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$_2$O), 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.

<table>
<thead>
<tr>
<th>Scale</th>
<th>Year</th>
<th>Period (days)</th>
<th>Date</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Start</td>
<td>End</td>
</tr>
<tr>
<td>Commissioning-A²</td>
<td>2014</td>
<td>23</td>
<td>Aug 27</td>
<td>Sept 19</td>
</tr>
<tr>
<td></td>
<td>2015</td>
<td>135</td>
<td>May 16</td>
<td>Sept 29</td>
</tr>
<tr>
<td></td>
<td>2016</td>
<td>87</td>
<td>May 2</td>
<td>Jul 28</td>
</tr>
<tr>
<td>Commissioning-B³</td>
<td>2016</td>
<td>63</td>
<td>Jul 29</td>
<td>Sept 30</td>
</tr>
<tr>
<td>Operational Period</td>
<td>2017</td>
<td>82</td>
<td>May 27</td>
<td>Aug 17</td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>Event</th>
<th>Key Activity</th>
<th>Flow Rate Setting m³/day (gal/min)</th>
<th>Dates</th>
<th>Effective Days of Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>CWTS Series 1</td>
<td>CWTS Series 2</td>
<td></td>
</tr>
<tr>
<td>CWTS constructed and planted</td>
<td>First sampling, water started.</td>
<td>*</td>
<td>*</td>
<td>August 27 – 31, 2014</td>
</tr>
<tr>
<td>Freeze up for winter</td>
<td>Feed water pumps turned off.</td>
<td>*</td>
<td>*</td>
<td>September 19, 2014</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Winter 2014/2015</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Commissioning-A¹</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Winter 2015/2016</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Commissioning-A¹</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Commissioning-B²</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Winter 2016/2017</td>
</tr>
<tr>
<td>Flow started</td>
<td>Flow started.</td>
<td>2.18 (0.40)</td>
<td>1.85 (0.34)</td>
<td>May 27, 2017</td>
</tr>
<tr>
<td>Evaporation Study</td>
<td>Flow stopped.</td>
<td>-</td>
<td>-</td>
<td>June 8, 2017</td>
</tr>
<tr>
<td>End of Evaporation Study</td>
<td>Flow re-started.</td>
<td>4.80 (0.88)</td>
<td>4.58 (0.84)</td>
<td>June 15, 2017</td>
</tr>
<tr>
<td>Flush CWTS</td>
<td>Flow increased.</td>
<td>5.07 (0.93)</td>
<td>4.20 (0.77)</td>
<td>June 15 – 19, 2017</td>
</tr>
<tr>
<td>Contango Site Visit #7</td>
<td>Microbiology, soils, and water tested.</td>
<td>2.07 (0.38)</td>
<td>1.42 (0.26)</td>
<td>June 20-22, 2017</td>
</tr>
<tr>
<td>(Spring Sampling)</td>
<td>Detritus decomposition trial started.</td>
<td></td>
<td></td>
<td>June 21, 2017</td>
</tr>
<tr>
<td>Saline Tracer Study</td>
<td>Salt added to cells for tracer study.</td>
<td>1.74 (0.32)</td>
<td>0.55 (0.10)</td>
<td>June 21 – July 2, 2017</td>
</tr>
<tr>
<td>Flow interruptions</td>
<td>Flow rates increased causing feed tank to collapse, and flow stoppage.</td>
<td>*</td>
<td>*</td>
<td>July 16, 2017</td>
</tr>
<tr>
<td>Contango Site Visit #8</td>
<td>Microbiology and soils tested.</td>
<td>*</td>
<td>*</td>
<td>July 25 – 26, 2017</td>
</tr>
<tr>
<td>(Summer Sampling)</td>
<td>Detritus bags collected.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow interruptions</td>
<td>Pump issues. Repairs required and new totalizer installed on CWTS 1.</td>
<td>*</td>
<td>*</td>
<td>July 25 - August 16, 2017¹</td>
</tr>
<tr>
<td>Sprayed for aphids</td>
<td>Insecticide applied 7 times to CWTS.</td>
<td>N/A</td>
<td>N/A</td>
<td>July 25 – September 13, 2017</td>
</tr>
<tr>
<td>Water level raised</td>
<td>Sand bags were added to the ends of each cell.</td>
<td>*</td>
<td>*</td>
<td>August 11, 2017</td>
</tr>
</tbody>
</table>

**Beginning of operational period**

| Summer Water Sampling                      | Not completed during Contango Site Visit #8 due to flow interruptions. | 2.40 (0.44) | 1.64 (0.30) | August 18, 2017 | 395 |

| 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 |

1 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>
<thead>
<tr>
<th>Testing Period</th>
<th>DO (mg/L)</th>
<th>Conductivity (µS/cm)</th>
<th>pH</th>
<th>ORP (mV)</th>
<th>Soil redox (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demonstration-scale 2015</td>
<td>10.0</td>
<td>817.9</td>
<td>8.11</td>
<td>147.9</td>
<td>-52</td>
</tr>
<tr>
<td>Demonstration-scale 2016</td>
<td>Commissioning-A¹</td>
<td>15.9</td>
<td>890.9</td>
<td>7.79</td>
<td>143.7</td>
</tr>
<tr>
<td></td>
<td>Commissioning-B²</td>
<td>8.4</td>
<td>1020</td>
<td>7.59</td>
<td>157.6</td>
</tr>
<tr>
<td>Demonstration-scale 2017</td>
<td>Commissioning-B³</td>
<td>4.3</td>
<td>795.9</td>
<td>7.43</td>
<td>18.7</td>
</tr>
<tr>
<td></td>
<td>Operational period⁴</td>
<td>5.3</td>
<td>879.7</td>
<td>7.36</td>
<td>124.9</td>
</tr>
</tbody>
</table>

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.

