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Minto Mine Reclamation and Closure Plan – Preliminary Design Report for Treatment Wetland

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MINTO MINE

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Executive Summary

Passive water treatment is desired in closure at the Minto Mine, with a focus on the constituents of cadmium (Cd), copper (Cu), and selenium (Se). To address this goal, a constructed wetland treatment system (CWTS) is being designed in a site-specific manner, through a phased approach.

This document outlines foundational scientific information used to select the passive water treatment technology and develop conceptual designs for the Minto Mine. This document then proceeds through to the preliminary CWTS design which is based on findings from phases that included: information gathering, site assessment, off-site pilot-scale testing, and preliminary on-site demonstration-scale confirmation and optimization.

This report specifically considers water treatment by a CWTS within the footprint of the water storage pond at the Minto Mine. The preliminary CWTS design described herein is a surface flow wetland, designed to create and maintain anaerobic conditions in the sediment to sequester cadmium and copper in sulphide mineral form, and selenium in a low bioavailable elemental form. The phased plan for site-specific design and optimization has demonstrated that these elements can be successfully and sustainably treated at the Minto Mine through passive treatment such as a CWTS. A CWTS of this type can be brought online effectively by having more rigorous monitoring and adjustments during an initial commissioning period, followed by progressive decreases in monitoring and maintenance requirements through early- and long-term operation. Conceptual monitoring and maintenance schedules are also described herein.

1. Introduction

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).

The purpose of this report is to describe the design considerations and conceptual monitoring and maintenance associated with a CWTS in the Water Storage Pond (WSP) area of the Minto Mine (Minto) in closure. The scope of this report resides with maintaining performance and treatment capacity, while engineering aspects to maintain hydrology (which in turn, is necessary for treatment) are addressed in Appendix A (SRK, 2016b).

2. Design

2.1. Treatment Technologies

Passive treatment systems are proposed as key mitigation measures for the achievement of acceptable water quality from the Minto site in the closure condition (Access, June 2013).

Passive treatment as a remediation method for mine-impacted water can be a sustainable method used during post-closure of a mine, as they generally involve significantly less direct capital costs, as well as lower operations and maintenance costs, when compared to traditional active treatment options (Kilbourn Inc., 1999).

A detailed review of the site-wide water balance confirmed that a significant portion of the mining impacted seepage, surface flow and contaminant load could be passively intercepted at a few specific areas which have sufficient space and topography for the incorporation of a wide variety of passive treatment systems (PTS) such as constructed wetland treatment systems (CWTS).

The various potential passive treatment technologies were evaluated and ranked in order to determine which passive treatment technologies held the greatest promise for incorporation in Minto water management and closure planning. A guidance document to help short list and then select an appropriate method for managing mine waste sites was created by The Interstate Technology and Regulatory Council (ITRC), a body of socio- economic and environmental regulators, industry, federal government, and stakeholders that work towards innovative environmental decision making (ITRC, 2010).

ITRC's "Mining Waste Treatment Technology Selection" guidance document (and associated literature reviews) is an interactive and iterative web-based decision tree which provides a systematic framework that can be used to identify a short list of appropriate technologies (ITRC, 2010). The ITRC decision tree framework was used for identifying the range of potential passive treatment technologies which may be applicable at the Minto Mine because it provides a straightforward and transparent method for selecting treatment technologies. It also provides legitimacy in the selection process by using an internationally recognized method that was created specifically for mining waste sites.

Following the identification of potential passive treatment technologies, a screening level evaluation and ranking of the potential passive treatment technologies was conducted. Some of the key considerations evaluating the various treatment technologies included:

- Work acceptably in cold weather;
- Sustainable in the long-term;
- Minimal/low intensity active maintenance scenario;
- Suitable for addressing Minto's specific constituents of potential concern (i.e., Cu, Cd, Se);
- Robust technology with adequate precedent of successful application;

- Amenable to collaboration with SFN and consistent with their aspirations for long-term employment and future land use;
- Cost effective; and
- Amenable to incorporation in an Adaptive Management Plan and modifying/expanding if initial design underperforms.

Based on key site-specific considerations, CWTS were deemed promising and were selected for further investigation at Minto. This report specifically considers water treatment by a CWTS within the footprint of the water storage pond.

2.2. Design Basis

PTS such as CWTS rely on transfers (e.g., sorption, filtration) and transformations (e.g., geochemical and biogeochemical reactions) to remove constituents from water (Haakensen et al., 2015; Rodgers and Castle, 2008). These processes require no or infrequent (periodic) electricity, amendment addition, substrate replacement, or flow management. Moreover, these processes can be targeted through specific design aspects, therefore identifying the desired processes and mechanisms to promote their activity and enhance their robustness promotion forms the foundation of the design basis of a CWTS.

Once CWTS have undergone commissioning, they can be relatively self-sustaining, operationally passive (or remotely operated), with minimal periodic maintenance or management required (e.g., addition of sources of carbon), and therefore can provide effective low-cost water treatment in remote environments. This, coupled with the ability to work in the absence of power or the need for active management, suggests that PTS are suitable as a component of a long-term solution to post-closure management of mine-influenced water quality.

The following sections discuss treatment mechanisms for constituents of concern at the Minto Mine.

2.2.1. Transfers

Some of the simplest treatment mechanisms within a CWTS are transfers. These include sorption and filtration, which are not greatly affected by the temperature of the water. While facilitating treatment in colder temperatures, the transfer sites need to be renewed as they are only present in a finite abundance. Transfer sites are renewed by the vegetation, which aids filtration (by submerged vegetation and aquatic roots), and provides sorption sites (on live and decomposing vegetation). Transfer sites are particularly abundant in aquatic mosses. Aquatic plants were selected for the Minto CWTS based on being obligate wetland plants, with a high generation of organic matter, and ideally being peat forming. Such plants were identified at the Minto site during the 2013 CWTS site assessment, with *Carex aquatilis* (known as Aquatic Sedge or Water Sedge) and aquatic bryophytes (aquatic mosses, capable of growing fully submerged in water) being selected as the most promising candidates, (Contango, March 2014) and confirmed through off-site pilot-scale testing (Contango, November 2014).

However, once the constituents have been transferred from one location (water) to another (soils, vegetation) within the wetland, they still need to be transformed to a more stable and less bioavailable form, otherwise known as a coupled biogeochemical reaction. As the CWTS design aspects associated with transfers are fairly generic, the remainder of the design basis was formed around the biogeochemical transformations needed for long-term treatment and sequestration of constituents.

