MEMORANDUM

Faro Pit Mine Chemistry - Transmittal

PREPARED FOR:	Government of Yukon
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PROJECT NUMBER:	673709

Purpose

This memo serves as a transmittal of the Technical Memorandum (TM) prepared by Dr. Roger Pieters and Dr. Gregory A. Lawrence entitled, "Salinity Stratification in Faro Pit Lake, 2004-2015", dated August 16, 2016 herein referred to as the TM.

Introduction

CH2M HILL Canada Limited (CH2M) was commissioned by Government of Yukon (YG) to assess the salinity stratification in the Faro Pit Lake under Task Authorization 009-001. The scope of work included assessing historical changes to the Faro Pit Lake salinity and stratification, as well as provide recommendation to re-establish the meromixis (fresh water cap) on the Faro Pit. Re-establishing the meromixis would provide a cleaner water source for lime slaking at the Interim Water Treatment System (IWTS) as well as biological contact with the pit lake.

To achieve this objective, CH2M engaged Dr. Roger Pieters and Dr. Gregory A. Lawrence, experts in pit lake mine chemistry. Attached is the Technical Memorandum prepared by Dr. Peiters and Dr. Lawrence. A brief review and comment is provided below, including additional information related to that presented by Dr. Pieters and Dr. Lawrence.

Review and Comment

Destratification of the Faro Pit occurred between 2013 and 2015. The destratification was related to the closure of the onsite water treatment plant in 2013 where two changes occurred; water was no longer pumped out of the Faro pit lake and Intermediate Dam Pond (ID Pond) and Emergency Tailings Area (ETA) water was transferred to the surface of the pit lake. Further, the influence of the S-wells salinity decreased the stability of the Faro pit steadily from 2009 to 2012.

Within the introduction of the TM it is noted the water within the Faro Pit is currently used to slake the lime for the lime neutralization IWTS. Based on the destratification of the Faro Pit, this water is high in sulfate, causing the formation of gypsum on the reaction with lime, rendering portions of lime unavailable for treatment. This portion of lime which is unavailable increases overall treatment costs of the IWTS with the need for additional lime.

The recommendations include the suggestion of limiting the influx of Faro Creek water into the Faro Pit. As suggested, this water may be considered as an alternate, fresher source of water for lime slaking at the IWTS. Alternately as the meromixis is re-established it may be possible to optimize the use of less saline surface water directly from the Faro Pit for slaking.

Closure

Should you have any questions on the TM, please contact Bryce Peterson at Bryce.peterson@ch2m.com or 867 68 2201.

Salinity Stratification in Faro Pit Lake, 2004-2015

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Faro pit lake, July 2008 (photograph courtesy of Ken Nordin, Laberge Environmental Services).

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Executive Summary

Observations of Faro pit lake indicate permanent salinity stratification (meromixis) from 2004 to 2012. This salinity stratification consisted of a fresher surface layer (mixolimnion) overlying more saline water at depth (monimolimnion, see Figure 1).

There are three distinct phases in the evolution of Faro pit lake. (1) The salinity stratification increased slowly from 2004 to 2008, as fresh water, dominated by Faro Creek seepage, was added to the surface, and the more saline water from the Zone II well was piped below 20 m. (2) The salinity stratification declined slowly from 2009 to 2012 with the addition to the surface of saline water from the S wells. (3) The salinity stratification declined rapidly from 2013 to 2015 with the addition to the surface of large volumes of more saline IP and ETA water. The profile data suggested the pit lake had mixed significantly by September 2014.

One recommendation for re-establishing salinity stratification in Faro pit lake is to place saline water as deep as possible. This will increase the stability of the pit lake and make it resistant to subsequent mixing as it was from 2004 to 2012. As an additional benefit, with small volume sources of high salinity water, there may be the potential to establish sulphide reduction in the deep water, and to sequester metal sulfides in the sediments.

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Introduction

Faro pit lake is a water filled mining void located in central Yukon. Faro pit lake is used to store water from a number of sources, and outflow is pumped from the surface of the pit lake to ensure the water level remains well below the level of a rock dyke. The surface water pumped from the pit lake is used to slake lime in the treatment plant. The presence of sulfate in the water results in the formation of gypsum, making that portion of lime unavailable for water treatment.

Observations from 2004 to 2012 indicate that Faro pit lake was meromictic, with a stable fresh water cap (e.g. Figure 1). Between 2013 and 2015 this cap disappeared. Here data from Faro pit lake is examined to assess the conditions that initially led to stable salinity stratification, and led to its subsequent destratification.

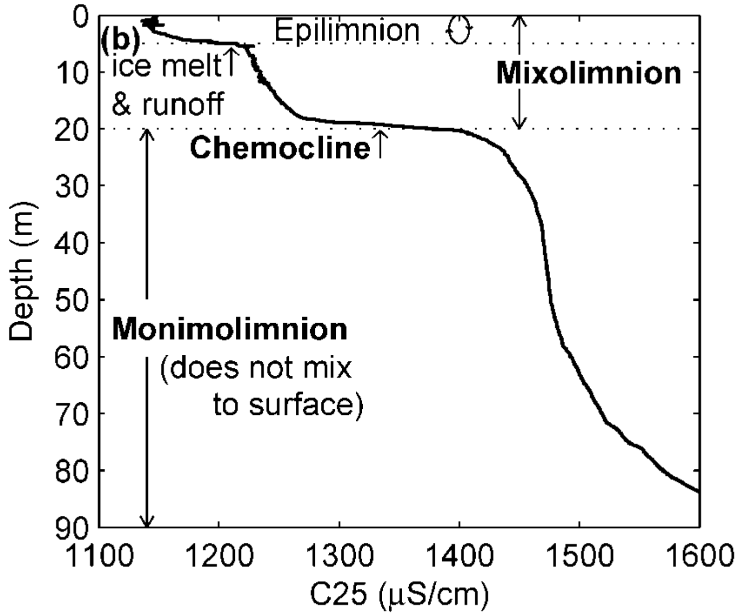


Figure 1 Conductivity profile in Faro pit lake, 11 June 2008. The fresher near surface water (mixolimnion) caps more saline deep water (monimolimnion); the transition between the two is known as the chemocline. The reduced conductivity of the surface layer from 0 to 4 m depth (epilimnion) is created by melted ice, seepage and runoff.