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.
<table>
<thead>
<tr>
<th>Year</th>
<th>Total Copper Concentrations</th>
<th>Dissolved Copper Concentrations</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td><img src="image" alt="2015 Total Copper" /></td>
<td><img src="image" alt="2015 Dissolved Copper" /></td>
</tr>
<tr>
<td>2016</td>
<td><img src="image" alt="2016 Total Copper" /></td>
<td><img src="image" alt="2016 Dissolved Copper" /></td>
</tr>
<tr>
<td>2017</td>
<td><img src="image" alt="2017 Total Copper" /></td>
<td><img src="image" alt="2017 Dissolved Copper" /></td>
</tr>
</tbody>
</table>

**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.

<table>
<thead>
<tr>
<th>COC (µg/L)</th>
<th>Commissioning period</th>
<th>Operational period</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2015¹</td>
<td>2016²</td>
</tr>
<tr>
<td>Cd</td>
<td></td>
<td></td>
</tr>
<tr>
<td>In</td>
<td>0.0505</td>
<td>0.0240</td>
</tr>
<tr>
<td>Out</td>
<td>0.0248</td>
<td>0.0142</td>
</tr>
<tr>
<td>%</td>
<td>49</td>
<td>40</td>
</tr>
<tr>
<td>Cu</td>
<td></td>
<td></td>
</tr>
<tr>
<td>In</td>
<td>54.5</td>
<td>61.6</td>
</tr>
<tr>
<td>Out</td>
<td>45.0</td>
<td>56.7</td>
</tr>
<tr>
<td>%</td>
<td>17</td>
<td>8</td>
</tr>
<tr>
<td>Mo</td>
<td></td>
<td></td>
</tr>
<tr>
<td>In</td>
<td>11.0</td>
<td>7.6</td>
</tr>
<tr>
<td>Out</td>
<td>11.3</td>
<td>7.6</td>
</tr>
<tr>
<td>%</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Se</td>
<td></td>
<td></td>
</tr>
<tr>
<td>In</td>
<td>11.0</td>
<td>3.7</td>
</tr>
<tr>
<td>Out</td>
<td>11.3</td>
<td>3.4</td>
</tr>
<tr>
<td>%</td>
<td>0</td>
<td>8</td>
</tr>
<tr>
<td>Zn</td>
<td></td>
<td></td>
</tr>
<tr>
<td>In</td>
<td>12.3</td>
<td>92.8</td>
</tr>
<tr>
<td>Out</td>
<td>6.8</td>
<td>49.0</td>
</tr>
<tr>
<td>%</td>
<td>42</td>
<td>47</td>
</tr>
</tbody>
</table>

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 (NO₂) 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 (NO₃) 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 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.

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.](image)

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, $C_f$ is the final concentration, $C_i$ 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).

\[
k = \frac{-\ln \left( \frac{C_f}{C_i} \right)}{HRT}
\]

**Equation 4 – Equation for calculation of first-order removal rate coefficient.**

$k$ is the removal rate coefficient; $C_f$ is the final concentration; $C_i$ is the initial concentration; $HRT$ is the operational hydraulic retention time.

\[
k = \frac{(C_i - C_f)}{HRT}
\]

**Equation 5 – Equation for calculation of zero-order removal rate coefficient.**

$k$ is the removal rate coefficient; $C_f$ is the final concentration; $C_i$ 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.

<table>
<thead>
<tr>
<th>COC</th>
<th>Pilot¹ $k\text{ day}^{-1}$</th>
<th>2016 Demonstration² (Commissioning) $k\text{ day}^{-1}$</th>
<th>2017 Demonstration³ (Operational) $k\text{ day}^{-1}$</th>
<th>Recommended⁴ $k\text{ day}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
<td>Dissolved</td>
<td>Total</td>
<td>Dissolved</td>
</tr>
<tr>
<td>Cd</td>
<td>1.142</td>
<td>0.172</td>
<td>0.174</td>
<td>&gt;0.521⁵</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&gt;0.226⁵</td>
</tr>
<tr>
<td>Cu⁶</td>
<td>1.171</td>
<td>0.0778⁶</td>
<td>0.0740⁶</td>
<td>&gt;0.3100⁶</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&gt;0.1356⁶</td>
</tr>
<tr>
<td>Mo</td>
<td>0.1010</td>
<td>0.0416</td>
<td>0.0468</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N/A</td>
</tr>
<tr>
<td>Se</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>0.3186</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.3069</td>
</tr>
<tr>
<td>Zn</td>
<td>1.144</td>
<td>0.195</td>
<td>0.183</td>
<td>0.512⁵</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.394⁶</td>
</tr>
<tr>
<td>Nitrate</td>
<td>0.559</td>
<td>0.0914</td>
<td>N/A</td>
<td>0.591</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N/A</td>
</tr>
<tr>
<td>Mo</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>0.0006</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.0006</td>
</tr>
<tr>
<td>Se</td>
<td>0.00181</td>
<td>0.000357</td>
<td>0.000316</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N/A</td>
</tr>
</tbody>
</table>