2.2.2. Transformations

Transformations in a CWTS are largely governed by biogeochemical reactions are catalyzed by microbes. Specific microbes (and therefore biogeochemical pathways) can be encouraged through the environmental conditions created by the design of a CWTS. For example, metals can be removed from water by forming insoluble compounds with sulphides. These sulphides are generated by bacteria (sulphide-producing bacteria) that use organic carbon sources (e.g., wood chips, plant matter, methanol) to reduce sulphate in the water under specific oxidation-reduction conditions (Figure 1 and Table 1). This mechanism can be used to treat multiple metals, however, some metals and metalloids will be more readily removed than others as a sulphide mineral, while others can be directly treated through oxidation or reductive processes (Table 1). Therefore, the constituents targeted for treatment at the Minto mine (cadmium, copper, and selenium) are individually addressed in the sections below.

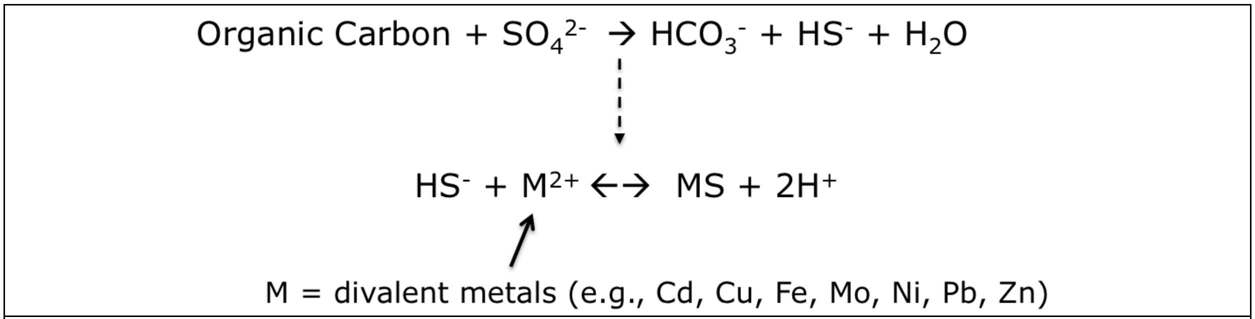

Figure 1 – Example equation of sulphate reduction and metals treatment.
The equation is not balanced and varies based on carbon source and pH. The equation shows the creation of alkalinity (HCO_3^-) and sulphides (HS^-), the latter which can then form insoluble metal sulphide complexes.

Table 1 – ORP values for various biochemical reactions.

Biochemical Reaction	ORP (mV)
Nitrification	+100 to +350
cBOD degradation with free molecular oxygen	+50 to +250
Biological phosphorus removal	+25 to +250
Denitrification	+50 to -50
Selenium reduction	-50 to -200
Sulphide formation	-50 to -250
Biological phosphorus release	-100 to -250
Acid formation (fermentation)	-100 to -225
Methane production	-175 to -400
Adapted from Gerardi, 2010.	

2.2.3. Copper treatment mechanisms

Copper treatment can be achieved in several ways, through oxidizing or reducing geochemical and biogeochemical reactions. When treated from water under appropriately designed reducing conditions, copper will form insoluble copper sulphides (Figure 1, Figure 2 and Figure 3). In contrast, in oxidizing conditions, copper can be removed from water as insoluble hydroxides, carbonates, or iron and manganese oxides (Figure 2).

Several copper treatment mechanisms can occur abiotically (i.e., geochemical reaction) given the right conditions and constituents in water (e.g., oxidizing and co-precipitation with iron). In contrast, formation of copper sulphides is generally biologically driven. It requires the production of sulphides by microbes under anaerobic (i.e., depleted dissolved oxygen) and reducing conditions (-50 to -250 mV; Table 1), with a carbon source to sustain the reaction. Although literature provides a range of -50 to -250mV for sulphate reduction, pilot-scale testing for the Minto CWTS, indicated the site-specific targeted soil redox is between -100 and -250 mV.

Within a CWTS, copper can be removed by both oxidizing and reducing conditions, oxidizing associated with actively growing aquatic mosses, and reduction associated with sediments and decaying mosses. These processes are often coupled, such that the long-term sequestration of the copper in the CWTS is as a copper sulphide. Some forms of mineralized copper are more stable and resistant to resolubilization, and the stability of these minerals is reflected by a K_{sp} value (Table 2 and Table 3). Generally, the minerals that have been catalyzed by microbiological activity cannot spontaneously resolubilize under conditions periodically encountered in CWTS. Additionally, the CWTS forms other minerals, such as amorphous FeS which serves as a buffer to re-oxidation of minerals such as copper sulphides (Table 2). For these reasons, reductive mineralization of copper sulphides was chosen as the preferred treatment pathway for copper in this CWTS.

