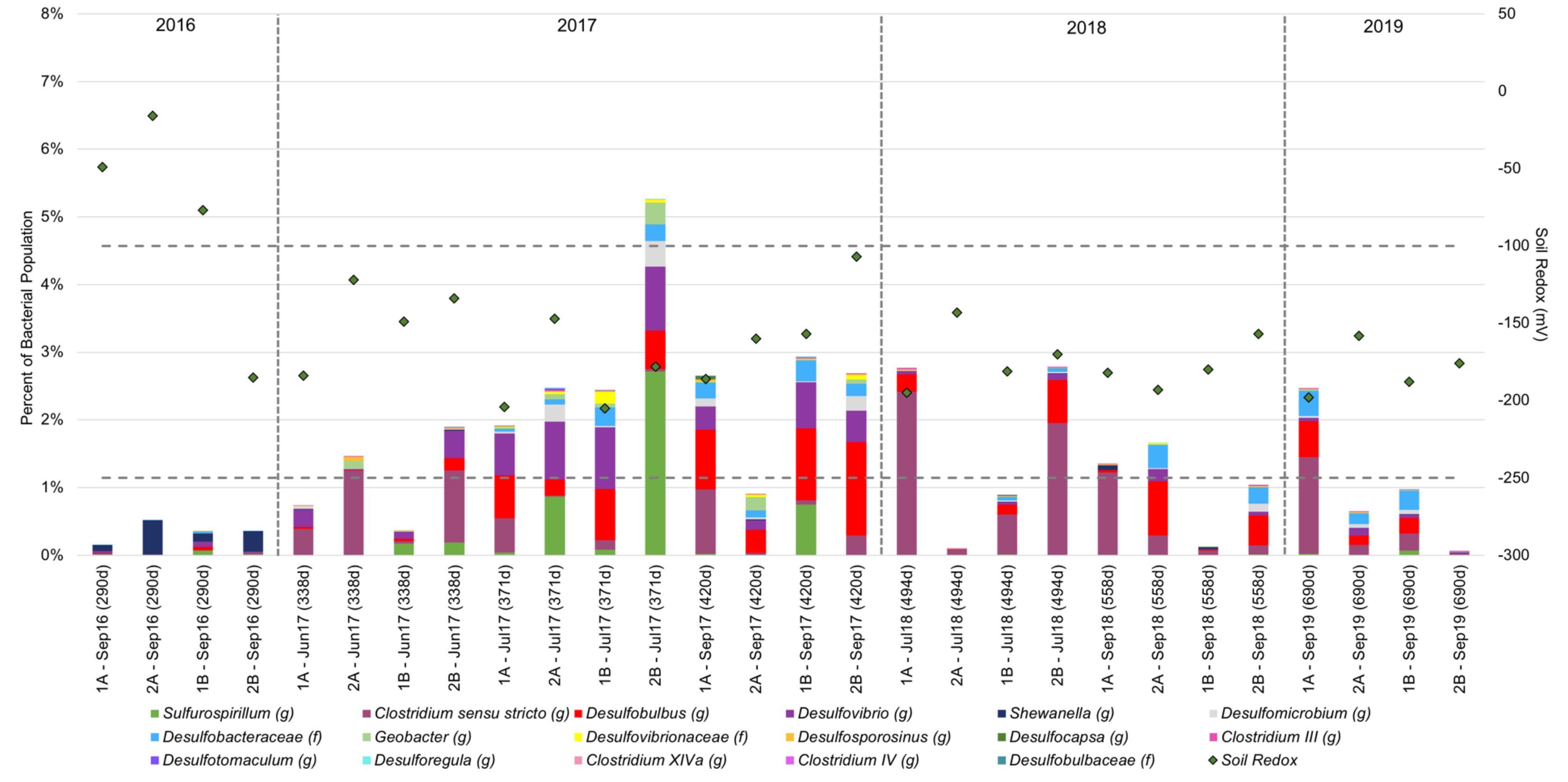


Figure 17 – Sulphide-producing bacteria associated with detritus alongside CWTS soil redox measurements. The primary y-axis provides the percentage of the bacterial population (relative abundance) that corresponds to sulphide-producing bacteria through the reduction of sulphate, sulphite, thiosulphate, and sulphur. The secondary y-axis provides the soil redox measurements that were closest to the microbiology sampling date. Horizontal dashed lines indicate the targeted soil redox range. Percentage of bacteria is based on identification via genetic sequencing. Organisms are either classified to the genus (g) or family level (f).

