# Summary of Site Specific Studies on Tundra Wetland Treatment Areas in Nunavut

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**September 18, 2015**

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## Acknowledgements

The authors would like to thank the many people who contributed to the CWRS research program that produced the data necessary to inform the development of this document. Especially the members of the Wastewater Treatment Advisory Committee (WTAC) who offered technical review. The WTAC committee was comprised of Dr. Barry Warner of the University of Waterloo, Dr. Donald Mavinic of the University of British Columbia, Dr. Graham Gagnon of Dalhousie University, Jamal Shirley of the Nunavut Research Institute, Dr. Bu Lam and Bill Westwell of the CGS department of the GN.

The authors express gratitude to the many people who provided support in the hamlet communities in Nunavut of Coral Harbour, Kugaaruk, and Grise Fiord. Thank you to the Nunavut Research Institute for providing laboratory space at the Northern Water Quality Laboratory in Iqaluit, NU. The research program was made possible with the hard work of many of the graduate students from Dr. Jamieson's lab. Thank you to the students.

# Table of Contents

## List of Figures

## List of Tables

## List of Abbreviations

| | |
|---|---|
| % | Percent |
| °C | Degrees Celsius |
| APHA | American Public Health Association |
| $BOD_5$ | Five-Day Biochemical Oxygen Demand |
| *C** | Background Concentration |
| CAWT | Centre for Alternative Wastewater Treatment |
| $CBOD_5$ | Five-Day Carbonaceous Biochemical Oxygen Demand |
| CCME | Canadian Council of Ministers of the Environment |
| CFU/100mL | Colony Forming Units per 100 mL |
| CGS | Community and Government Services |
| cm | Centimetre |
| CWRS | Centre for Water Resources Studies |
| d | Day |
| DO | Dissolved Oxygen |
| *E. coli* | *Escherichia coli* |
| EC | Environment Canada |
| *et al.* | *Et alii* |
| GN | Government of Nunavut |
| GPS | Global Positioning System |
| ha | Hectare |
| HLR | Hydraulic Loading Rate |
| HRT | Hydraulic Retention Time |
| *i.e.* | *Id est* |
| ISE | Ion Selective Electrode |
| $k$ | Areal First Order Rate Constant |
| $k_{20}$ | Areal First Order Rate Constant Normalized to 20°C |
| km | Kilometre |
| L | Litre |
| m | Metre |

| | |
|---|---|
| $m^2$ | Square Metre |
| $m^3$ | Cubic Metre |
| mg | Milligram |
| mL | Millilitre |
| mm | Millimetre |
| MPN/100mL | Most Probable Number of Colony Forming Units per 100mL |
| *N* | Number of Tanks |
| *n* | Sample Number |
| $NH_3$-N | Un-ionized Ammonia Nitrogen |
| $NO_3$-N | Nitrate Nitrogen |
| NPS | National Performance Standards |
| NU | Nunavut |
| NWB | Nunavut Water Board |
| NWT | Northwest Territories |
| O&M | Operation and Maintenance |
| *P* | Apparent Number of Tanks |
| RTK | Real Time Kinematic |
| RWT | Rhodamine WT |
| Sp. cond. | Specific Conductivity |
| SSF | Subsurface flow |
| St. Dev. | Standard Deviation |
| TAN | Total Ammonia Nitrogen |
| TIS | Tanks-In-Series |
| TN | Total Nitrogen |
| TP | Total Phosphorus |
| TSS | Total Suspended Solids |
| VSS | Volatile Suspended Solids |
| WS | Wetland Segment |
| WSER | Wastewater Systems Effluent Regulations |
| WSP | Wastewater Stabilization Pond |

| | |
|---|---|
| WTA | Wetland Treatment Area |
| WTAC | Wastewater Treatment Advisory Committee |
| WWTP | Wastewater Treatment Plant |
| $\mu S$ | Micro Siemen |

## Executive Summary


This document summarizes the main findings from field studies conducted on several tundra wetland treatment systems in the Territory of Nunavut. The summary was prepared by the Centre for Water Resources Studies (CWRS) at Dalhousie University for the Community and Government Services (CGS) department of the Government of Nunavut (GN). This summary of the treatment performance of tundra wetland treatment areas (WTAs) is a deliverable of a research contract on municipal wastewater infrastructure in Nunavut funded by the GN and granted to CWRS.

Sixteen out of twenty-five of the hamlets in Nunavut treat municipal wastewater with a wastewater stabilization pond (WSP), or an un-engineered lake lagoon, in combination with a tundra WTA. Water quality improvements have been documented in many of these tundra WTAs, and in wetlands in other cold climate conditions in peer-reviewed literature. However, there has been a lack of design criteria and modeling tools to allow for development of a standardized design process due to the limited comprehensive datasets from tundra WTAs in the Canadian Arctic. This study was conducted in recognition of the need for more information on the functioning of these WTAs to inform the formation of regulations and design criteria.