Methods and site description

Profiles of high accuracy temperature and electrical conductivity were collected using a Seabird SBE19 profiler. This profiler was lowered at a rate of approximately 0.2 m/s, and data was collected at 4 Hz, giving a vertical resolution of about 5 cm. The Seabird has a unique conductivity cell which is highly accurate and stable in fresh and brackish waters. All conductivity used in this report has been adjusted to conductivity at 25°C, C25. Conductivity (µS/cm) is a measure of the salinity or total dissolved solids content of the water (mg/L), where 1 µS/cm ≈ 0.8 mg/L.

Flows to and from Faro pit lake are listed in Table 1. In this report, monthly average flow data from January 2006 to April 2015 were used, as plotted in Appendix 1. Conductivity data for each inflow is shown in Appendix 2, and these data were used to compute monthly average values. Missing monthly values were linearly interpolated.

Characteristics of Faro pit lake at various water levels are given in Table 2. Hypsographic curves are given in Appendix 3. At the mean water level for 2006 to 2012, the volume of the pit lake was 30 Mm^3; 1/3 of this volume (10.2 Mm^3) was above 20 m depth and 2/3 of this volume (19.8Mm^3) was below 20 m.

Table 1 Inflow and outflows from Faro pit lake.

No.	Description (chemistry code)	Abbreviation	Depth	Comments
1	Faro Creek Seepage (A30)	Seepage	Surface	
2	Runoff from the drainage surrounding the pit lake	Runoff	Surface	
3	Precipitation to the pit lake surface	Precip	Surface	
4	Water pumped from Zone II well (X26, 2006-2013 and CH12-Z2-PW01, 2013-16)	Zone II Well	At depth(1)	
5	Water pumped from S Wells (SRK08-SPW3)	S Wells	Surface(2)	Began Jan 2009
6	New well (RGC14-PW06)	New Well	Surface(2)	Began Mar 2014
7	Intermediate Pond (X4)	IP	Surface(3)	May 2013 – Oct 2014
8	Emergency Tailings Area water pumped to Faro pit lake (ETA combined)	ETA	Surface(3)	Aug-Oct 2013
9	Water pumped from Faro pit lake (X22B)	Pump Out	Surface	
10	Evaporation	Evap	Surface	

(1) The nominal depth of discharge is 30 m, however, features in the Seabird profiles suggest the depth of discharge may have been around 20 m much of the time.

(2) The new well joins the S wells 4” pipe; this and the S wells 2” pipe discharge to a ditch above the pit lake, which runs west of the ramp down to the surface of the pit lake.

(3) IP and ETA water were combined in one pipe, that discharged above the pit and cascaded down the benches to the surface of the pit lake.

Table 2 Characteristics of Faro pit lake at selected elevations.

	Elevation (m ASL)	Max Depth (m)	A (ha)	V (Mm^3)
Estimated minimum pumping limit	1138.793	88.793	54.52	28.40
Minimum in record, 2004-2015	1140.7	90.7	55.51	29.45
Mean 2006-2012	1141.8	91.8	56.16	30.06
Max recommended pumping limit	1144.341	94.341	57.33	31.50
Maximum in record	1153.2	103.2	64.02	36.86
Overflow to Zone II	1158	108	66.65	39.99

Results and Discussion

The water level in Faro pit lake for 2004 to 2016 is shown in Figure 2. From 2004 to 2012, the water level was maintained with a consistent pattern of increasing water level during the winter, and decreasing water level during the open water season when pumping was active. In 2013, the water treatment plant was out of service and two changes occurred: water was no longer pumped out of Faro pit lake, and IP and ETA water was transferred to the surface of the pit lake. Both of these changes contributed to a rapidly increasing water level, which nevertheless remained below the level of the rock dyke (1158 m).

A water balanced was used to estimate the water level in the pit lake; the resulting water level agrees reasonably well with the observed water level (Figure 2). The standard deviation between the observed and estimated water level was 0.44 m, and the maximum difference was 0.55 m.