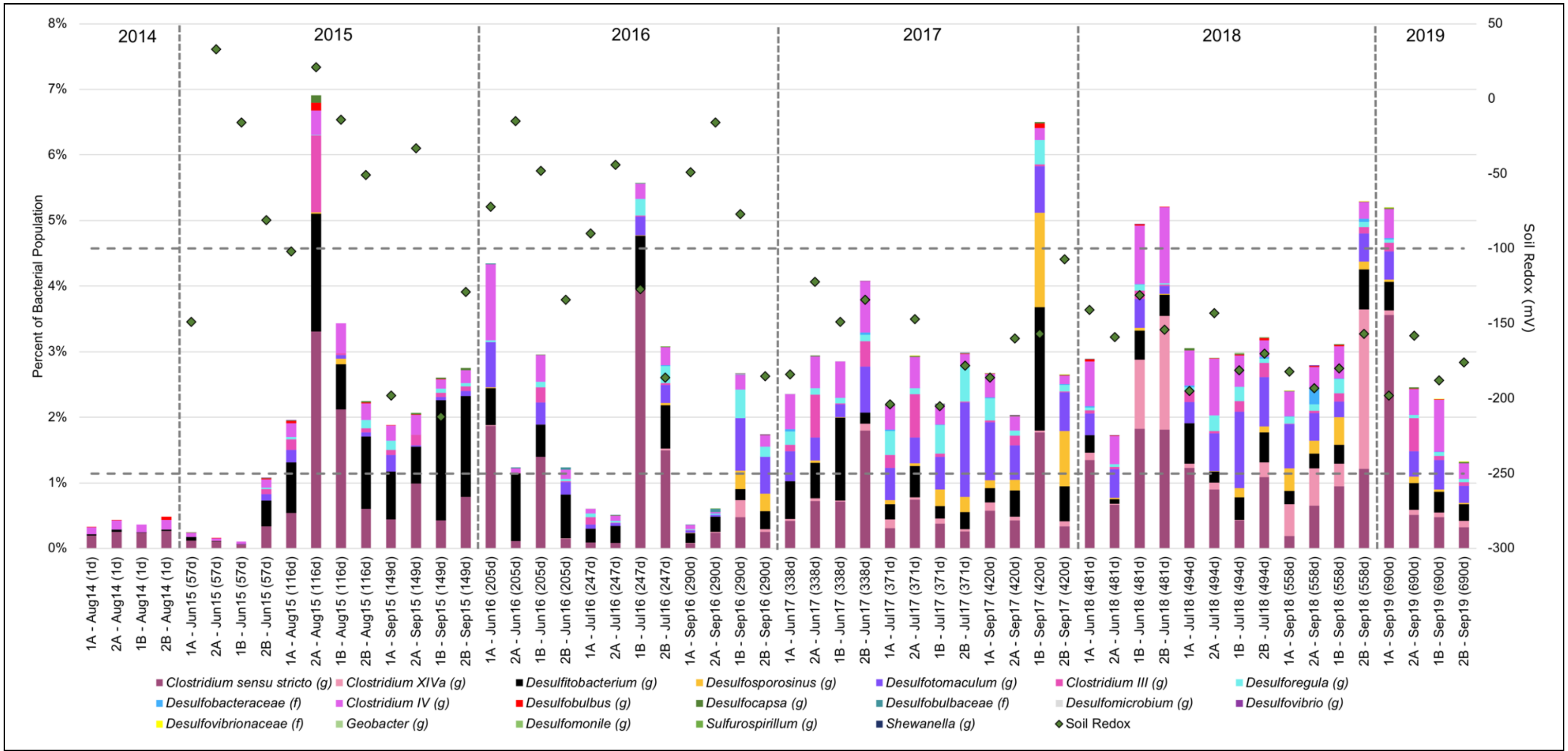


Figure 18 – Sulphide-producing bacteria associated with soil alongside CWTS soil redox measurements. The primary y-axis provides the percentage of the bacterial population (relative abundance) that corresponds to sulphide-producing bacteria through the reduction of sulphate, sulphite, thiosulphate, and sulphur. The secondary y-axis provides the soil redox measurements that were closest to the microbiology sampling date. Horizontal dashed lines indicate the targeted soil redox range. Percentage of bacteria is based on identification via genetic sequencing. Organisms are either classified to the genus (g) or family level (f).