The CWRS research program was conducted from 2011 to 2013 to assess the treatment performance and to identify the key components required to facilitate the design and assessment of WTAs in Nunavut. The tundra WTAs in the hamlets of Coral Harbour, Kugaaruk, and Grise Fiord were assessed with comprehensive site-specific studies. The studies involved detailed characterization of the hydrology, hydraulics, and hydrogeology of the WTAs. Additionally, the physical environment and treatment performance of these WTAs were assessed.

Results from the studies indicated that: (1) comprehensive site-specific hydrological, hydraulic, and hydrogeological studies are recommended for any WTA that is to be used for municipal wastewater management; (2) temporal changes in treatment performance should be characterized; (3) a modified version of a tanks-in-series (TIS) model was demonstrated to be an effective tool to predict treatment performance of WTAs; and (4) an initial assessment of first order rate constants are comparable to lower range values derived from wetlands operating in cold, but non-arctic, regions.

This study showed that tundra WTAs can be an important component of the treatment train, with some of the WTAs meeting southern regulatory standards of 25/25 mg/L for $BOD_5$ and TSS, and 1.25 mg/L for $NH_3$-N. However, this was not consistent in all three of the WTAs studied. The studies demonstrated that the performance of WTAs is affected by the unique set of natural physical attributes of each site. Therefore design and management strategies for these systems will have to recognize and address these intersystem differences.

## Preface

In 2012, National Performance Standards (NPS) were introduced by Environment Canada (EC) to harmonize the nation-wide treatment requirements for municipal wastewater (Government of Canada, 2012, CCME 2009). The EC Wastewater Systems Effluent Regulations (WSER) stipulate that all wastewater treatment facilities with effluent capacities of 100 $m^3$/d or greater must comply with discharge quality objectives of 25 mg/L for $CBOD_5$ and TSS, and 1.25 mg/L for $NH_3$-N. In recognition of the unique challenges associated with wastewater treatment in Canada's Northern provinces and territories, a grace period was granted to the Northwest Territories, Nunavut, and above the 54$^{th}$ parallel in Quebec and Newfoundland and Labrador, to facilitate research on northern treatment facilities. The resulting research is meant to inform the development of regulations specifically for the Northern provinces and territories.

The summary of treatment performance of tundra WTAs presented herein describe the research outcomes obtained during the grace period. It is hoped that the information collected during the site-specific studies will provide the data necessary to enable: (i) an assessment of the treatment performance and driving factors affecting performance, and (ii) development of design guidelines based on the factors affecting treatment performance.

This guideline document has been written by the Centre for Water Resources Studies (CWRS) at Dalhousie University. The Community and Government Services (CGS) department of the Government of Nunavut (GN) awarded funding to CWRS to conduct site-specific research programs at the sites described within this document. The site-specific studies took place during the summer treatment seasons from 2011 to 2013. The funding was also granted to develop design guidelines based on the site-specific research findings. These design guidelines are presented under a separate cover CWRS (2015).

Readers looking for further technical information on tundra wetland treatment areas in Nunavut may refer to:

- Hayward, J., Jamieson, R., Boutilier, L., Goulden, T., & Lam, B. (2014). Treatment performance assessment and hydrological characterization of an arctic tundra wetland receiving primary treated municipal wastewater. *Ecol. Eng.* 73, 786-797.
- Hayward, J. & Jamieson, R. (2015). Derivation of treatment rate constants for an arctic tundra wetland receiving primary treated municipal wastewater. *Ecol. Eng.* 82, 165-174.
- CWRS (2015). Guidelines for the design and assessment of tundra wetland treatment areas in Nunavut. Report prepared for the CGS Government of Nunavut. Centre for Water Resources Studies. Halifax, NS.

# 1.0 Introduction

## 1.1 Purpose

This document provides a summary of the treatment performance of tundra wetland treatment areas (WTAs) for applications in municipal wastewater treatment in Nunavut, Canada. Until recently, there has been a lack of information on the performance expectations of tundra wetland treatment areas. As a result, the process of including tundra WTAs as a component of the wastewater treatment train in the Far North has not been standardized.

The findings from this report provides regulators with an assessment on the performance of existing WTAs. Additionally, the driving factors affecting treatment performance have been identified. End-users such as wetland designers may refer to this report to assess potential treatment performance. The findings from this report informed the formation of the design guideline recommendations presented in "*Guidelines for the design and assessment of tundra wetland treatment areas in Nunavut"* by CWRS (2015).