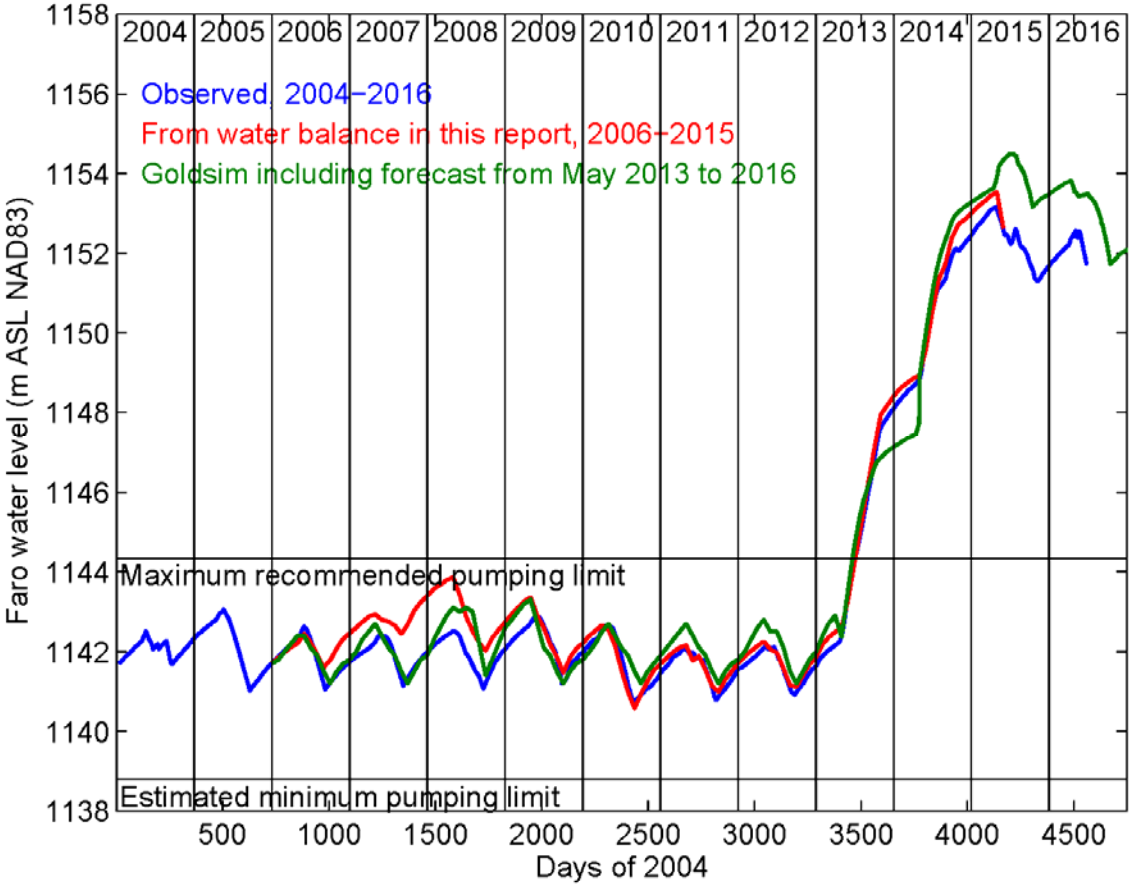


Figure 2 Observed and predicted water level in Faro pit lake, 2004-2016. (The line for Goldsim represents a fit to data for 2006 to April 2013, and a forecast for May 2013 to December 2016).

The inflows and outflows are summarized for three periods in Table 3. The largest inflow was the seepage from Faro Creek, which accounted for ~ 80% of the net inflow for 2006 to 2012. Evaporation is ~30% larger than precipitation to the pit lake surface. Runoff and precipitation minus evaporation is about 13% of the net inflow for 2006 to 2012.

Table 3 Average inflow and outflow to Faro pit lake for selected periods

No.	Flow	2006-2008 (m^3/mo)	2009-2012 (m^3/mo)	2013-2016 (m^3/mo)
1	Seepage	121,425	121,425	121,425
2	Runoff	23,887	21,648	25,789
3	Precip	17,930	16,227	21,345
4	Zone II Well	5,825	5,589	7,286
5	S Wells	0	5,373	4,660
6	New Well	0	0	321
7	IP	0	0	109,483
8	ETA	0	0	1,104
9	Pump Out	130,717	158,279	36,246
10	Evap	22,307	22,288	24,104

The flow weighted average conductivity for the corresponding flows are given in Table 4. The characteristics of the runoff from the natural drainage are not known. Generally, the impacted well water is very high in conductivity.

Table 4 Flow weighted average conductivity of Faro flow for selected periods.

No.	Location	2006-2008 (µS/cm)	2009-2012 (µS/cm)	2013-2014 (µS/cm)
1	Seepage	1,251	875	1,469
2	Runoff	Unknown	Unknown	Unknown
3	Precip	0	0	0
4	Zone II Well	4,821	4,508	4,870
5	S Wells	-	5,675	9,722
6	New Well	-	-	18,000
7	IP	-	-	1,992
8	ETA	-	-	8,996
9	Pump Out	1,189	1,170	911
10	Evap	0	0	0

Stratification

Over the last twelve years, profiles of high accuracy temperature and conductivity were collected from Faro pit lake using a Seabird SBE19 profiler. Selected profiles are shown in Figure 3. The temperature and conductivity profiles for 2004 to 2012 indicate meromixis. The seasonal cycle in Faro pit lake was described in Pieters and Lawrence (2014): Faro had a fresh water cap throughout the year, and spring turnover, fall turnover and under-ice mixing did not occur. During this time, the temperature below 20 m was relatively uniform, and increased slightly with depth (see inset with expanded scale). The conductivity also increased slightly with depth.

From 2004 to 2012, there was also a small but consistent increase over time in both temperature (0.02 °C/year) and conductivity (16 µS/cm/year) below 20 m. Most of the increase in salinity is accounted for by inflow of Zone II well water as will be described below.

The most striking change in 2013, 2014 and particularly 2015 is the reduction in the fresh water cap at the surface; in October 2015 the contrast in conductivity between the surface and deep water is gone, and the conductivity is almost uniform from top to bottom. The temperature of the pit lake is also quite uniform, and the deep water in the pit lake has cooled significantly from ~4.5 °C in 2013 and earlier years, to 3.7 °C in 2015. The temperature of the entire pit lake in 2015 was close to the temperature of maximum density adjusted for salinity, 3.7 °C. Clearly, Faro is no longer meromictic and has mixed from top to bottom.