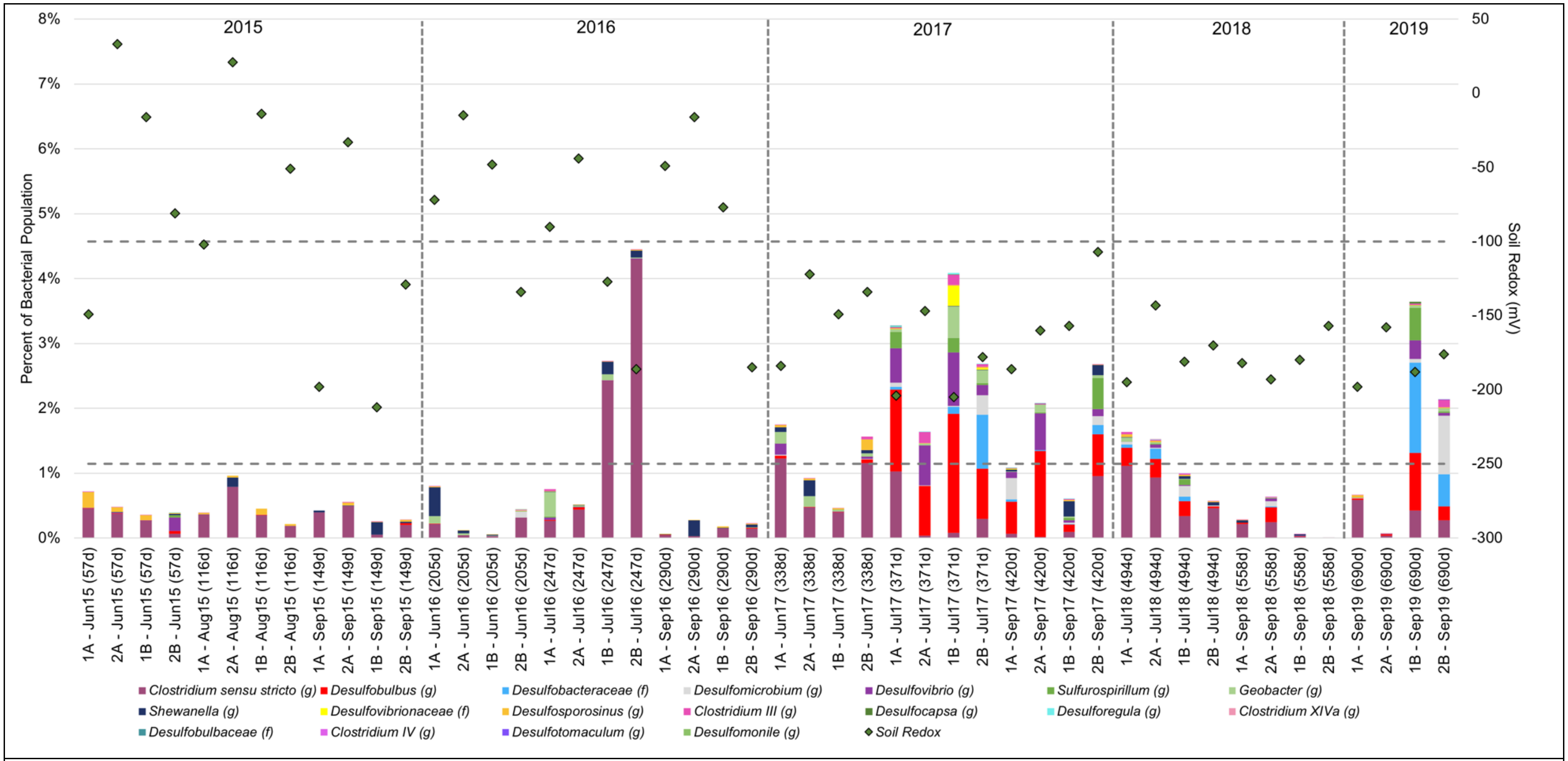


Figure 19 – Sulphide-producing bacteria associated with moss alongside CWTS soil redox measurements. The primary y-axis provides the percentage of the bacterial population (relative abundance) that corresponds to sulphide-producing bacteria through the reduction of sulphate, sulphite, thiosulphate, and sulphur. The secondary y-axis provides the soil redox measurements that were closest to the microbiology sampling date. Horizontal dashed lines indicate the targeted soil redox range. Percentage of bacteria is based on identification via genetic sequencing. Organisms are either classified to the genus (g) or family level (f).

9. Summary of Results

The overriding objective of the Minto Mine demonstration-scale CWTS program was to advance proof of concept and ultimately site design of a full-scale CWTS for the Minto Mine. The primary objective in 2019 was to assess performance under a wide range of conditions that mimic the full-scale CWTS. The demonstration-scale CWTS was able to operate under these conditions while successfully treating most COC and notably removing more load of COC than any previous year. Removal rate coefficients (RRC) have been developed throughout operations of the demonstration-scale CWTS which will be used to advance the design of a full-scale CWTS at the Mine. Additional sampling occurred at the end of the 2019 season to evaluate the fate and distribution of COC within the CWTS which indicated that COC were being retained within the demonstration-scale CWTS as intended. Key findings are outlined below from each section of the report.