## 1.2 Wastewater treatment in Nunavut

Conventional wastewater treatment plants (WWTPs) have repeatedly been cited as an inappropriate option for many remote and relatively small communities. The prohibitively high capital and maintenance costs, and intensive requirement for technical supervision and optimization, renders mechanical treatment plants a less favorable choice for most communities in Nunavut (Yates et al., 2012, Krkosek et al., 2012, Hayward et al., 2014, Chouinard et al., 2014a).

As a result, passive methods of municipal wastewater treatment tend to be the most successful in Nunavut due to the low operation and maintenance requirements. Passive treatment of wastewater in Nunavut occurs in most communities during a three to four month period spanning from the spring freshet in June to the freeze-up in September. This period is termed the treatment season.

Municipal wastewater treatment in Nunavut consists of a combination of methods. There are twenty-five hamlets located in Nunavut, of which sixteen use a wastewater stabilization pond (WSP), or an un-engineered lake lagoon, in combination with a tundra wetland treatment area (WTA). There are also a few hamlets that directly discharge untreated effluent into WTAs, natural ponds, and marine receiving environments. The WSPs can have a scheduled decant or passively discharge effluent onto the WTAs during the treatment season. There are only three hamlets that use mechanical WWTPs in Nunavut (Johnson et al., 2014).

## 1.3 Tundra wetland treatment areas

Wetlands have natural attenuation processes that provide treatment of some of the contaminants in municipal wastewater effluent. This tendency of wetlands to naturally attenuate contaminants has been harnessed with the use of constructed wetlands, which are engineered to emulate the treatment processes occurring in natural wetlands. Tundra WTAs consist of saturated and/or ponded areas of the tundra where wastewater has been applied either directly or following primary treatment. Tundra WTAs are different from constructed wetlands, as they are typically un-engineered, and possibly not intentionally created (Hayward et al., 2014, Chouinard et al., 2014a).

Tundra WTAs are characterized by the natural physical attributes of the landscape such as the topography, soil depth, and drainage area. Despite the similarity to natural wetlands, the tundra WTAs are distinctly different from natural tundra wetlands in their hydrology, vegetation, nutrient availability, and organic loading (Chouinard et al., 2014b, Hayward et al., 2014). Figure 1 and Figure 2 shows tundra WTAs in comparison to natural tundra wetlands. There are notable differences, especially in terms of vegetation biomass. In some cases, the discharge of effluent onto the tundra has created a wetland area that was not in existence prior to receiving effluent (Hayward et al., 2014).