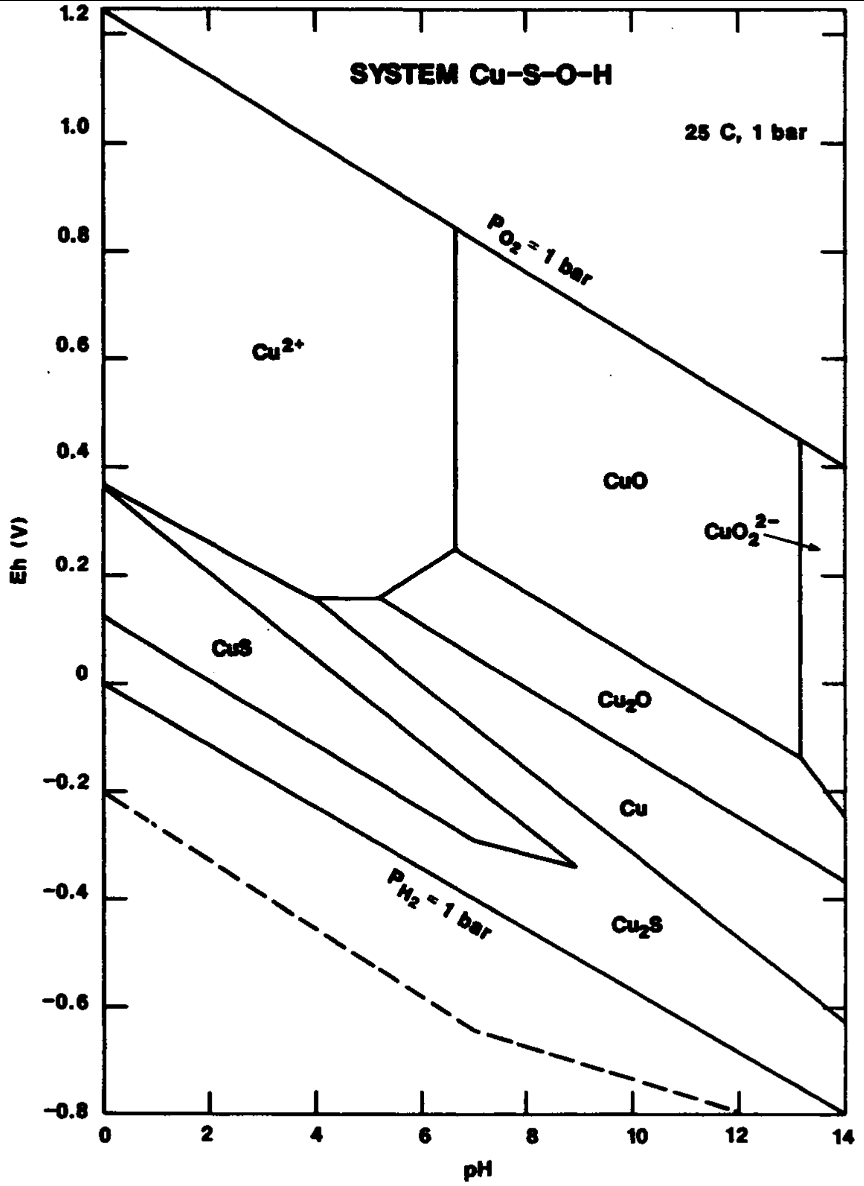

Figure 2 – Eh-pH diagram for part of the system Cu-S-O-H.
See Table 3 for thermodynamic data (Brookins 1988).

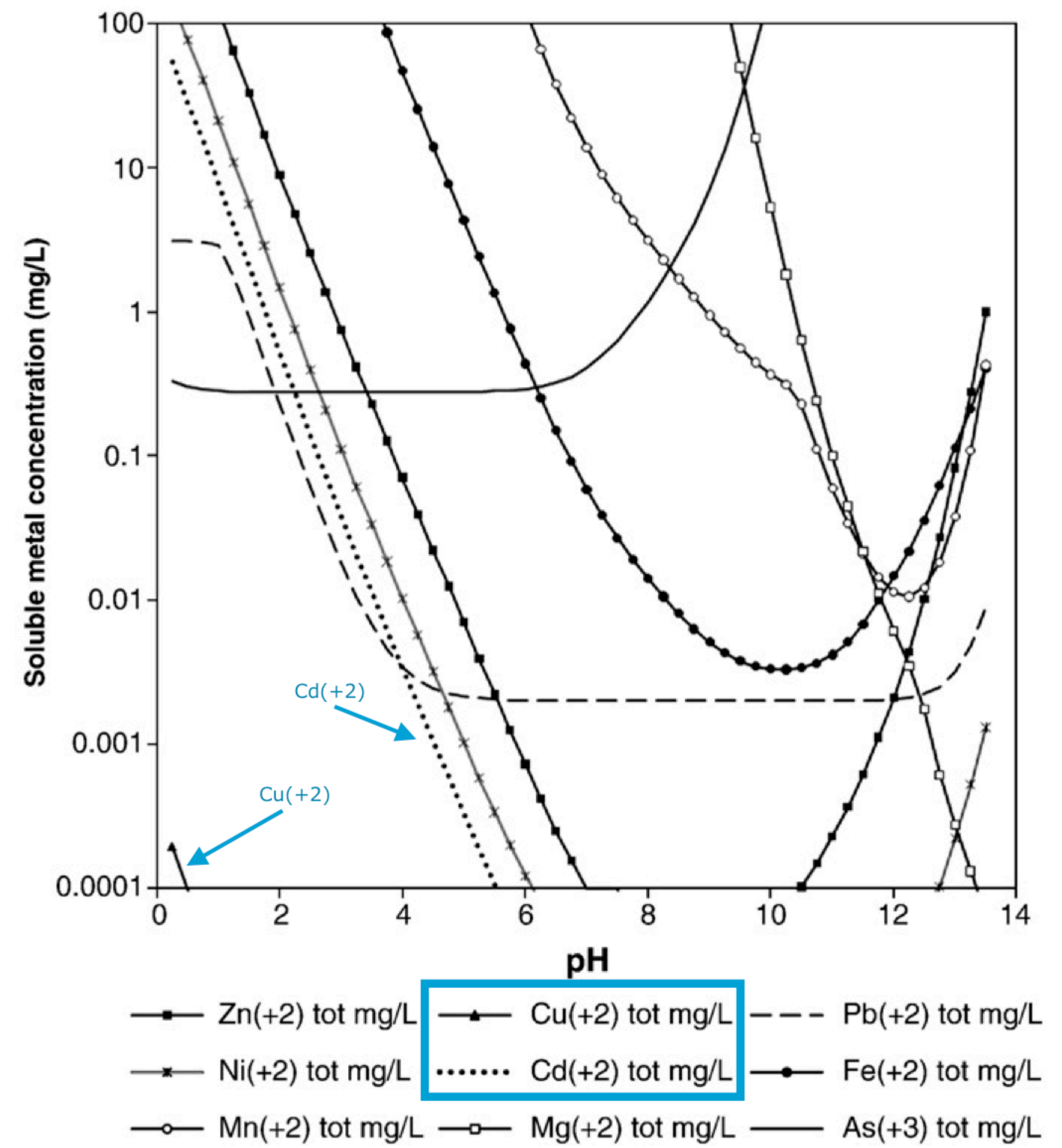

Figure 3 – pH dependence of metal sulphide solubility.
Copper- and cadmium-sulphide solubility indicated with blue arrows and box. Adapted from Lewis (2010).

Table 2 – Solubility of sulphide minerals.

Metal Sulphide	**Log K_{sp} [1]**
CdS	-25.8
CuS	-36.1
Cu_2S	-47.7
FeS	-18.1

[1] Solubility product (K_{sp}). Table adapted from Jackson (1986).

Table 3 – Thermodynamic data for copper.

Species State	**ΔG^0_f(kcal/gfw)**
$Cu_{(c)}$	0.00
$Cu^{+}_{(aq)}$	+11.94
$Cu^{2+}_{(aq)}$	+15.65
$Cu_2S_{(c)}$	-20.60
$CuS_{(c)}$	-12.81
$Cu_2O_{(c)}$	-34.98
$CuO_{(c)}$	-31.00
$CuO_{2\,(aq)}^{2-}$	-43.88
$Cu_2(CO_3)(OH)_{2\ (c)}$	-213.58
$Cu_3(CO_3)_2(OH)_{2\ (c)}$	-314.29

Adapted from Brookins, 1988; aq – aqueous (dissolved/soluble), c – crystalline (solid).