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/m² 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/m² 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/m² (Table 6). These results are consistent with pilot-scale results from another CWTS planted with Carex where 5.1 L/day/m² 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.
Equation 6 – Equation for the calculation of the water loss due to evapotranspiration.

\[ \text{Water loss} \text{ (\%)} = \frac{ET}{Q} \times 100 \]

Q is the flow rate (L/day); ET is the evapotranspiration rate (L/day).

Table 6– Water loss through evapotranspiration in the CWTS.

<table>
<thead>
<tr>
<th>Study</th>
<th>Cell</th>
<th>Water loss(^1)  (L/day)</th>
<th>Water loss(^2)  (L/day/m(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial 1: May 16 – 24, 2017</td>
<td>1A</td>
<td>575.0</td>
<td>8.3</td>
</tr>
<tr>
<td></td>
<td>1B</td>
<td>143.7</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>2A</td>
<td>509.0</td>
<td>8.8</td>
</tr>
<tr>
<td></td>
<td>2B</td>
<td>152.7</td>
<td>2.6</td>
</tr>
<tr>
<td>L/day/m(^2) Average</td>
<td></td>
<td></td>
<td>5.4</td>
</tr>
<tr>
<td>Trial 2: June 8 – 11, 2017</td>
<td>1A</td>
<td>580.8</td>
<td>8.3</td>
</tr>
<tr>
<td></td>
<td>1B</td>
<td>116.2</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>2A</td>
<td>775.7</td>
<td>13.3</td>
</tr>
<tr>
<td></td>
<td>2B</td>
<td>339.4</td>
<td>5.8</td>
</tr>
<tr>
<td>L/day/m(^2) Average</td>
<td></td>
<td></td>
<td>7.3</td>
</tr>
<tr>
<td>Trial 3: June 11 – 15, 2017</td>
<td>1A</td>
<td>292.7</td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td>1B</td>
<td>27.9(^3)</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>2A</td>
<td>273.4</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td>2B</td>
<td>203.6</td>
<td>3.5</td>
</tr>
<tr>
<td>L/day/m(^2) Average</td>
<td></td>
<td></td>
<td>3.2</td>
</tr>
<tr>
<td>L/day/m(^2) Overall Average</td>
<td></td>
<td></td>
<td>5.3</td>
</tr>
</tbody>
</table>

\(^1\) Water loss (L/day) = (initial depth (m) – final depth (m)) \times area of CWTS (m\(^2\)) \times 1000 L/m\(^2\)/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.

\[
\text{Load}_{\text{in}} = C_i \times V
\]

**Equation 7 – Equation for the calculation of load of a constituent into a CWTS over a period of time.**

*Load*$_{\text{in}}$ 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.

\[
\text{Load}_{\text{out(ET)}} = \text{Water Out}_{\text{ET}} \times C_f
\]

**Equation 8 – Equation for the calculation of the load out of a constituent over a period of time, adjusted for evapotranspiration.**

*Load*$_{\text{out(ET)}}$ is load out of a constituent over a period of time, adjusted for evapotranspiration; *Water Out*$_{\text{ET}}$ 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.

<table>
<thead>
<tr>
<th>COC</th>
<th>Form</th>
<th>Load in (mg/day)</th>
<th>Load out$^1$ (mg/day)</th>
<th>Load out Adjusted for evapotranspiration$^2$ (mg/day)</th>
<th>Load removed adjusted for evapotranspiration (mg/day)</th>
<th>Load removed$^3$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cd</td>
<td>D</td>
<td>0.0476</td>
<td>0.0162</td>
<td>0.0131</td>
<td>0.0345</td>
<td>71</td>
</tr>
<tr>
<td></td>
<td>T</td>
<td>0.0283</td>
<td>0.0094</td>
<td>0.0076</td>
<td>0.0207</td>
<td>73</td>
</tr>
<tr>
<td>Cu</td>
<td>D</td>
<td>89.7</td>
<td>31.4</td>
<td>25.4</td>
<td>64.3</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>T</td>
<td>96.2</td>
<td>38.4</td>
<td>31.1</td>
<td>65.1</td>
<td>67</td>
</tr>
<tr>
<td>Mo</td>
<td>D</td>
<td>11.5</td>
<td>4.8</td>
<td>3.9</td>
<td>7.6</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>T</td>
<td>12.6</td>
<td>5.2</td>
<td>4.2</td>
<td>8.3</td>
<td>66</td>
</tr>
<tr>
<td>Se</td>
<td>D</td>
<td>7.2</td>
<td>0.9</td>
<td>0.7</td>
<td>6.5</td>
<td>89</td>
</tr>
<tr>
<td></td>
<td>T</td>
<td>6.4</td>
<td>0.9</td>
<td>0.7</td>
<td>5.7</td>
<td>88</td>
</tr>
<tr>
<td>Zn</td>
<td>D</td>
<td>90.0</td>
<td>3.4</td>
<td>2.8</td>
<td>87.2</td>
<td>97</td>
</tr>
<tr>
<td></td>
<td>T</td>
<td>91.6</td>
<td>7.5</td>
<td>6.0</td>
<td>85.5</td>
<td>93</td>
</tr>
</tbody>
</table>