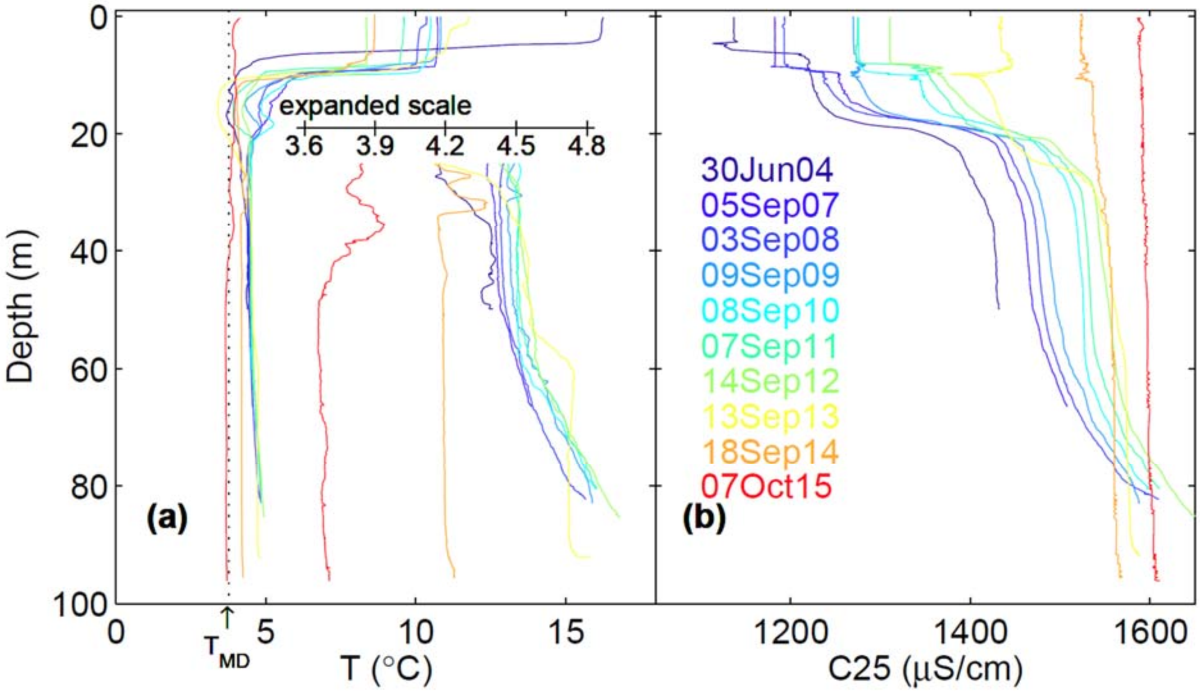


Figure 3 Selected profiles of (a) temperature and (b) conductivity, Faro pit lake, 2004-2015. From 2004-2012, the chemocline is located at 20 m, separating less saline water above (mixolimnion) from more saline water at depth (monimolimnion).

The volume weighted average conductivity of the pit lake is shown in Figure 4, along with that above 20 m and below 20 m. From 2004 to 2008, the conductivity of the entire pit and the deep water increased steadily (16 µS/cm/yr). While the conductivity of the top 20 m increased slightly, it increased at a slower rate (7 µS/cm/yr), which resulted in an increasing salinity stratification.

Once pumping of water from the S wells to the surface of Faro pit lake began in 2009, the salinity of the surface water began to increase more rapidly (28 µS/cm/yr). During this time the salinity stratification began a slow decline, as the salinity difference between the surface and deep water decreased.