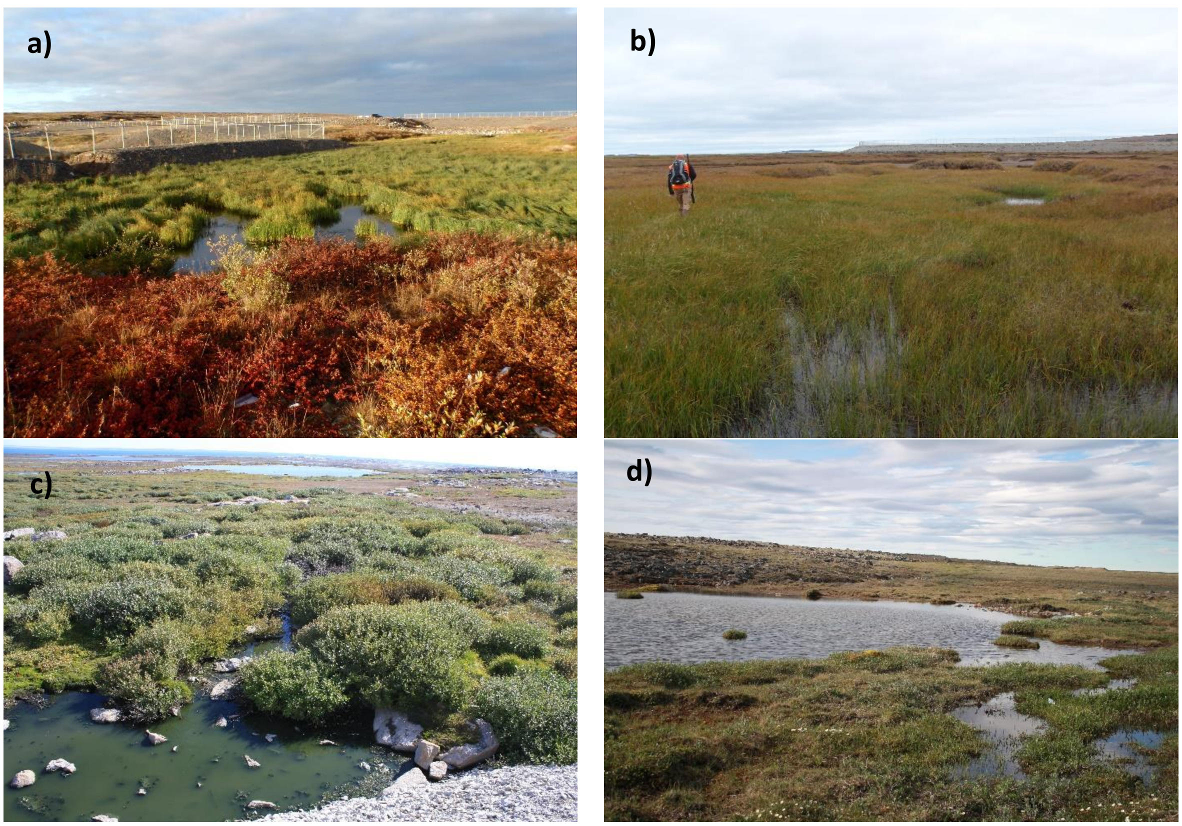



Figure 1. Photographs of: (a) the WTA in Kugluktuk, NU taken on August 30, 2012, (b) a natural wetland in Kugluktuk, NU taken on August 30, 2012, (c) the WTA in Coral Harbour, NU taken on September 4, 2011, and (d) the reference natural wetland in Coral Harbour, NU taken on July 11, 2012.