$^1$ 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

<table>
<thead>
<tr>
<th>Fraction</th>
<th>Description</th>
<th>When COCs Become Unstable and Release to the Water Column</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Exchangeable fraction for adsorbed minerals</td>
<td>Readily released (i.e., soluble and exchangeable)</td>
</tr>
<tr>
<td>2</td>
<td>Mineral fraction bound to carbonates or solubilized at pH 5</td>
<td>Decreased pH</td>
</tr>
<tr>
<td>3</td>
<td>Oxidized mineral fraction bound to Fe-Mn oxides</td>
<td>Reducing conditions</td>
</tr>
<tr>
<td>4</td>
<td>Reduced mineral fraction and sulphides</td>
<td>Oxidizing conditions</td>
</tr>
<tr>
<td>5</td>
<td>Residual mineral fraction (primary and secondary minerals)</td>
<td>Not expected to be released in solution over time under conditions normally encountered in nature</td>
</tr>
</tbody>
</table>

1Method 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.

<table>
<thead>
<tr>
<th></th>
<th>Initial weight of C. aquatilis (g)</th>
<th>Dry weight after 34 days (g)</th>
<th>Decrease in weight after 34 days (%)</th>
<th>Dry weight after 82 days (g)</th>
<th>Decrease in weight after 83 days (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>5.0&lt;sup&gt;1&lt;/sup&gt;</td>
<td>2.1</td>
<td>57%</td>
<td>1.7</td>
<td>65%</td>
</tr>
<tr>
<td>1B</td>
<td></td>
<td>2.1</td>
<td>59%</td>
<td>1.7</td>
<td>67%</td>
</tr>
<tr>
<td>2A</td>
<td></td>
<td>2.3</td>
<td>54%</td>
<td>2.0</td>
<td>61%</td>
</tr>
<tr>
<td>2B</td>
<td></td>
<td>2.4</td>
<td>52%</td>
<td>1.9</td>
<td>63%</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td><strong>2.2</strong></td>
<td>56%</td>
<td><strong>1.8</strong></td>
<td>64%</td>
</tr>
</tbody>
</table>

<sup>1</sup> Initial weight prior to bags being placed in CWTS.
<sup>2</sup> Weights of C. aquatilis corrected by subtracting the increase in weight from the polyester fiber fill 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., chalcolite [CuS], covellite [Cu$_2$S]). 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 (H₂S) and other sulfide species (i.e., bisulfide ion (HS⁻), sulfide ion [S²⁻]; 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.

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>2014 &amp; 2015</th>
<th>2016</th>
<th>2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>detritus</td>
<td>NT</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>moss</td>
<td>3</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>root</td>
<td>6</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>soil</td>
<td>4</td>
<td>8</td>
<td>9</td>
</tr>
</tbody>
</table>

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\(_2\)O), 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...
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 regimen 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.

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**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/m² 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.