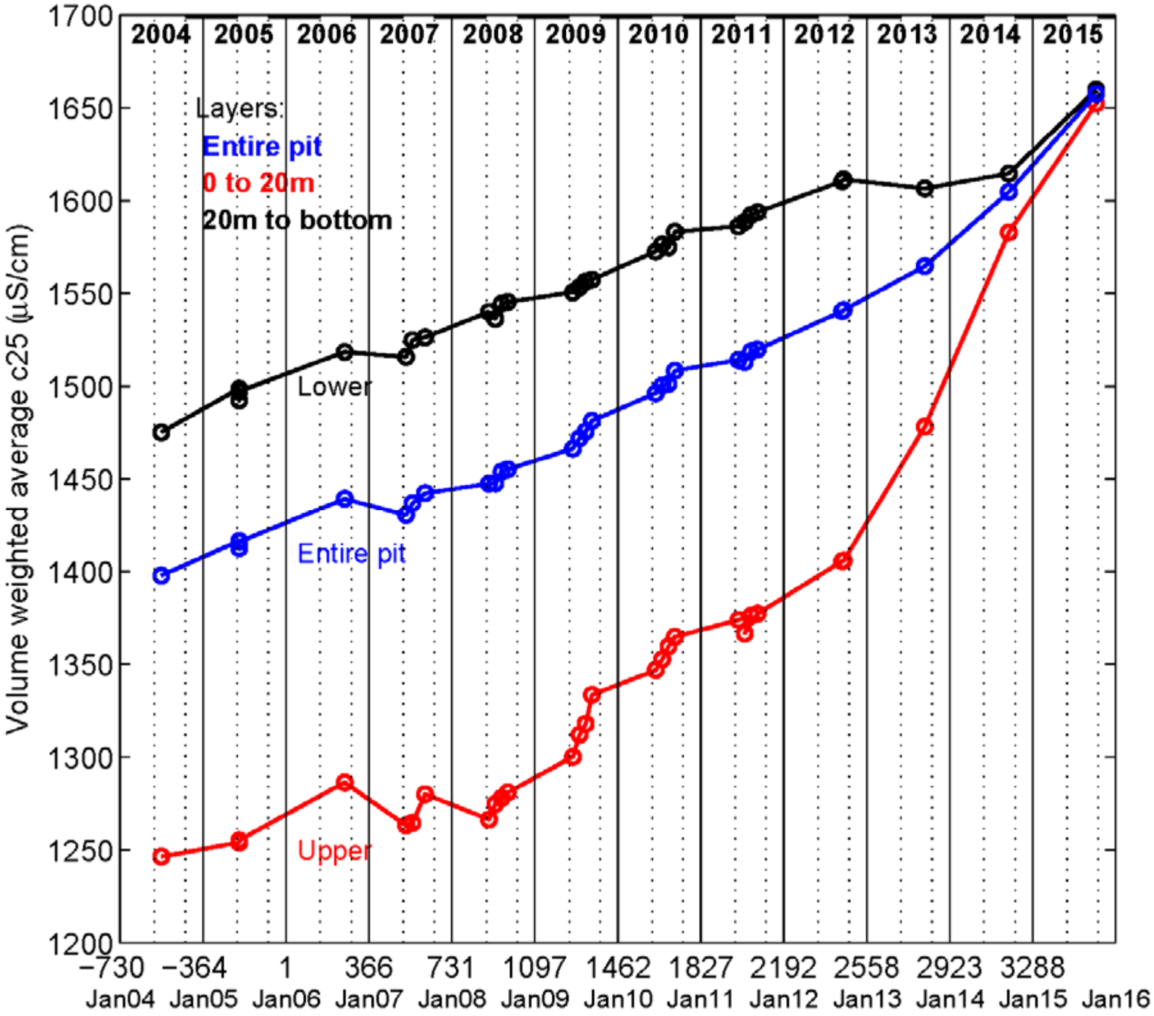


Figure 4 Volume weighted average conductivity of Faro pit lake from all open water Seabird profiles, 2004-2015. The dotted lines mark June 1 and October 15, the approximate time of ice-on and ice-off, respectively.

The salinity stability for Faro pit lake is shown in Figure 5. The salinity stability is the work against gravity needed to raise denser fluid at depth, namely the energy needed to mix the pit lake. From 2004 to 2012 the stability was high, ~850 J/m^2. While there is some noise in the plot, it is clear that the stability increased from 2004 to 2008. From 2009 to 2012 there was a gradual decrease in the stability as a result of saline inflow from the S wells to the surface during this time. Finally, as the surface became more saline from 2013 to 2015 (Figure 4), the stability decreased dramatically (Figure 5).

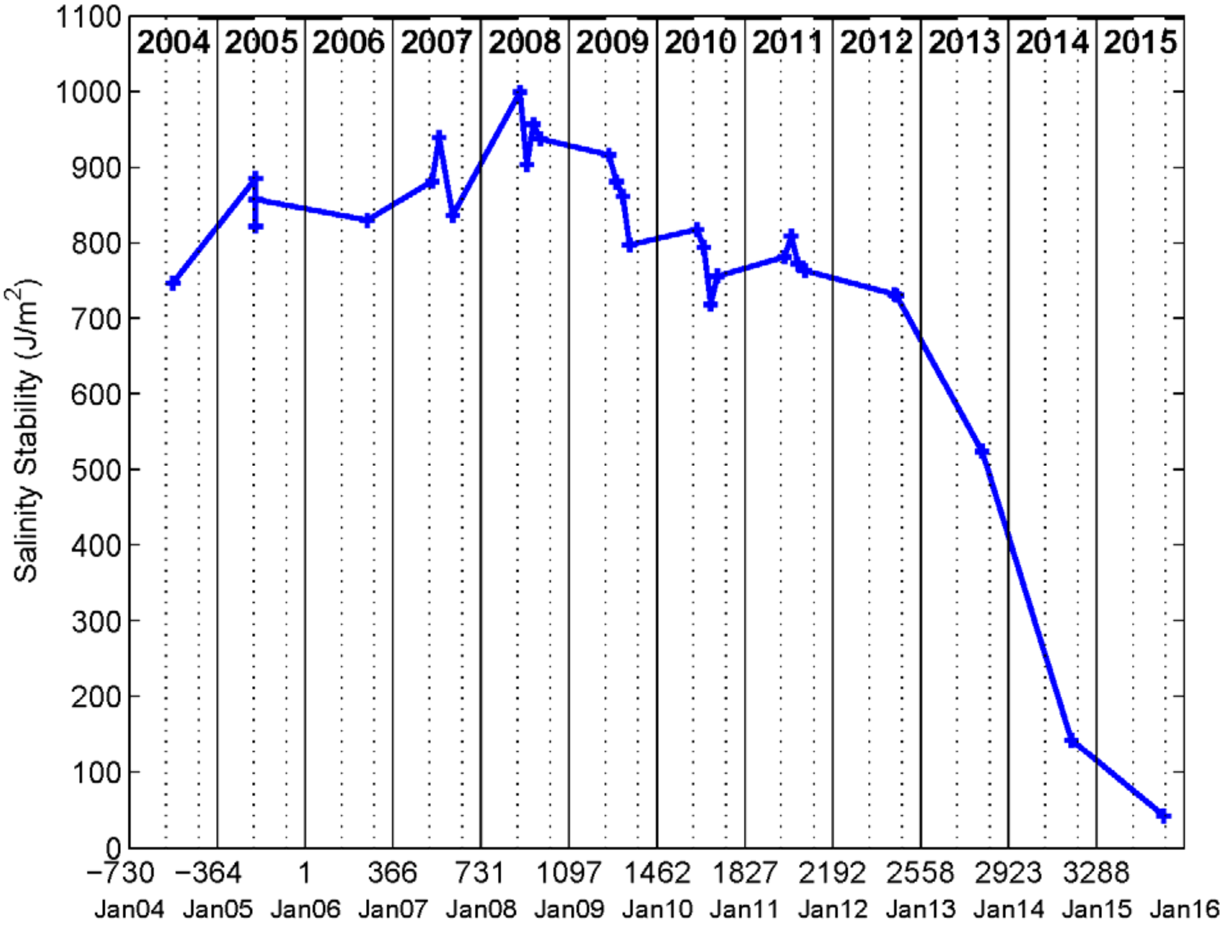


Figure 5 Salinity stability of Faro pit lake from all open water Seabird profiles, 2004-2015.