9.1 Monitoring Explanatory Parameters

- Lower DO and ORP measurements were achieved in 2019, likely from improved placement of the YSI unit probe below the dense mats of vegetation that had developed as the CWTS matured, allowing for measurements to be taken at the base of the CWTS where treatment was occurring.
- Soil redox was unaffected by the increased flow rates in 2019, indicating that reducing conditions can be maintained in the substrate while flowing at rates expected for the full-scale CWTS.
- Redox-active metals, such as manganese and iron, showed no increases in dissolved concentrations in the water for most of 2019, indicating that sulphide reduction likely was not maintained likely due to a lack of carbon.

9.2 Carbon Demand and Decomposition

- Decomposition of *C. aquatilis* occurs quickly when initially submerged in the CWTS with 48% decomposition occurring in 82 days (1 operating season). Decomposition remains stable around 55% decomposition after 82 days throughout the 768 day study (including two winter seasons/freezing periods).
- The partial decomposition of *C. aquatilis* biomass from the previous year results in accumulation of organic matter over time (accretion) which is an important process in the CWTS as it buries treated minerals making them more stable.
- Testing in 2019 has identified that the carbon demand for the CWTS may be greater than what is available through annual *C. aquatilis* growth when nitrate loads are high. As high nitrate loads may be experienced during early closure, it is recommended a forebay be evaluated for the full-scale CWTS design for carbon supplementation.