<table>
<thead>
<tr>
<th>Timing</th>
<th>Task</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>April 2018</td>
<td>Develop a flow rate schedule for 2018.</td>
<td>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.</td>
</tr>
<tr>
<td></td>
<td>Develop sampling plan for 2018</td>
<td>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.</td>
</tr>
<tr>
<td></td>
<td>Develop aphid control and monitoring and plan for 2018</td>
<td>A consistent control and monitoring plan will aid efforts to control the aphid population residing in the demonstration-scale CWTS.</td>
</tr>
<tr>
<td>April/May 2018</td>
<td>Start water flow to CWTS</td>
<td>Begin 2018 demonstration-scale CWTS program</td>
</tr>
<tr>
<td></td>
<td>Add sandbags on top of existing sandbags along edges of CWTS</td>
<td>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)</td>
</tr>
<tr>
<td></td>
<td>Add sandbags to the end of the CWTS cells to increase the water depth to ~20 cm</td>
<td>Raising the water levels will promote the desired reducing conditions in the CWTS.</td>
</tr>
<tr>
<td></td>
<td>Implement aphid control using insecticide on a routine schedule</td>
<td>Begin applications in early May when vegetation begins to become green, in order to control the aphid population before an infestation occurs.</td>
</tr>
<tr>
<td>Ongoing through 2018 sampling season</td>
<td>Routine sampling program</td>
<td>Follow sampling plan from May to September 2018 for routine collection of water, soil, microbial, plant, and detritus samples.</td>
</tr>
<tr>
<td></td>
<td>Monitor for the presence of aphids in the CWTS and surrounding areas (W10 and W15 areas).</td>
<td>Determine if the aphid presence is isolated to the CWTS. Determine if more aggressive control measures are needed.</td>
</tr>
<tr>
<td>July/Aug 2018</td>
<td>Conduct a vegetation plot harvest. Collect all above water biomass of <em>C. aquatilis</em> in a 1m x 1m plot</td>
<td>To determine quantity of biomass per m²</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------------------------------------------------------------------------------------------</td>
<td>----------------------------------------</td>
</tr>
<tr>
<td></td>
<td>Conduct evapotranspiration study</td>
<td>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.</td>
</tr>
<tr>
<td>Sept 2018 (If needed)</td>
<td>Replant CWTS</td>
<td>Replant areas of the CWTS that were impacted by aphids if needed.</td>
</tr>
<tr>
<td>December 2018</td>
<td>Report</td>
<td>2018 Update Report</td>
</tr>
</tbody>
</table>
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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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.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Series 1</th>
<th></th>
<th>Series 2</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1A</td>
<td>1B</td>
<td>2A</td>
</tr>
<tr>
<td>Width (m)</td>
<td>Inflow</td>
<td>3.6</td>
<td>3.8</td>
<td>3.6</td>
</tr>
<tr>
<td></td>
<td>Outflow</td>
<td>3.3</td>
<td>3.8</td>
<td>3.3</td>
</tr>
<tr>
<td>Length (m)</td>
<td></td>
<td>9.8</td>
<td>9.5</td>
<td>8.7</td>
</tr>
<tr>
<td>Approximate surface area at soil (m²)</td>
<td></td>
<td>33.8</td>
<td>36.1</td>
<td>30.0</td>
</tr>
<tr>
<td>Total area of system at soil (m²)</td>
<td></td>
<td>69.9</td>
<td>58.2</td>
<td></td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>Test method</th>
<th>Pilot-scale</th>
<th>Demonstration-scale</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial soil</td>
<td>Tested soil (June, 2014)</td>
</tr>
<tr>
<td>SPLP Copper (mg/L)¹</td>
<td>-</td>
<td>0.00546-0.0296²</td>
</tr>
<tr>
<td>Total Copper (mg/kg)</td>
<td>5.3-5.5</td>
<td>210-1400²</td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>Water</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dissolved and total metals</td>
<td>Weekly, outflow of each cell and feed</td>
</tr>
<tr>
<td>Ammonia</td>
<td></td>
</tr>
<tr>
<td>Nitrate</td>
<td></td>
</tr>
<tr>
<td>Nitrite</td>
<td></td>
</tr>
<tr>
<td>Flow rate</td>
<td>Weekly, feed</td>
</tr>
<tr>
<td>pH, DO, ORP, Conductivity (in situ)</td>
<td>Weekly, all cells and feed</td>
</tr>
<tr>
<td>Anion Sum</td>
<td></td>
</tr>
<tr>
<td>Cation Sum</td>
<td></td>
</tr>
<tr>
<td>Hardness (CaCO₃)</td>
<td></td>
</tr>
<tr>
<td>Ion Balance</td>
<td></td>
</tr>
<tr>
<td>Total Dissolved Solids (TDS)</td>
<td></td>
</tr>
<tr>
<td>Chloride (Cl)</td>
<td></td>
</tr>
<tr>
<td>Sulphate (SO₄)</td>
<td></td>
</tr>
<tr>
<td>Nitrogen (Total)</td>
<td></td>
</tr>
<tr>
<td>Alkalinity</td>
<td>Monthly, outflow of each cell and feed</td>
</tr>
<tr>
<td>pH</td>
<td></td>
</tr>
<tr>
<td>Conductivity</td>
<td></td>
</tr>
<tr>
<td>Chemical Oxygen Demand (COD)</td>
<td></td>
</tr>
<tr>
<td>Total Organic Carbon (TOC)</td>
<td></td>
</tr>
<tr>
<td>Total Kjeldahl Nitrogen (TKN)</td>
<td></td>
</tr>
<tr>
<td>Total Suspended Solids (TSS)</td>
<td></td>
</tr>
<tr>
<td>Dissolved Organic Carbon (DOC)</td>
<td></td>
</tr>
<tr>
<td>Bicarbonate (HCO₃)</td>
<td></td>
</tr>
<tr>
<td>Carbonate (CO₃)</td>
<td></td>
</tr>
<tr>
<td>Hydroxide (OH)</td>
<td></td>
</tr>
</tbody>
</table>
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.