Conductivity Budget

A conductivity budget of the entire pit lake for 2006 to 2012 indicates that the conductivity of the drainage flow would need to have been high, ~ 2000 µS/cm, in order to match the observed increase in the conductivity of the pit lake (Figure 4). Confirming the conductivity of the runoff might be done by comparing to occasional data from around the pit lake walls.

The conductivity of the deep layer (≥ 20 m) was observed to increase by 16 µS/cm/yr from 2006 to 2012. The addition of Zone II well water accounts for much of this increase, 11 µS/cm/yr. Other processes may also contribute to the increase in conductivity of the deep layer, such as inflows of ground water or decomposition (remineralization) of organic matter.

Recommendations

1. Use of Faro Creek The major source of water to Faro pit is the seepage from Faro Creek. This water has relatively good water quality with lower conductivity and sulfate. In effect, fresher Faro Creek water is being mixed with more saline water of low quality in Faro pit. If there was the possibility of reducing this seepage by, for example, sealing the diversion channel, this would result in less water to be removed from Faro pit, and Faro Creek water might be used to slake lime.

2. Use of near surface water after ice off Exclusion of salt from the ice results in a fresh water cap after ice melt. The water pumped from the pit lake shows dips in conductivity (and sulfate) during spring which likely results from withdrawing this water before it is mixed with saltier water below as the summer progresses (see Appendix 2). The epilimnion just after ice off is often only a few meters thick (e.g. Figure 1). There may be the potential to optimize the withdrawal of water from the surface of the pit lake to select for this thin surface water.

3. Re-establish meromixis To increase the salinity stratification, water that is more saline than average should be discharged as deep as possible, and water that is less saline than average should be discharged to the surface. These discharges should be engineered to minimize vertical mixing. This would enhance stability and re-establish meromixis.

4. Sulfate reduction One interesting option would be to setup conditions suitable for sulfate reduction in the deep water of Faro pit lake. This would have the dual benefit of removing both sulphate and metals by precipitation as metal sulphides. The sulfur and metals would then, in the absence of oxygen, be sequestered in the sediments.

The establishment of sulfate reduction, requires a strong and permanent salinity stratification (meromixis) to isolate the deep water. The second requirement is sufficient oxygen demand in the deep water so that the deep water becomes anoxic, and to ensure consumption of oxygen that is transported into the deep water by the saline inflows (Fisher and Lawrence 2006).

Oxygen demand could be increased by, for example, fertilization of the surface water, resulting in increased phytoplankton activity, with a corresponding increase in the flux of organic matter to depth. As phytoplankton are known to adsorb metals which are carried to depth at senescence, a side benefit of fertilization would be a decrease in the concentration of metals in the surface water.

Further analysis (in particular an oxygen budget) would be needed to evaluate the potential for achieving sulfate reduction. Success is most likely in cases where the mass of oxygen transported by the inflow is minimized, namely for small and concentrated inflows. The three inflows of well water to Faro pit lake are candidates, given their small flows and high conductivity and sulfate (Zone II well, S wells and the new well).

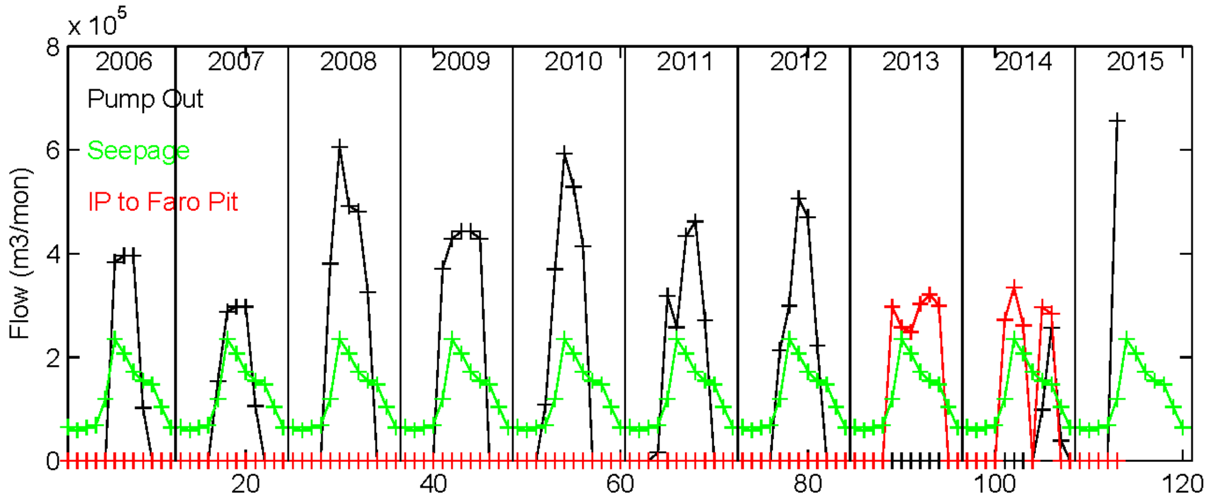
5. Monitoring Ongoing monitoring with a high accuracy Seabird profiler is recommended to track the evolution of the stratification.