9.3 Water

- Load removed per day of all COC was higher in 2019 compared to other operational years.
- The extent of removal (concentration (mg/L) achieved at the outflow of the CWTS) and removal rate coefficients of cadmium, copper, and zinc were similar to previous years despite less reducing conditions.
- Molybdenum and selenium (somewhat) treatment was impacted by the less reducing conditions and decreased nitrate removal in the CWTS.
- No leachable copper was observed in the water column in 2019.
- The lowest concentration consistently achievable for the treatment design (performance limit) appears to have been reached for dissolved cadmium after 1.5 days. However, the performance limit identification is challenging as cadmium consistently achieved low concentrations in the demonstration-scale CWTS, where greater variability (i.e., fluctuation) is expected with decreased analytical precision. Performance limits have historically been met for cadmium, copper, zinc, and nitrate, indicating the full-scale CWTS could be larger if there is available space.
- Removal rate coefficients developed throughout operations of the demonstration-scale CWTS will be used to advance the full-scale design. Increased flow rates allowed for better resolution of treatment kinetics for cadmium and zinc in 2019.

9.4 Fate and Distribution

- In 2019 leachable copper concentrations in soils remained low in the top 0-10 cm, while total copper concentrations were within ranges previously measured.
- Since commissioning, most constituents (including copper), have shifted primarily into stable reduced and residual minerals fractions in the soil.
- COC loads into the CWTS have been treated with minimal uptake by plant and moss.
- Acid volatile sulphides (AVS) was detected for the first time in 2017 and continued to be detected in 2019; however concentrations have remained low in 2019.

9.5 Health and Establishment of CWTS Vegetation

- An aphid infestation occurred in 2016 and 2017 likely due to the isolated location of the demonstration-scale CWTS. There was impact observed on the above water biomass in July 2017 due to aphids. Aphids were controlled through routine application of insecticidal soap and plants have predominantly recovered.
- Pesticide application is not expected to be needed in the full-scale CWTS as it will not be in an isolated location (Contango, 2017b).

9.6 Treatment Mechanisms

- A robust population of sulphide-producing, denitrifying, and selenium-reducing bacteria have been found associated with all sample types in the demonstration-scale CWTS, and quantities have remained stable despite less reducing conditions in 2019 than previous years.

- The denitrifying bacterial population has demonstrated the capacity to remove higher nitrate loads through 2019.

10. Recommendations and Next Steps for 2020

The 2019 demonstration-scale CWTS testing program showed an increased carbon demand on the wetland due to the high nitrate load. Testing in 2020 is therefore intended to inform design considerations for the full-scale CWTS in early closure, when higher nitrate loads may be experienced. An action plan for operating and testing the demonstration-scale CWTS in 2020 has been developed based on results observed to date. Key activities proposed in the action plan for 2020 include:

- Addition of a forebay (tote) with organics upstream of the demonstration-scale CWTS to provide additional carbon for higher nitrate load removal. This testing will refine the amount and frequency of carbon addition that is required to reduce nitrate loads that may be encountered in the full-scale CWTS, and will refine the full-scale CWTS design.
- Operate the CWTS at a HRT that mimics the full-scale system.
- Develop a sampling plan for monthly monitoring of the CWTS performance through 2020, which will include *in situ* YSI and soil redox, as well as analytical testing with ALS including but not limited to total and dissolved metals, nitrate, nitrite, sulphate, sulphide, and dissolved organic carbon.

Additionally, bench- and pilot-scale *in situ* pit lake treatment testing is also planned for 2020 and 2021 and the results of these tests will help contribute to the full-scale CWTS design for nitrate loads going to the CWTS.

11. Closure

We trust the information herein satisfies your present requirements. Should you have any questions, please contact the persons listed below. We appreciate the opportunity to provide the services detailed in this report, and look forward to discussing any comments you may have.

Regards,

Contango, an AEG company

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