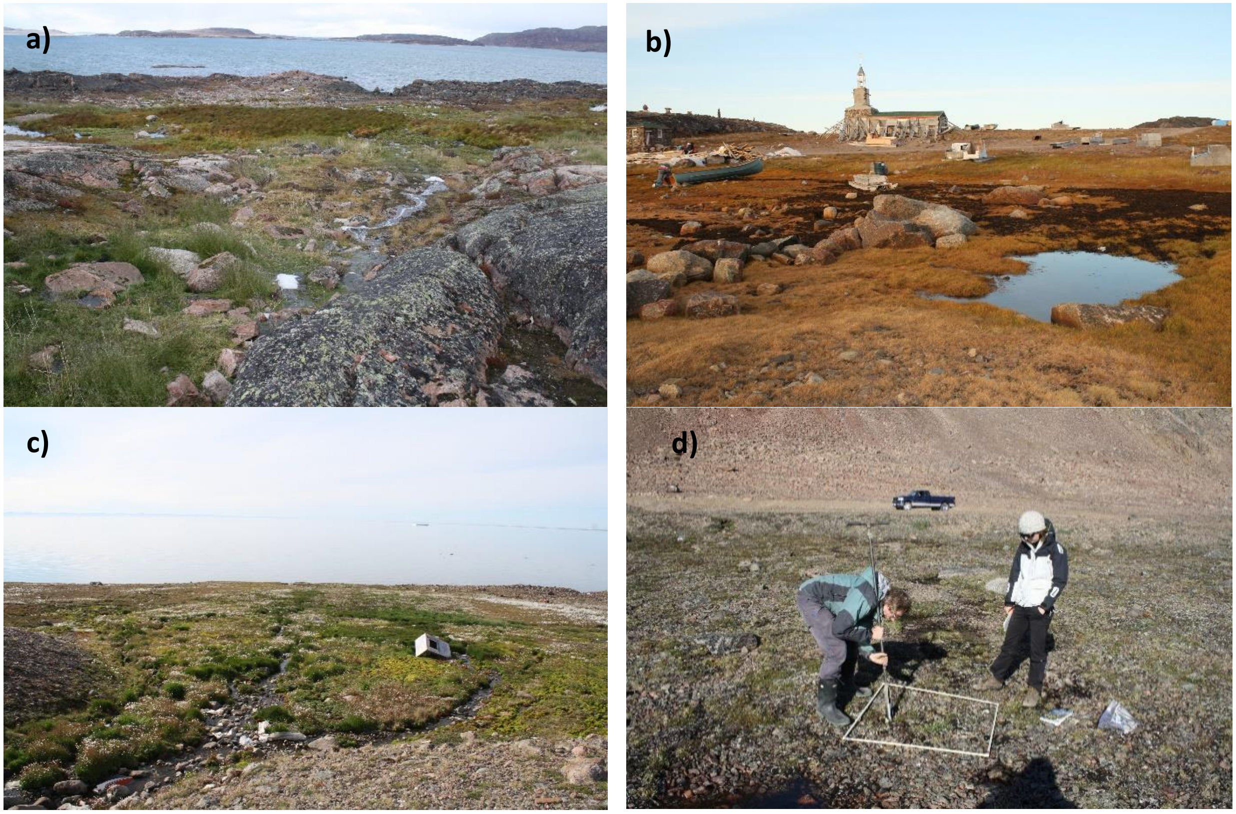



FIGURE 2. (A) THE WTA IN KUGAARUK, NU TAKEN ON SEPTEMBER 5, 2012, (B) A NATURAL WETLAND IN KUGAARUK, NU TAKEN ON SEPTEMBER 11, 2012, (C) THE WTA IN GRISE FIORD, NU TAKEN ON JULY 27, 2011, AND (D) THE REFERENCE NATURAL WETLAND GRISE FIORD, NU TAKEN ON AUGUST 3, 2011.

Tundra wetland treatment areas have been shown to improve the water quality of effluent prior to discharge into receiving environments. Early work by Doku and Heinke (1993, 1995) demonstrated the potential for WTAs in Northwest Territories and Yukon before the establishment of Nunavut. Doku and Heinke (1995) observed water quality improvements at multiple sites across the northern territories and recommended that design criteria be developed. Wright (1974) studied a 32 ha WTA swampland in Hay River, NWT and observed contaminant reductions above 95% for all parameters measured. Doku and Heinke (1993) showed that the Hay River swampland continued to meet regulatory requirements (i.e., of 40 mg/L for $BOD_5$, 60 mg/L for TSS and $1x10^4$ CFU/100mL) consistently for over twenty years after the study. Dubuc et al. (1986) observed over 90% contaminant reductions in a natural peat wetland receiving domestic wastewater in Northern Quebec.

Research conducted more recently has provided more information about these systems and their treatment performance. Yates et al. (2012) showed that water quality improvements occur over an entire treatment season in six tundra WTAs in Nunavut. In all cases for $CBOD_5$, and in all but one case for TSS, the concentrations were below the southern Canadian Environment Canada (EC) Wastewater Systems Effluent Regulations (WSER) regulations (Yates et al., 2012; Government of Canada, 2012). Hayward et al. (2014) and Hayward (2013) conducted a treatment performance assessment and hydrological characterization of a tundra WTA in Coral Harbour, Nunavut. The effluent from the 14 ha WTA met the southern WSER regulations during all study periods. Hayward et al. (2012) and Hayward et al. (2014) also emphasized that the hydrological setting has a large influence on the functioning and performance of the wetland.

Chouinard et al. (2014a) summarized results from a study conducted by the Centre for Alternative Wastewater Treatment (CAWT) funded by Environment Canada. This study was conducted on seven tundra WTAs located in the Northwest Territories and Nunavut. The results of the study indicated that five out of seven of the wetlands were able to reduce the $CBOD_5$ to below Environment Canada's WSER southern standard (Chouinard et al., 2014a). All of the study wetlands were able to reduce un-ionized ammonia to below the EC WSER for southern systems (Chouinard et al., 2014a). There was suspected autochthonous generation of TSS from within the wetlands which complicated the interpretation of this parameter (Chouinard et al., 2014a). The wetlands summarized in the CAWT EC study by Chouinard et al. (2014a) demonstrated considerable ability to improve water quality significantly beyond the primary treated influent levels entering the wetlands.

However, there are challenges associated with tundra WTAs that will require special consideration due to the uniqueness of each site. For instance, the inlet and outlet locations of many of the tundra WTAs are not always static (Chouinard et al., 2014a, Hayward et al., 2014). The positioning of the inlets and outlets may change seasonally, or with varying hydraulic conditions, which can lead to complications in selecting a representative compliance sampling point (Chouinard et al., 2014a). In addition, the boundaries of tundra WTAs are open and diffuse, and not well defined, with flows that can change on an annual basis (Yates et al., 2014, Chouinard et al., 2014a). These variable characteristics of WTAs will require comprehensive datasets to facilitate informed decision-making regarding their use.

In summary, all of these studies have repeatedly demonstrated that many of the tundra WTAs in Canada's Far North can meet or exceed the southern WSER set by EC. Tundra WTAs present a low cost and low maintenance option for secondary and tertiary levels of treatment in Nunavut. The uncertainties with their use will likely be reduced with comprehensive site-specific datasets to verify that adequate treatment is provided.

### 1.4 Regulation

Currently, a standardized approach for incorporating WTAs in municipal wastewater treatment systems in Nunavut has been lacking. Despite this, regulatory provisions are becoming available to incorporate the WTAs into the wastewater treatment system. These provisions may comprise of compliance sampling and/or monitoring of water quality at the outlets of select tundra WTAs. In order to incorporate a WTA into the facility there may be a requirement for a wetland assessment.