2.2.4. Cadmium treatment mechanisms

Passive treatment mechanisms for cadmium are the same as copper, with precipitation as sulphides, hydroxides, carbonates, and iron and manganese oxides as means for removal depending on water chemistry and conditions (Figure 1, Figure 3, Figure 4, and Table 4). Both sulphides and iron and manganese oxides will achieve the ultralow concentrations desired for the Minto CWTS. Based on site-specific considerations and water chemistry at the Minto Mine, cadmium treatment is targeted to be removed in the most stable and low-bioavailable form, and therefore will be removed by the same mechanism as copper, by precipitation as a metal sulphide (cadmium sulphide, CdS; Table 2).

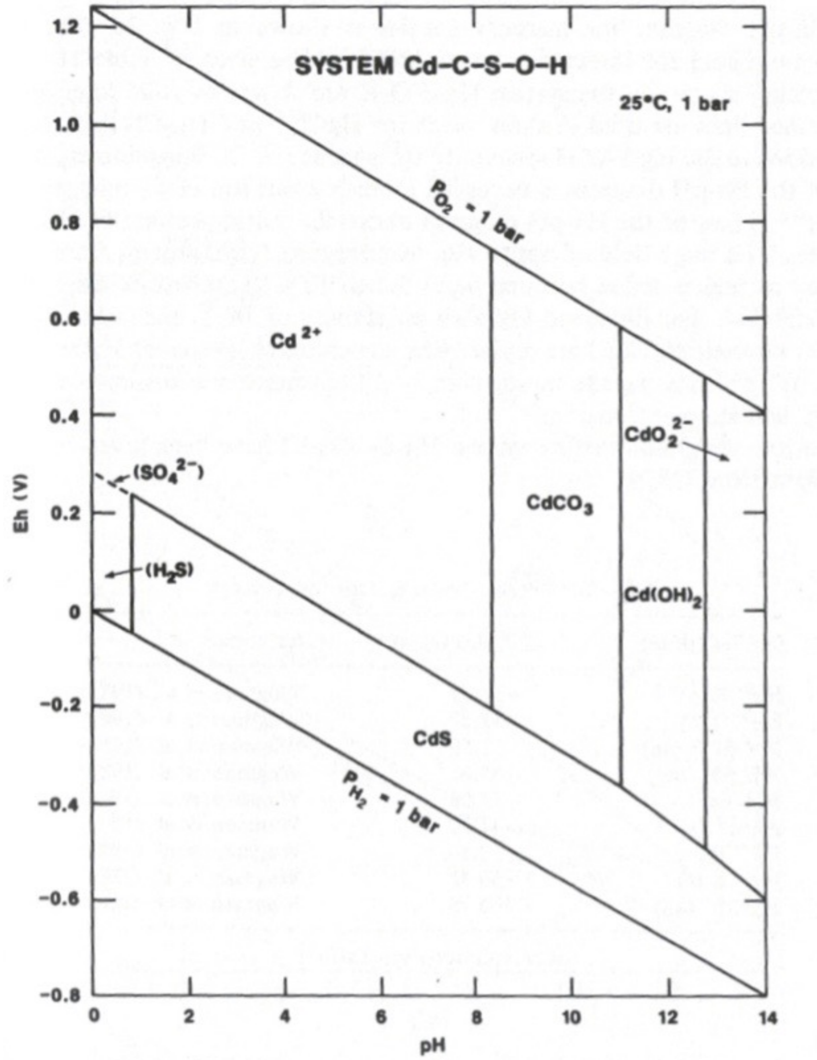

Figure 4 – Eh-pH diagram for cadmium.

Table 4 – Thermodynamic data for cadmium.

Species State	ΔG^0_f(kcal/gfw)
$Cd^{2+}_{(aq)}$	-18.55
$Cd(OH)_{2\,(c)}$	-113.19
$CdS_{(c)}$	-37.40
$CdO_{2\,(aq)}^{2-}$	-67.97
$CdCO_{3\,(c)}$	-160.00
$CdSO_{4\,(c)}$	-196.33
$CdO_{(c)}$	-54.59

Adapted from Brookins (1988); aq – aqueous (dissolved/soluble), c – crystalline (solid).

2.2.5. Selenium treatment mechanisms

The mechanism for selenium treatment is more direct, through microbially catalyzed dissimilatory selenium reduction. This is performed directly by bacteria acting on the selenium. The most common forms of aqueous Se are selenite and selenate, with valence states of Se(IV) and Se(VI), respectively. When these are reduced in a wetland to an insoluble state, Se precipitates as elemental Se(0) (Figure 5), which is the lowest bioavailability (Chapman et al., 2010).

While selenium can be directly treated through microbial reduction in a CWTS, there are constituents that can interfere with this process. Most notably, nitrate has a high affinity for available electrons and is preferentially reduced before other compounds including selenium and sulphate. Nitrate especially interferes with selenium reduction, as it may be performed by the same metabolic pathways in the same bacteria (Oremland et al., 1989 and Oremland et al., 1990). While it is known that over time through closure nitrate concentrations will decrease as the source (blasting residue) has ceased, during early closure nitrate may affect the CWTS treatment capacity for selenium. As such, the pilot-scale CWTSs were subjected to a 6-week trial of synthetic water that mimicked an early closure scenario, with nitrate concentrations based on predicted maximum worst-case ammonia and nitrate concentrations. This was followed by a second phase of testing with depleted nitrate concentrations to simulate the chemistry expected in long-term closure (Contango, November 2014).