<table>
<thead>
<tr>
<th>Soil</th>
<th>Analyses completed on soil sample</th>
<th>Analyses completed on special leach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative soil redox (in situ)</td>
<td>Monthly, all probes (6 per cell)</td>
<td>Seasonally (3x per year) from a depth of 0-10 cm.</td>
</tr>
<tr>
<td>Analyses completed on soil sample</td>
<td>SAR, pH, EC, %sat, Ca, F, Mg, Na, K, Cl, SO4</td>
<td>Seasonally (3x per year) from a depth of 0-10 cm.</td>
</tr>
<tr>
<td>Available NPK and sulphur</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alkalinity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bicarbonate (HCO₃)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbonate (CO₃)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Organic Carbon (TOC)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metals Analysis (Total)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sulfur by LECO</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metals Leach</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AVS+SEM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sequential Leaching (5 Acid Test)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metals SPLP</td>
<td></td>
<td>Spring Sampling (1x per year).</td>
</tr>
<tr>
<td>Analyses completed on special leach</td>
<td>Bromide (Br)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Chloride (Cl)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sulphate (SO₄)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fluoride (F)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Alkalinity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bicarbonate (HCO₃)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Carbonate (CO₃)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hydroxide (OH)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dissolved Organic Carbon (DOC)</td>
<td>Seasonally (3x per year)</td>
</tr>
<tr>
<td></td>
<td>Ammonia</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nitrate</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nitrite</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total Dissolved Solids (TDS)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Anion Sum</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cation Sum</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cation/EC ratio</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ion Balance</td>
<td></td>
</tr>
</tbody>
</table>

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 HNO₃ 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 *Carex aquatilis* and moss samples were collected for metals analysis at the final sampling period of the demonstration-scale CWTS. Above water vegetation for *Carex 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>
<thead>
<tr>
<th>Plant tissue samples</th>
<th>Carex aquatilis and aquatic moss, each cell, year end</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Metals by ICPMS (Co, Cu, Fe, Pb, Li, Mg, Mn, Mo, Ni, P, K, Se, Ag, Na, Sr, Ti, Sn, Ti, U, V, Zn, Zr)</td>
<td></td>
</tr>
</tbody>
</table>

### 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 m³ tank was added to the CWTS area, and another HRT tracer study was conducted. The 1 m³ 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 m³ 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°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.

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, α=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.

Equation A1 – Equation for the calculation of load of a constituent into a CWTS over a period of time.

\[ \text{Load}_{\text{in}} = C_i \times V \]

Equation A2 – Equation for the calculation of the load of a constituent out of a CWTS over a period of time.

\[ \text{Load}_{\text{out}} = C_f \times V \]

Equation A3 – Equation for the calculation of the load removed over a period of time.

\[ \text{Load Removed} = \text{Load}_{\text{in}} - \text{Load}_{\text{out}} \]

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/m², 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 m², and for series 2 the surface area is 58.2 m². 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.
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 ($C_i$) and outflow ($C_f$) 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.
\[
k = \frac{-\ln \left( \frac{C_f}{C_i} \right)}{\text{HRT}}
\]

**Equation A9 – Equation for calculation of first-order removal rate coefficient.**

\(k \) is the removal rate coefficient, \(C_f\) is the final concentration, \(C_i\) is the initial concentration, and HRT is the hydraulic retention time.

\[
k = \frac{(C_i - C_f)}{\text{HRT}}
\]

**Equation A10 – Equation for calculation of zero-order removal rate coefficient.**

\(k \) is the removal rate coefficient, \(C_f\) is the final concentration, \(C_i\) is the initial concentration, and HRT is the hydraulic retention time.
A7. References


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### Table B1 - Summary of extractable fractions from sequential extraction procedure for the speciation of metals\(^1\).  

<table>
<thead>
<tr>
<th>Fraction</th>
<th>Description</th>
<th>COCs unstable when</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Exchangeable fraction for adsorbed minerals</td>
<td>Readily released (i.e., soluble and exchangeable)</td>
</tr>
<tr>
<td>2</td>
<td>Mineral fraction bound to carbonates or solubilized at pH 5</td>
<td>Decreased pH</td>
</tr>
<tr>
<td>3</td>
<td>Oxidized mineral fraction bound to Fe-Mn oxides</td>
<td>Reducing conditions</td>
</tr>
<tr>
<td>4</td>
<td>Reduced mineral fraction and sulphides</td>
<td>Oxidizing conditions</td>
</tr>
<tr>
<td>5</td>
<td>Residual mineral fraction (primary and secondary minerals)</td>
<td>Not expected to be released in solution over time under conditions normally encountered in nature</td>
</tr>
</tbody>
</table>

\(^1\)Method based on Tessier et al., 1979.
### Table B2 – Total and leachable soil copper concentrations in first year of operations.