This wetland assessment may involve a requirement for an ecological and/or vegetation assessment of the WTA and an estimate of the required hydraulic retention time to achieve the treatment objectives. Other requirements may include measurements of the gradient of the site, an estimate of the volume of wetland available for treatment, the delineation of the total area of the wetland to be used for effluent treatment, and installation of signage and identification of outlet points. Acute lethality tests may be required to ensure that local aquatic species in the receiving water are not adversely impacted. Alternatively, in cases where insufficient information is available on the treatment capacities of a wetland, the wetland is not incorporated in the treatment train. In these cases, there may still be a requirement for water quality monitoring of wetland effluent without a compliance treatment objective.

Table 1 summarizes the hamlets in Nunavut that currently have some provisions for monitoring and regulating WTAs within their Nunavut Water Board (NWB) water licence. If wetland assessments have been conducted, the hamlets would have formal recognition within their water licence of the treatment provided by the WTAs. Other hamlets have insufficient information on the WTA, therefore their compliance points are set at the last point of engineered control of the effluent. In these cases, there may still be a requirement for water quality monitoring within the WTA. The treatment objectives and monitoring strategies are not standardized across the territory.

TABLE 1. WETLANDS IN NUNAVUT THAT ARE MONITORED AS PART OF NWB WATER LICENCES.

| Hamlet[1] | Wetland Type | Treatment objectives at outlet | Water quality monitoring at inlet & outlet[2] | Acute toxicity monitoring | Source |
|---|---|---|---|---|---|
| Arctic Bay | Vegetated Filter Strip | Not specified | 3 times annually at the beginning, middle, and end of the decant at two sample points in surface and groundwater | Not specified | NWB (2014a) |
| Arviat | Wetland treatment area | 80 mg/L $BOD_5$<br>100 mg/L TSS<br>$1x10^4$ CFU/100mL fecal coliforms<br>pH 6 – 9 | Monthly during the months of May to August | Rainbow Trout, crustacean once at middle of the decant | NWB (2010a) |
| Baker Lake | Wetland treatment area | 80 mg/L $BOD_5$<br>100 mg/L TSS<br>$1x10^4$ CFU/100mL fecal coliforms<br>pH 6 – 9 | Annually during periods of flow (if present) | Not specified | NWB (2010b) |
| Cape Dorset | Wetland pathway | Not specified | Once at the beginning and end, and weekly during decant | Rainbow Trout, crustacean once at middle of the decant | NWB (2008a) |
| Chesterfield Inlet | Wetland treatment area | 80 mg/L $BOD_5$<br>100 mg/L TSS<br>$1x10^4$ CFU/100mL fecal coliforms<br>pH 6 – 9 | Monthly during periods of observed flow | Not specified | NWB (2010c) |
| Clyde River | Vegetated Filter Strip | Not specified | 3 times annually at the beginning, middle, and end of the decant at two sample points in the surface and groundwater | Not specified | NWB (2009b) |
| Coral Harbour | Wetland treatment area | 30/30 mg/L $BOD_5$ & TSS<br>$1x10^4$ CFU/100mL fecal coliforms<br>pH 6 – 9 | 3 times annually at the beginning, middle, and end of the observed periods of flow | Rainbow Trout, crustacean once at middle of the the discharge | NWB (2008b) |

TABLE 1 (CONT'D). WETLANDS IN NUNAVUT THAT ARE MONITORED AS PART OF NWB WATER LICENCES.

| Hamlet[1] | Wetland Type | Treatment objectives at outlet | Water quality monitoring at inlet & outlet[2] | Acute toxicity monitoring | Source |
|---|---|---|---|---|---|
| Hall Beach | Wetland treatment area | Not specified | Monthly during periods of observed flow | Rainbow Trout, crustacean once at middle of the discharge | NWB (2015a) |
| Igloolik[3] | Wetland treatment area | 100 mg/L $BOD_5$ & 120 mg/L TSS $1x10^6$ CFU/100mL fecal coliforms<br>pH 6 – 9 | Monthly during periods of observed flow | Not specified | NWB (2015b) |
| Kimmirut[3] | Wetland treatment area | Not specified | Monthly during periods of observed flow | Not specified | NWB (2009c) |
| Kugaaruk | Wetland treatment area | 45/45 mg/L $BOD_5$ & TSS<br>$1x10^4$CFU/100mL fecal coliforms<br>pH 6 – 9 | 3 times annually at the beginning, middle, and end of the decant | Rainbow Trout and crustacean once at middle of decant. | NWB (2007) |
| Qikitarjuaq[3] | Wetland treatment area | 45/45 mg/L $BOD_5$ & TSS<br>$1x10^4$CFU/100mL fecal coliforms<br>pH 6 – 9 | Once annually at the beginning, middle, and end of the decant | Not specified | NWB (2014b) |
| Repulse Bay[3] | Vegetated Filter Strip | 80 mg/L $BOD_5$<br>70 mg/L TSS<br>$1x10^6$ CFU/100 mL fecal coliforms<br>pH 6 – 9 | Once annually at the beginning, middle, and end of the decant | Not specified | NWB (2015c) |
| Taloyoak[3] | Wetland treatment area | 25/25 mg/L $BOD_5$ & TSS<br>1.25 mg/L $NH_3$-N<br>$1x10^4$ CFU/100mL<br>pH 6 – 9 | Monthly over the treatment season | Rainbow Trout once at middle of the discharge | NWB (2014c) |
| Whale Cove | Wetland treatment area | Not specified | Monthly during periods of observed flow | Not feasible due to distance from laboratory | NWB (2009d) |