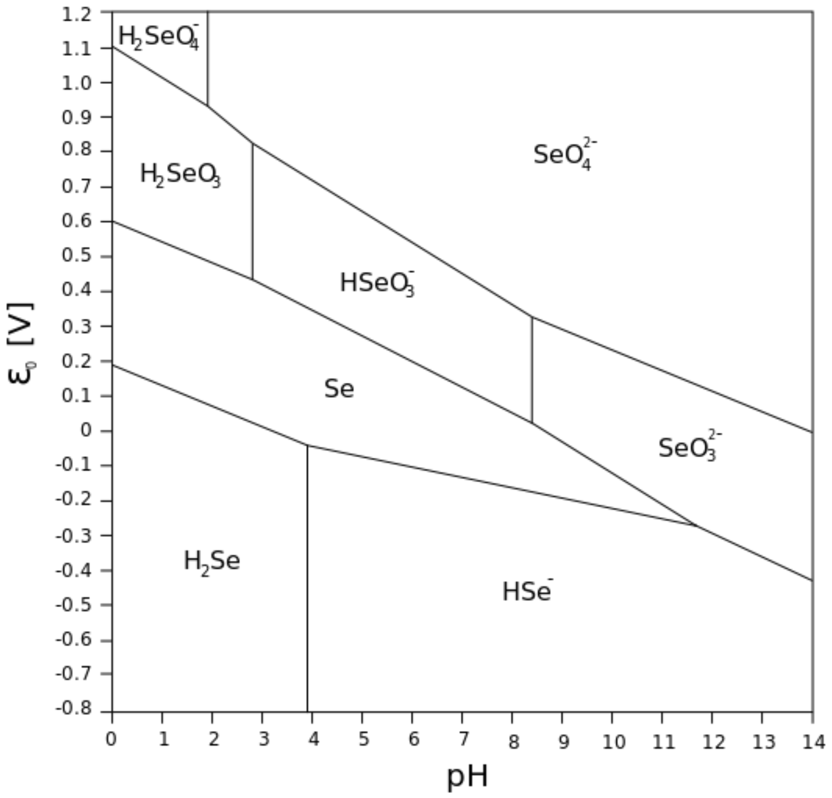

Figure 5 – Eh-pH diagram for selenium.

2.3. Design selection

There are numerous layouts and configurations that can be implemented for treatment wetlands, with varied hydrology, performance parameters, and operation and maintenance requirements. The most passive design was chosen as the goal of final mine site closure is to ensure long-term physical and geochemical stability and to minimize reliance on long-term active treatment. To meet the requirements for water treatment with minimal intervention, the selected passive treatment wetland design is one where there is no operational management necessary, and only minimal periodic maintenance is required, which could be performed by manpower (i.e., without machinery). Based on these guiding objectives, the selected configuration at the Minto Mine is a horizontal surface flow treatment wetland (Figure 6).

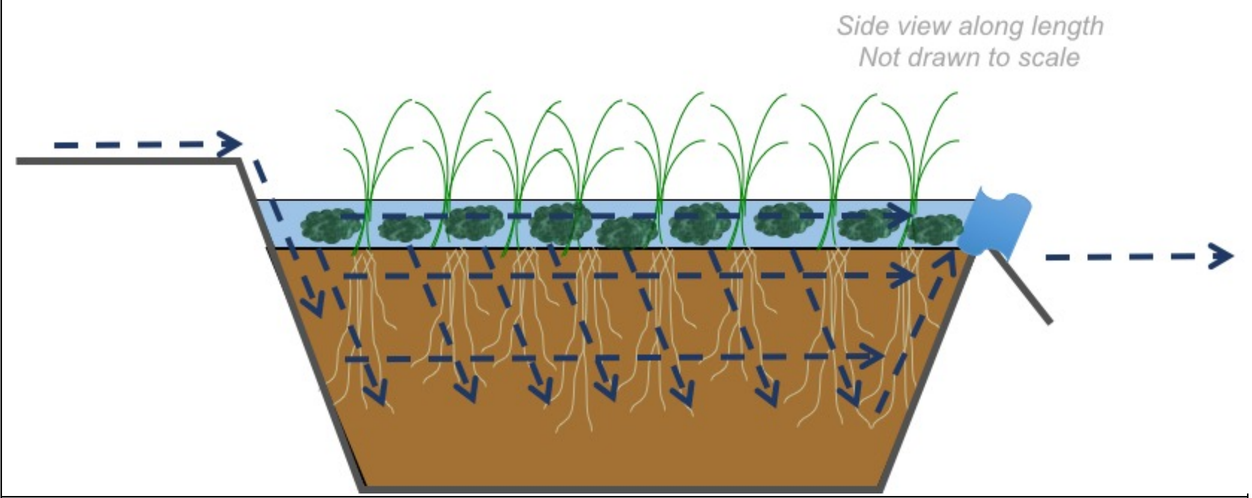

Figure 6 – Conceptual diagram of horizontal surface flow wetland.
Dotted arrows show flow path through wetland and into substrate and root zone. Vegetation in this example includes both emergent macrophytes (e.g., *Carex aquatilis* known as aquatic sedge), and bryophytes (aquatic mosses).

2.3.1. Plants

For the CWTS, *Carex aquatilis* (aquatic 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 (Contango, March 2014). Moss was also used in pilot-scale CWTS designs, as locations at Minto with shallower water had *Carex* and Moss coexisting. The demonstration-scale CWTS was planted with *C. aquatilis* and mosses, as was determined by pilot-scale testing as being the best design for this site and application (Contango, November 2014).

2.3.2. Substrate

The recommended soil for the CWTS is sand, with approximately 2-7% by volume as organic material (e.g., woodchips, straw). In the pilot-scale systems (Contango, November 2014), 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), and it was found that a higher concentration would likely decrease the duration of the commissioning period. 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. Additionally, sandy soil will support weight while wet for planting the CWTS.

2.3.3. Water Depth

The recommended water depth for the CWTS is based on plant selection. Once plants are well established and showing signs of colonizing through the wetland, the water depth may be increased to approximately 25-40 cm and the flow rate may also be increased.

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. The vegetation selected for the CWTS (*C. aquatilis* and aquatic mosses) are known to form peat, which will accrete in a generally uniform manner through the CWTS as long as it is initially planted uniformly and bare spots are addressed through commissioning.

2.3.4. Flow Field

A uniform flow field is necessary in the CWTS to avoid channeling, as the plants will avoid higher flows and preferentially establish in low flow areas. As such, to ensure a uniform flow field, a distribution mechanism at the inflow and outflow areas of the CWTS is needed and will be addressed in the final wetland engineering design.

2.3.5. Water Velocity

Linear flow velocity for the CWTS was selected to be no greater than 35 cm/s according to the Hjulstrom Curve (Figure 7) based on the selected substrate of coarse sand (grain diameter = 1mm). This maximum linear flow velocity is considered to be highly conservative, as it is based on resuspension of substrate to avoid scouring, and does not account for plant roots retaining the sediments in high flows. However, references specific for maximum flow velocity in CWTS recommend the ideal flow velocity for treatment should be less than 15 cm/s for effective treatment capacity (ITRC, 2003). Therefore, the flow through the CWTS should ideally be less than 15 cm/s under normal conditions, and not exceed 35 cm/s under high flow events. These flow rates should be tested in a site-specific manner through the reclamation research program, as actual tolerances will vary depending on plant species, substrates used, and targeted treatment processes.