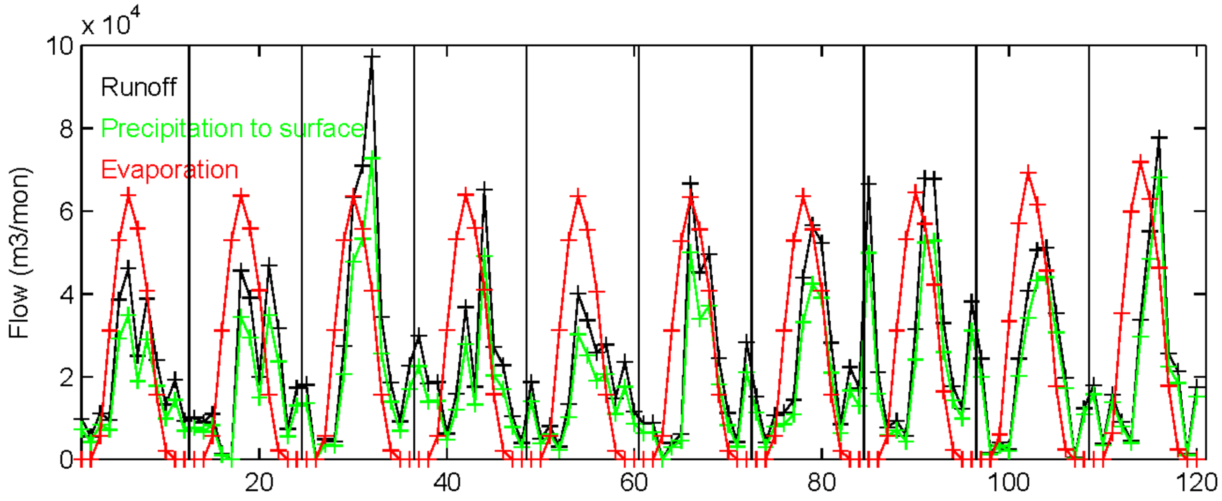
References

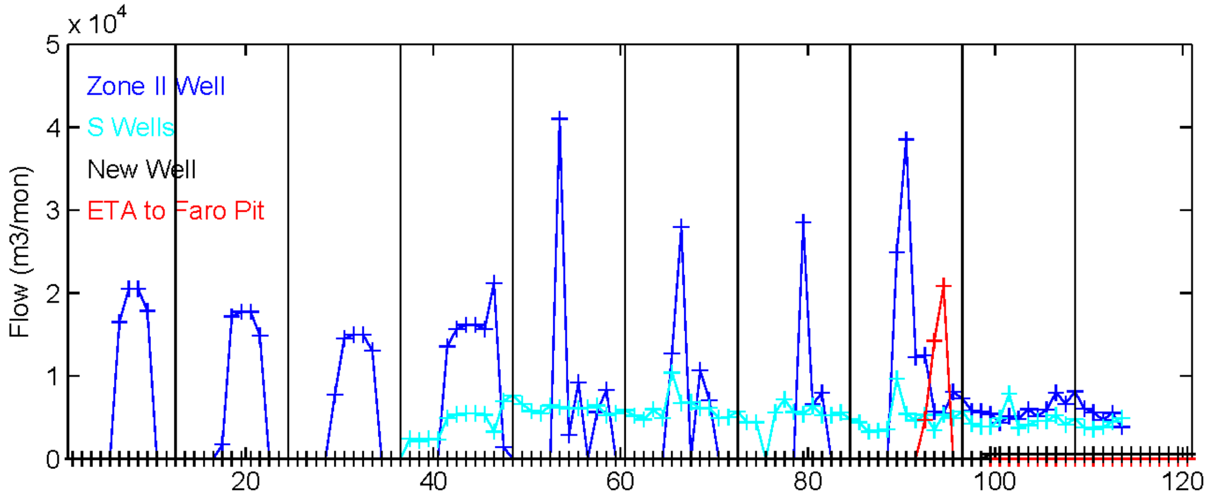
Fisher T.S.R. and G.A. Lawrence, 2006. Treatment of acid rock drainage in a meromictic mine pit lake. Journal of Environmental Engineering-ASCE 132 (4):515-526.

Pieters, R. and G.A. Lawrence. 2014. Physical processes and meromixis in pit-lakes. Canadian Journal of Civil Engineering, 41(6): 569-578, http://dx.doi.org/10.1139/cjce-2012-0132