[1]Other hamlets have wetlands but do not monitor under conditions of their water licence.

[2]Some hamlet water licences also prescribe water quality sampling at interim points within the wetland.
[3]New wetland treatment area may not yet be commissioned.

# 2.0 Methodology

## 2.1 Dalhousie University research program

The Centre for Water Resources Studies (CWRS) at Dalhousie University conducted a research program on wastewater treatment infrastructure in Nunavut, Canada from 2011 to 2014. The research program was a collaborative effort with, and funded by, the Community and Government Services (CGS) department of the Government of Nunavut (GN). A focus area of the broader infrastructure research program was to evaluate the treatment performance, hydrology, and treatment mechanisms of WTAs receiving primary treated wastewater effluent from wastewater stabilization ponds.

Comprehensive site-specific wetland studies were conducted in the hamlet communities of Coral Harbour, Kugaaruk, and Grise Fiord, Nunavut (Figure 3). The study sites were selected to include different geographic localities to ensure that the climatic variability across Nunavut was represented. Other justifications for the site selection included primary treatment of the wastewater prior to discharge into the wetlands, and minimal solid waste facility leachate interaction with the municipal wastewater effluent.

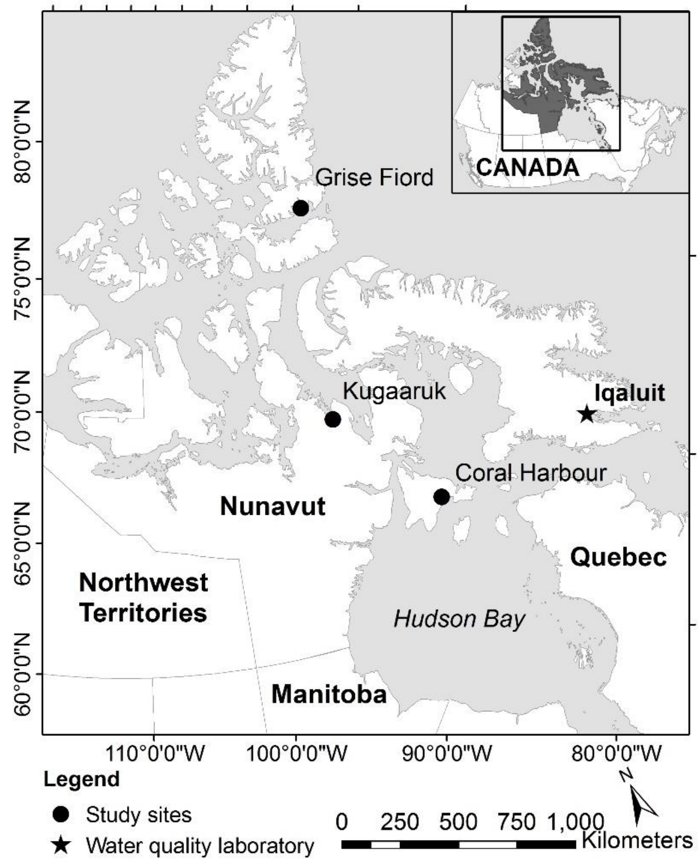



FIGURE 3. SITE LOCATOR MAP FOR THE SITE-SPECIFIC STUDIES ON THE WTAS IN CORAL HARBOUR, KUGAARUK, AND GRISE FIORD, NUNAVUT.

The objectives of the studies on the WTAs were to:

i) Assess the treatment performance;
ii) Characterize the implications of hydrological setting on the treatment performance;
iii) Identify treatment mechanisms; and
iv) Develop a model to determine first order rate constants for use in design.