<table>
<thead>
<tr>
<th>CWTS Cell</th>
<th>Sampling Date</th>
<th>Days in Operation</th>
<th>Sample Depth (cm)</th>
<th>Total Cu (mg/kg)</th>
<th>SPLP Cu (mg/L)</th>
<th>Leachable Cu (mg/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>28-Aug-14</td>
<td>1</td>
<td>Initial Composite</td>
<td>-</td>
<td>0.298 (0.148-0.608)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>19-Jun-15</td>
<td>58</td>
<td>0-5</td>
<td>960</td>
<td>0.055†</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>16-Aug-15</td>
<td>116</td>
<td>10-20</td>
<td>950</td>
<td>0.187</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>18-Sep-15</td>
<td>149</td>
<td>10-20</td>
<td>1300</td>
<td>0.049</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>29-Sep-15</td>
<td>160</td>
<td>10-20</td>
<td>910</td>
<td>0.069</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>15-Jun-16</td>
<td>194</td>
<td>0-10</td>
<td>1440</td>
<td>-</td>
<td>0.953</td>
</tr>
<tr>
<td></td>
<td>15-Jun-16</td>
<td>194</td>
<td>10-20</td>
<td>1210</td>
<td>-</td>
<td>0.66</td>
</tr>
<tr>
<td></td>
<td>8-Jul-16</td>
<td>217</td>
<td>0-10</td>
<td>1430</td>
<td>-</td>
<td>0.603</td>
</tr>
<tr>
<td></td>
<td>8-Jul-16</td>
<td>217</td>
<td>10-20</td>
<td>1730</td>
<td>-</td>
<td>0.832</td>
</tr>
<tr>
<td></td>
<td>7-Sep-16</td>
<td>247</td>
<td>0-10</td>
<td>1290</td>
<td>-</td>
<td>0.449</td>
</tr>
<tr>
<td></td>
<td>20-Jun-17</td>
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<td>0-10</td>
<td>1470</td>
<td>0.315</td>
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</tr>
<tr>
<td></td>
<td>25-Jul-17</td>
<td>371</td>
<td>0-10</td>
<td>1630</td>
<td>0.529</td>
<td>0.463</td>
</tr>
<tr>
<td></td>
<td>12-Sep-17</td>
<td>420</td>
<td>0-10</td>
<td>1490</td>
<td>0.590</td>
<td>0.481</td>
</tr>
<tr>
<td>1B</td>
<td>28-Aug-14</td>
<td>1</td>
<td>Initial Composite</td>
<td>-</td>
<td>0.298 (0.148-0.608)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>19-Jun-15</td>
<td>58</td>
<td>0-5</td>
<td>1400</td>
<td>0.033†</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>16-Aug-15</td>
<td>116</td>
<td>10-20</td>
<td>1400</td>
<td>0.209</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>18-Sep-15</td>
<td>149</td>
<td>10-20</td>
<td>830</td>
<td>0.065</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>29-Sep-15</td>
<td>160</td>
<td>10-20</td>
<td>880</td>
<td>0.059</td>
<td>-</td>
</tr>
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<td></td>
<td>15-Jun-16</td>
<td>194</td>
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<td>1130</td>
<td>-</td>
<td>1.01</td>
</tr>
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<td></td>
<td>15-Jun-16</td>
<td>194</td>
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<td>8-Jul-16</td>
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<td>0-10</td>
<td>1250</td>
<td>-</td>
<td>1.11</td>
</tr>
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<td>8-Jul-16</td>
<td>217</td>
<td>10-20</td>
<td>1620</td>
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<td>1.21</td>
</tr>
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<td></td>
<td>7-Sep-16</td>
<td>247</td>
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<td>0.197</td>
</tr>
<tr>
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<td>20-Jun-17</td>
<td>336</td>
<td>0-10</td>
<td>1290</td>
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<td>0.338</td>
</tr>
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<td></td>
<td>25-Jul-17</td>
<td>371</td>
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<td>1100</td>
<td>0.290</td>
<td>0.165</td>
</tr>
<tr>
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<td>12-Sep-17</td>
<td>420</td>
<td>0-10</td>
<td>1100</td>
<td>0.716</td>
<td>0.492</td>
</tr>
</tbody>
</table>

† 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.

<table>
<thead>
<tr>
<th>CWTS Cell</th>
<th>Sampling Date</th>
<th>Days in Operation</th>
<th>Sample Depth (cm)</th>
<th>Total Cu (mg/kg)</th>
<th>SPLP Cu (mg/L)</th>
<th>Leachable Cu (mg/kg)</th>
</tr>
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<tbody>
<tr>
<td>2A</td>
<td>28-Aug-14</td>
<td>1</td>
<td>Initial Composite</td>
<td>-</td>
<td>0.298 (0.148-0.608)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>19-Jun-15</td>
<td>58</td>
<td>0-5</td>
<td>1175</td>
<td>0.037</td>
<td>-</td>
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<td></td>
<td>16-Aug-15</td>
<td>116</td>
<td>10-20</td>
<td>660</td>
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<td>-</td>
</tr>
<tr>
<td></td>
<td>18-Sep-15</td>
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<td>10-20</td>
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<td>2B</td>
<td>28-Aug-14</td>
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<td>Initial Composite</td>
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<td>0-5</td>
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<td>1140</td>
<td>0.596</td>
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</table>

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.