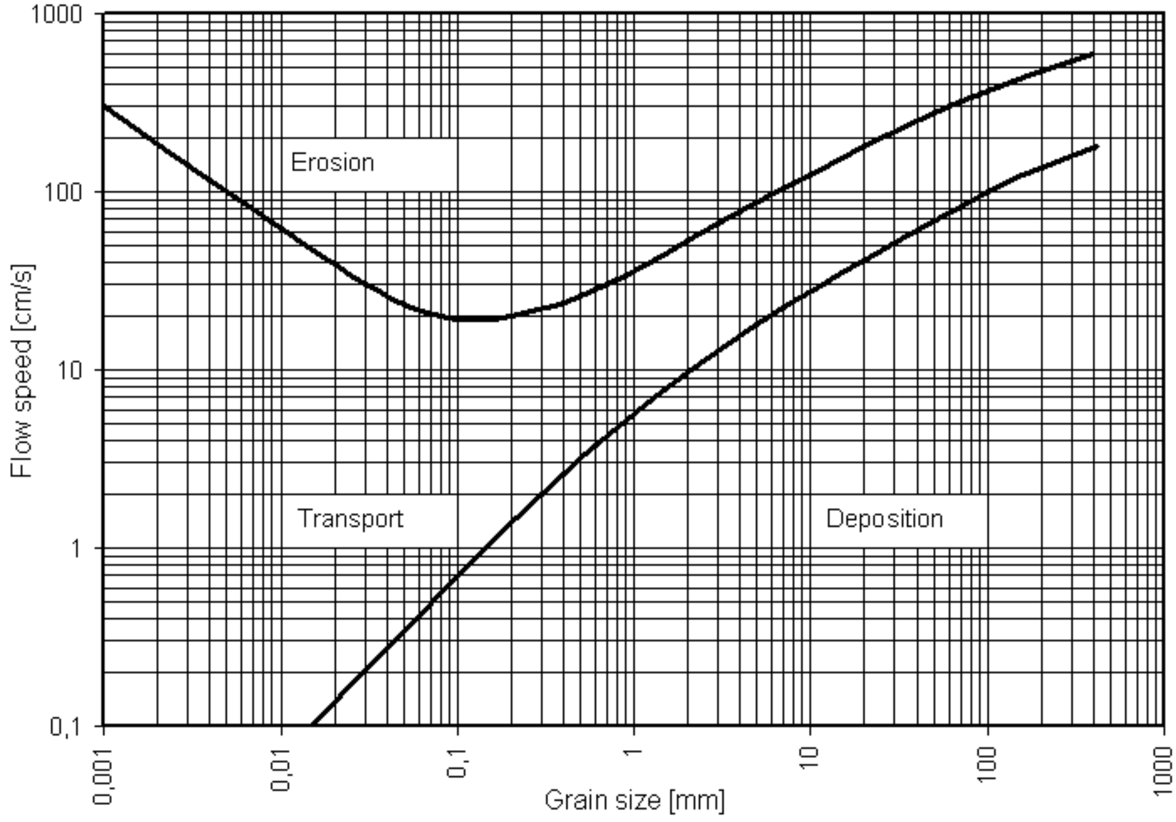

Figure 7 – Hjulstrom curve, demonstrating flow speed associated with resuspension of soils.

2.4. Removal Rate Coefficients and Calculations

An important factor for wetland design is the rate of treatment, also known as the treatment rate coefficient (*k*). The treatment 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. The treatment rate coefficients in Table 5 are based on pilot-scale testing (Contango, November 2014) and are currently being refined with demonstration-scale (on site) testing (Contango March 2015, and Contango March 2016).

Based on pilot-scale testing for the Minto CWTS (Contango, November 2014), the treatment rate coefficient (k) applied for Se follows a zero-order reaction kinetic, while the rate coefficients for Cu and Cd follows first-order kinetics. In Equations 1-4, *Cf* is final concentration, *Ci* is initial concentration, V is volume of water in the system, and Q is flow rate. Using the removal rate coefficients (*k*) in Table 5 and Equations 1-4, parameters can be rearranged to solve for those of interest, such as the outflow concentration, given the available footprint in the WSP area.

Table 5 – Element treatment rate coefficient (*k*) values based on pilot-scale testing.

Element	k [1]
Cd	0.065
Cu	0.05
Se	0.0001

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

$$k = \frac{-\ln\left(\frac{Cf}{Ci}\right)}{V} \, x \, Q$$

Equation 1. Equation for calculation of first-order removal rate coefficient.

$$Cf = Ci \times e^{-k \, x \, \frac{V}{Q}}$$

Equation 2. Equation for calculation of first-order removal rate coefficient, rearranged to solve for outflow concentration.

$$k = \frac{(Ci - Cf)}{V} \, x \, Q$$

Equation 3. Equation for calculation of zero-order removal rate coefficient.

$$Cf = Ci - k \, x \, \frac{V}{Q}$$

Equation 4. Equation for calculation of zero-order removal rate coefficient, rearranged to solve for outflow concentration.

2.5. Thermodynamic minimum concentrations

Through all periods of pilot-scale testing, the outflow concentration of copper for any given system did not vary significantly, indicating that the thermodynamic minimum for copper removal has likely been approached within the system, with an average outflow concentration of 18 ± 5 μg/L. 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. It remains to be experimentally determined through the on-site demonstration-scale testing whether it is possible to achieve lower outflow concentrations of selenium and copper with this wetland design. Thermodynamic minimums developed through the site-specific testing for the Minto CWTS, have been applied to the conceptual performance modelling of a full-scale CWTS (SRK, 2016a), these are: cadmium, 0.000009 mg/L; copper, 0.015 mg/L; and selenium, 0.004 mg/L. This is not to say that lower concentrations may not periodically occur through the CWTS treatment, however these are values that should be consistently attainable if sufficient retention time is provided, and lower concentrations and not expected to be consistently achieved.

2.6. Evapotranspiration

Evapotranspiration is another plant-mediated CWTS characteristic that must be considered (Beebe et al., 2014; Haakensen et al., 2015). Evapotranspiration can be defined as the total sum of water removed from a CWTS by evaporation from surface water of the system and transpiration from plant leaves. The degree of evapotranspiration is dependent primarily on the plant species/ecotype and controlled by meteorological conditions such as air temperature, relative humidity, and wind. Evapotranspiration drives an important aspect of the hydrology of a CWTS by enhancing the effective treatment area of surface flow wetlands.