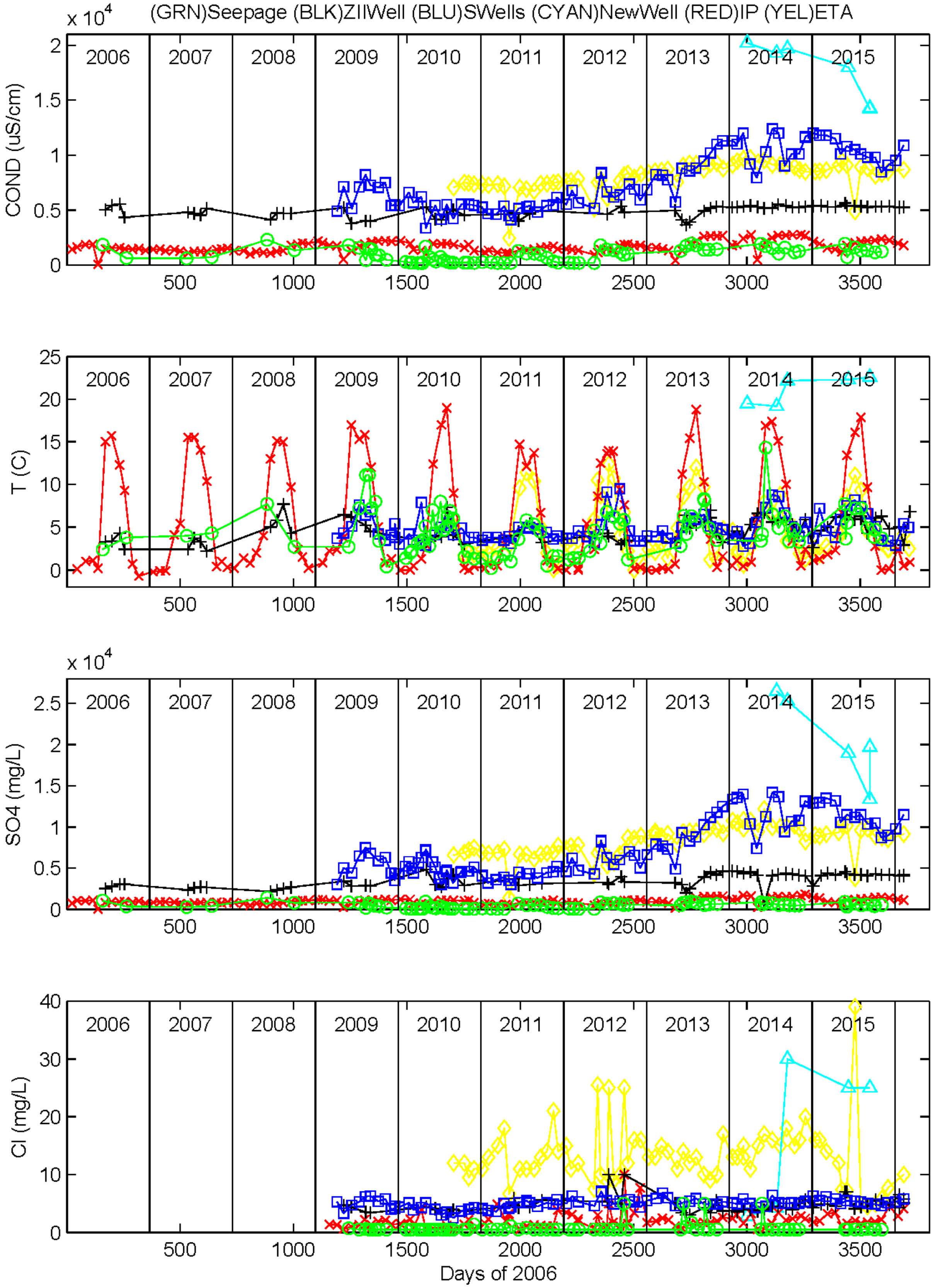
Appendix 1 Flow data



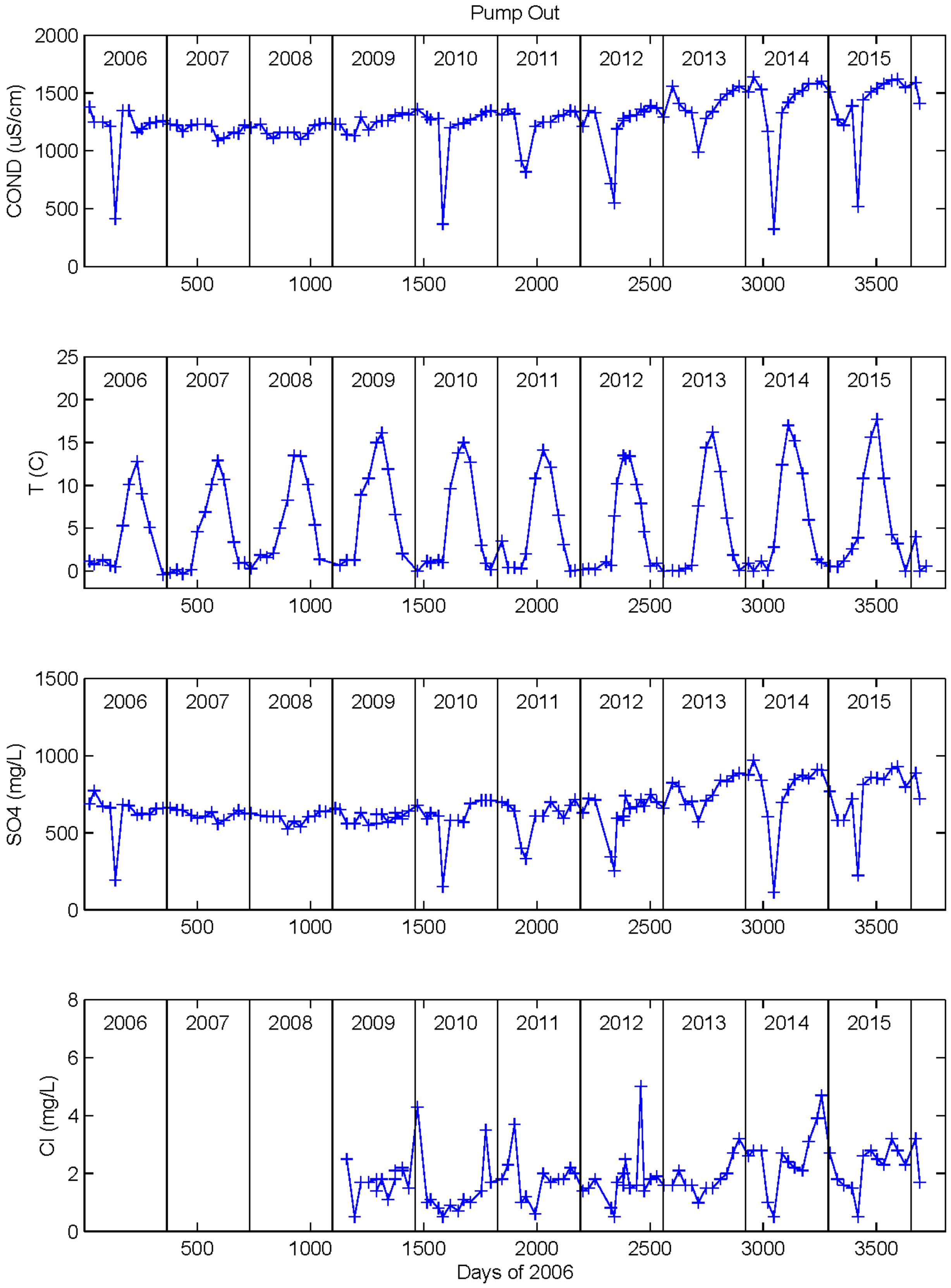




Appendix 2 Conductivity and other data



Appendix 2 Conductivity and other data (continued)



Appendix 3 Hypsographic Curves