<table>
<thead>
<tr>
<th></th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total</strong></td>
<td><img src="image1.png" alt="Graph" /></td>
<td><img src="image2.png" alt="Graph" /></td>
<td><img src="image3.png" alt="Graph" /></td>
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<tr>
<td><strong>Dissolved</strong></td>
<td><img src="image1.png" alt="Graph" /></td>
<td><img src="image2.png" alt="Graph" /></td>
<td><img src="image3.png" alt="Graph" /></td>
</tr>
</tbody>
</table>

### Notes:
- CWTS 1 15-Aug-2015 (Day 115) and CWTS 2 15-Aug-2015 (Day 115) are shown for the Total graph.
- CWTS 1 17-Sep-2015 (Day 148) and CWTS 2 17-Sep-2015 (Day 148) are shown for the Dissolved graph.
- The Maxxam (2015 results) detection limit (DL) 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.
<table>
<thead>
<tr>
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<tr>
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</tr>
</tbody>
</table>

**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.
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 B7 – Copper concentrations in the demonstration-scale wetland in 2017.**
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

<table>
<thead>
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<th>Item</th>
<th>Date</th>
<th>Activities</th>
<th>Actual</th>
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<tr>
<td></td>
<td></td>
<td><strong>Construction</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>June 1-14 2014</td>
<td>Identify potential location for demonstration scale CWTS (Contango site visit – 1 scientist)</td>
<td>Completed</td>
</tr>
<tr>
<td></td>
<td>June - July 2014</td>
<td>Engineering and geotechnical (Minto)</td>
<td>Completed</td>
</tr>
<tr>
<td></td>
<td>July 2014</td>
<td>Construction (Minto)</td>
<td>Completed</td>
</tr>
<tr>
<td></td>
<td>August 2014</td>
<td>Planting and bringing system online (Contango site visit – 1 scientist, 1 technologist), coordinate for local students to assist</td>
<td>Completed (no students available, brought 2 technologists)</td>
</tr>
<tr>
<td></td>
<td>2014</td>
<td>Acclimation and maturation at constant flow rate, ~20 hr HRT</td>
<td>Completed</td>
</tr>
<tr>
<td></td>
<td>September</td>
<td>Contango site visit/checkup (1 technologist, 1 scientist)</td>
<td>Did not occur because construction was last week of August</td>
</tr>
<tr>
<td></td>
<td>2015</td>
<td>Continued commissioning. Operation at constant flow rate, ~20 hr HRT</td>
<td>Completed (at shorter HRT)</td>
</tr>
<tr>
<td></td>
<td>Spring</td>
<td>Contango site visit/checkup (1 technologist, 1 scientist), includes micro sampling</td>
<td>Completed</td>
</tr>
<tr>
<td></td>
<td>Summer - Increase depth from 10 cm to 20 cm (1 technologist), includes micro sampling</td>
<td>Completed (scientist)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fall - Contango site visit/checkup (1 technologist), includes micro sampling</td>
<td>Completed (scientist)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2016</td>
<td>Minto to add sandbags prior to first site visit and begin W15 creek monitoring</td>
<td>Completed May/June 2016</td>
</tr>
<tr>
<td></td>
<td>Spring</td>
<td>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.</td>
<td>Completed June 2016</td>
</tr>
<tr>
<td></td>
<td>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.</td>
<td>Completed July 2016</td>
<td></td>
</tr>
<tr>
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<td>Fall - Contango site visit/checkup (1 technologist), includes microbial sampling and tasks outlined in Table 5 of report</td>
<td>Completed September 2016</td>
<td></td>
</tr>
<tr>
<td>Year</td>
<td>Event Description</td>
<td>Completion Date</td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>--------------------</td>
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</tr>
<tr>
<td>2017</td>
<td>Continued commissioning operations at constant flow rate.</td>
<td>Completed May 2017</td>
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</tr>
<tr>
<td></td>
<td>Two evapotranspiration studies were completed</td>
<td>May/June 2017</td>
<td></td>
</tr>
<tr>
<td></td>
<td>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.</td>
<td>Completed June 2017</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Summer - Contango site visit/checkup (1 scientist), includes microbial sampling and tasks outlined in Appendix A of report.</td>
<td>Completed July 2017</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Minto added sandbags to outflows of CWTS cells to increase water depth</td>
<td>August 2017</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Commissioning completed and beginning of operational period</td>
<td>Completed August 2017</td>
<td></td>
</tr>
<tr>
<td>2017</td>
<td>Fall – Contango site visit/checkup (1 scientist), includes microbial sampling and tasks outlined in Table 5 of report.</td>
<td>Completed by Minto, after being taught microbial sampling by Contango. No site visit needed by Contango.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Monitor soil redox. Determine when it consistently reaches targeted range.</td>
<td>Completed throughout 2017</td>
<td></td>
</tr>
<tr>
<td>2017</td>
<td>Perform water sampling</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2017</td>
<td>Performance monitoring</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fluctuate flow rates, based on expected amount of water for full-scale wetland (scaled to size). Evaluate performance of wetland at different key periods.</td>
<td>Throughout 2018,</td>
<td></td>
</tr>
<tr>
<td>2018</td>
<td>Develop a flow rate schedule, sampling plan, and aphid control and monitoring plan for 2018</td>
<td>March, 2018</td>
<td></td>
</tr>
<tr>
<td>2018</td>
<td>Operations</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>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</td>
<td>April/May 2018</td>
<td></td>
</tr>
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</table>
### 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
- Conduct evapotranspiration study for warmer months
- July/August 2018

### Fall
- Contango site visit (if necessary), replanting if needed.
- September 12, 2018

### Reporting
- 2014-2018
- Reporting will be performed annually, with verbal and/or emailed interim updates
- On Schedule

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