Evapotranspiration can also affect the perceived treatment in a CWTS because removing water from the system concentrates the constituents, but also results in an increase of the hydraulic retention time (Beebe et al., 2014). That is to say, when evaporation and transpiration levels are high, an increased CWTS footprint may actually result in a higher outflow concentration of elements than is seen partway through the system, even though the total load of an element is lower at the outflow based on treatment.

Trials are being undertaken through the reclamation research program with the demonstration-scale CWTS to determine and model the effects of evapotranspiration on load removal, and current estimates are that approximately 1cm of water will be lost per day (equal to ~10 L per square meter of CWTS).

3. CWTS Implementation Overview

3.1. Timeline overview

The conceptual schedule for implementation of the CWTS is currently being refined through the reclamation research plan as part of the RCP. Through the reclamation research plan the monitoring and maintenance requirements for closure will be refined (research is currently planned through 2018 with the on-site demonstration-scale CWTS). Table 6 therefore provides the best estimate of site-specific maintenance and monitoring requirements for the CWTS based on information at this time.

Table 6 – Conceptual timeline.

Closure		**CWTS**	**Period**	**Comments**
Period	**Year**	**Year**		
Interim and Active Closure	5	0	Construction	Construction and planting of system.
Post Closure I	6-7	1-2	Commissioning	Water from outflow can be recycled through CWTS or be sent to active water treatment if additional treatment is necessary.
	8-10	3-5	Early operation	System meeting performance targets, with frequent monitoring ongoing to refine site-specific long-term monitoring and maintenance requirements of CWTS. Minor adjustments may still be needed.
Post Closure II	11-20	6+	Long-term operation	Performance monitoring at reduced frequency, for confirmatory purposes. Maintenance as needed.

3.2. Construction

Physical construction of the CWTS is described in Appendix A (SRK, 2016b), and therefore only vegetation is covered here. Either before or after planting, a bed of straw and/or wood chips, approximately 5-10 cm deep, should be laid on top of the substrate to serve as an initial source of carbon for the beneficial microbes and to initiate reductive processes and contribute to accretion in early years while there is less plant matter being produced. If planted at the same density (5 plants per square meter) as the demonstration-scale CWTS (on site), *Carex aquatilis* would take approximately 2 years to fill in the CWTS, and based on results from the demonstration-scale CWTS, it is expected that a range of 3 – 5 *C. aquatilis* plants per square meter would be sufficient to fill the CWTS within 2 years. It is recommended that the aquatic mosses be added much more densely than originally distributed in the demonstration-scale CWTS, in order to avoid needing to add additional moss through the year. Approximately 3,000 cm^3 of moss (moist but compressed) is recommended per m^2 of area within the CWTS. It is expected that a team of 4 people can plant a hectare of wetland per day. It is expected that a sufficient quantity of plants for the full-scale wetland can be sourced from the demonstration-scale CWTS, and the W10 area (the original source of plants for the demonstration-scale CWTS), if required additional borrow sources will be utilized.

3.3. Commissioning

The time period between construction of the CWTS and achieving expected treatment performance is referred to as the commissioning period. This period is needed for operational adjustments (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), and preliminary results from on-site demonstration-scale operations (Contango, March 2016), the estimated commissioning period for the full-scale system is 4 – 8 months (of active growing season, or 1 – 2 calendar years). Progress through the commissioning period is assessed through a monitoring program, such as the conceptual schedule inTable 7.

The commissioning period involves guiding the CWTS from construction through to early operation. Commissioning activities can be divided into the categories of: flow management, vegetation establishment, and establishment of conditions for treatment. Flow management includes ensuring the flow field is as uniform as reasonably possible, with wide inflow and outflow berms. Flow management is addressed in Appendix A (SRK, 2016b). Establishment of vegetation will also aid in flow management, and based on observations from the on-site demonstration-scale CWTS (Contango, March 2016), is expected to take a period of approximately 2 years depending on seasonal variations and planting densities. During this time, it may be necessary to supplement vegetation in some areas of the CWTS depending upon transplantation success. The on-site demonstration-scale CWTS had >95% survival of planted vegetation, and a similar rate would be expected at full scale. Variable water depths can sometimes aid in vegetation establishment, and slow (or stagnant) water flows can aid in development of microbial populations. Therefore, during the first months of commissioning, water may be intermittently pumped to the CWTS and allowed to evaporate (but not allowed to dry out), rather than a constant flow. With an estimation of ~1 cm evapotranspiration per day (with *C. aquatilis* vegetation), water could be flowed through the CWTS for 1 week of every month, with the remaining time non-flowing.

4. Monitoring

Monitoring and maintenance schedules contained herein are conceptual, and are being refined with the guidance of the reclamation research plan. The monitoring parameters and schedules are selected to inform potential maintenance needs, and in turn, possible maintenance activities are designed to address performance considerations. The conceptual schedules outlined here are conservative, but not prescriptive. Monitoring includes testing for performance (i.e., decrease of cadmium, copper, and selenium concentrations), and during earlier periods (commissioning, early operations Table 1, Table 2). Explanatory parameters are quantifiable aspects of a CWTS environment that can explain the performance of a CWTS. The end goal of explanatory parameters is to develop a decision management tree to guide maintenance activities associated with treatment performance of the CWTS. This allows for prediction of potential performance issues so they can be addressed before they occur, or the ability to detect and appropriately respond to upsets. There are many parameters that can be included as explanatory parameters, and it is important to identify those which are informative to the constituents being treated, and the site-specific context. For the Minto Mine CWTS, the explanatory parameters are being developed through a phased reclamation research plan, and pilot-scale testing has thus far identified pH, dissolved oxygen (DO), oxidation-reduction potential (ORP), conductivity, temperature, total organic carbon (TOC), nitrate, and soil redox potential as useful to understanding the performance of the CWTS. The explanatory parameters are continuing to be refined through the on-site demonstration-scale operation. Actual parameters and frequency of testing should be guided by the scientific analysis of the results from the previous operational period, therefore, the commissioning will be guided by the on-site demonstration, the early operations by the commissioning, and so forth. Maintenance of the system should be performed as necessary, and based on the results of monitoring activities.

4.1. Monitoring during commissioning (Years 1 – 2)

The commissioning period involves the most rigorous monitoring, to ensure the system is brought online effectively. Because biological systems are dynamic and could take several paths to maturation, rigorous monitoring during the commissioning phase is important to track progress and make corrections as necessary, allowing for the system to be guided through the desired maturation path. During the commissioning period, both performance and explanatory parameters are monitored in order to assess both the effectiveness and mechanisms of function of the CWTS. Some of these parameters would conceptually require weekly monitoring (e.g., visual inspections, water quality testing for total and dissolved metals, nitrate, pH, dissolved oxygen, oxidation reduction potential, and monitoring of plant health and establishment), while others would be tested less frequently. For example, water may be tested monthly for dissolved organic carbon and substrates for redox potential, while parameters such as substrate microbiology, nutrient and organic carbon content may be tested seasonally, and soils metals assays may occur on an annual basis. Parameter lists and testing schedules are being refined through the on-site demonstration-scale CWTS as part of the reclamation research plan.

Table 7 – Conceptual monitoring schedule.

Closure Period		**Year 1 - 5 (Interim and Active Closure)**	**Year 6 - 10 (Post Closure I)**								**Year 11 -20 (Post Closure II)**			
CWTS Stage		**Construction**	**Commissioning (Year 6-7)**				**Early Operation (Year 8-10)**				**Long-term Operation (Year 11-20)**			
Site	**Description**	**No Monitoring Required**	**Water**	**Substrate**	**Flow**	**Plants**	**Water**	**Substrate**	**Flow**	**Plants**	**Water**	**Substrate**	**Flow**	**Plants**
CWTS IN	CWTS Inflow	NA	W,M	NA	W,M	NA	M	NA	M	NA	SSF	NA	SSF	NA
CWTS MID	Within CWTS	NA	W,M	M,SSF,A	W,M	W,M,A	M	M,A	NA	SSF,A	A	A	A	A
CWTS OUT	CWTS Outflow	NA	W,M	NA	W,M	NA	M	NA	M	NA	SSF	NA	SSF	NA

W – weekly; M – monthly; SSF – spring, summer, fall; A – annually; NA – not applicable.
Where two frequencies are separated by a comma, multiple parameters are being tested, and on different schedules.

4.2. Monitoring during early operation (Years 3 – 5)

The CWTS will be transitioned from the commissioning monitoring schedule and considered to be operating in "Early Operations" once the explanatory parameter of targeted soil redox and outflow performance objectives for copper and cadmium are met. At this period targeted performance for selenium may or may not be met, depending on the depletion rate of residual nitrate concentrations. During Early Operations period, the CWTS is expected to be consistently meeting performance targets; however, frequent monitoring is continued to refine site-specific long-term monitoring and maintenance requirements of this system (Table 3). During early operations, the CWTS should be meeting performance targets, but with monitoring of performance and explanatory parameters ongoing to refine site-specific long-term monitoring and maintenance requirements of CWTS. Minor operational adjustments may still be needed during this period. Parameters that would conceptually continue on a monthly monitoring schedule include visual inspections, water quality testing for total and dissolved metals, nitrate, pH, dissolved oxygen, oxidation reduction potential, substrate redox potential, and general plant health. Parameters such as substrate microbiology, nutrient and organic carbon content, and metals assays may occur on an annual basis. Parameter lists and testing schedules are being refined through the on-site demonstration-scale CWTS as part of the reclamation research plan.

4.3. Monitoring during long-term operation (Years 6 – 10)

During long-term operation of the CWTS, monitoring is conducted mostly for performance, with a reduced frequency of monitoring for explanatory parameters (as defined from commissioning and early operations periods). The decision tree that was developed during demonstration-scale operation (and refined in full-scale commissioning and early operations) is applied to guide maintenance activities. During long-term operations, the CWTS should be meeting performance targets, with monitoring of performance and only those key explanatory parameters defined as leading indicators of performance (through the reclamation research plan and early operations of the full-scale CWTS). Conceptually, seasonal testing will be performed for performance (dissolved metals), and soil redox. Parameter lists and testing schedules are being refined through the on-site demonstration-scale CWTS as part of the reclamation research plan, and will be further refined through testing in commissioning and early operations of the full-scale CWTS.

5. Maintenance and operational adjustments

Maintenance of engineering and flow-management structures associated with the CWTS are covered in Appendix A (SRK, 2016b), and only performance related aspects are addressed here. Activities commonly associated with maintaining the performance of a CWTS are detailed in Table 8. The frequency of these activities should be guided by the monitoring activities, and is being refined through the on-site demonstration-scale CWTS as part of the reclamation research plan. A decision matrix based on the explanatory parameters is being developed through the reclamation research plan, and will be used to guide the operation of the full-scale CWTS. Additionally, periods of more intensive monitoring during commissioning and early operations will further guide the appropriate frequency of site-specific maintenance and refine the decision matrix. During early operations, minor adjustments may still be needed to the system, such as addition of solid phase organic materials (e.g., straw or wood chips), and corrections to non-uniform flows (e.g., adding sand bags at inflow and outflow of cells).

Table 8 – Conceptual maintenance actions.

Observation	Monitoring	Item Addressed	Action	Follow up
Soil redox drifting upwards	Nutrients, TOC, microbiology	Decrease of treatment effectiveness due to low microbial activity or lack of food for microbes.	Add nutrients (fertilizer), and/or organic carbon.	Soil redox testing weekly until within stable range. Microbiology, TOC and/or nutrients testing bi-weekly until within desired range.
	Flow rates	Water volume to carbon ratio is too high.	Check inflow mechanism.	If ongoing issue (and not addressed by adding organic carbon), adjust inflow mechanism.
Water depth decreasing	Flow rates, accretion	System is designed to accrete (increase mass of soil), which causes soils to build within CWTS. Expected rate of 0.5-2mm/year (Robinson and Moore, 1999).	Increase height of outflow (and inflow) berms.	Record accretion rate to schedule for next depth increase event.
Undesirable plants	Vegetation monitoring	Channeling or decreased treatment effectiveness due to competing microbial habitats.	Remove undesirable plants.	Monitor to ensure undesirable plants have successfully been removed.
Wildlife interferences	Visual monitoring	Non-uniform flow field due to wildlife interferences (e.g., beaver dam) and decreased treatment performance.	Remove wildlife interferences.	Monitor to ensure interference is not re-established.
Channeling	Flow rates	Channeling can be due to undesirable plants, non-uniform flow fields, or flow rates beyond CWTS design.	Check inflow mechanism.	If ongoing issue, adjust inflow mechanism.
Flow blockages	Flow rates, visual monitoring	Blockages can be due to debris (fallen branches) and wildlife activity (beavers).	Remove blockages.	Adjust monitoring frequency accordingly.
Poor plant health	Nutrients	Decreased treatment effectiveness due to less active treatment zone if plants not actively transpiring and moving water through root zone.	Add nutrients (fertilizer).	Nutrients testing bi-weekly until within desired range.

6. 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 Strategies Ltd.

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