The following sections summarize the results obtained from the research program. The findings from these site-specific studies were used to inform the development of the guidelines presented under a separate cover CWRS (2015). Comprehensive and additional details on the Coral Harbour tundra WTA are available in Hayward (2013), Hayward et al. (2014), and Hayward and Jamieson (2015).

## 2.2 Treatment performance assessment

The treatment performance assessments consisted of collecting water samples at key points in the WTAs and analyzing for a suite of parameters including five-day carbonaceous biochemical oxygen demand ($CBOD_5$), total suspended solids (TSS), volatile suspended solids (VSS), *Escherichia coli* (*E. coli*), total nitrogen (TN), total ammonia nitrogen (TAN), un-ionized ammonia nitrogen ($NH_3$-N), and total phosphorus (TP) according to APHA (2012). Discrete measurements of water quality indicators consisting of pH, dissolved oxygen (DO), specific conductivity, and temperature were made with handheld YSI multi-parameter sondes. Additional detail on the methodology used for the treatment performance assessment are provided in Hayward et al. (2014) and Hayward (2013).

## 2.3 Site characterization

The physical attributes of the study sites were characterized with vegetation assessments as described in Hayward (2013). A detailed topographic survey was completed at each of the sites with a real-time kinematic (RTK) GPS survey with the methodology described in Hayward (2013) and Hayward et al. (2014).

Characterization of the hydraulics and hydrology of the sites involved the measurement of the influent and effluent discharges from the WTAs. As well, intermediate flow measurement points in the WTAs were established when external hydrologic contributions were suspected. The stream flow was measured with a Gurley Precision Instruments Pygmy meter according to Dingman (2002). Continuous measurements of flow in the WTAs were obtained by developing stage-discharge curves based on automated water level data from HOBO water level loggers. The measurement of the hydrology of the sites and calculation of the hydraulic parameters is described in greater detail in Hayward et al. (2014) and Hayward (2013).

The hydraulic tracer tests were conducted with Rhodamine WT (RWT) fluorescent dye tracer and sodium bromide salt tracer. Measurement of the tracers was completed *in situ* with an optical fluorescent probe and with an ion selective electrode (ISE) probe. Analysis of the tracer test data and calculation of the hydraulic parameters is described in detail in Hayward (2013) and Hayward et al. (2014). A modified tanks-in-series (TIS) first order chemical reactor model was used to derive the first order rate constants. This procedure is described in detail in Hayward and Jamieson (2015) and CWRS (2015).

## 2.4 Site descriptions

### *2.4.1 Coral Harbour*

The hamlet of Coral Harbour (64° 08’ 13” N, 083° 09’ 51” W) has an estimated population of 834 (Statistics Canada, 2012). The Coral Harbour WTA site-specific study was conducted from June 14 to 25, 2011; September 9 to 17, 2011; June 28, 2012 to July 14, 2012; and August 31, 2012 to September 1, 2012. Average air temperatures range from –26 °C and –34 °C in January, and from 14 °C and 5 °C in July. Precipitation averages 155 mm as rainfall, and 1335 mm as snow, for a total of 286 mm of precipitation (Government of Canada, 2014a). Approximately 95 $m^3$/d (34 779 $m^3$/year) of primarily domestic municipal wastewater is generated daily (NWB, 2013). Wastewater is transported by pump trucks to the wastewater treatment facility located approximately 3 km north of the hamlet. The wastewater treatment facility consists of an unlined single cell WSP (surface area of water approximately 1.2 ha) and tundra WTA (approximately 14 ha).

The WTA discharges to a freshwater lake (1 ha), which eventually discharges to a marine estuary. The WTA consists of wetland areas characterized by willows, organic matter, mosses, and grasses, as well as, upland areas characterized by bedrock outcrops, lichens and grasses. Topography in the WTA is characterized by a 3% west to east downward sloping terrain. The active layer depth ranges from 0.5 to 1.5 m.

The WSP discharges effluent into the WTA at an uncontrolled rate through the berm throughout the treatment season. The direction of effluent flow in the wetland changes seasonally in relation to the amount of discharge occurring, as shown in Figure 4a. Therefore, the locations of the inlet and outlets changed seasonally with the direction of effluent flow. The spring freshet flow area was distributed over the southern portion of the wetland treatment area. Whereas, the post-freshet flow area was distributed across the northern portion of the wetland treatment area (Figure 4a). Effluent flow in the WTA was characterized mainly by surface flow. During low flow periods after the spring freshet, the upstream segment of the wetland was characterized by subsurface flow (SSF). The wetted area, which is the area available to facilitate wastewater treatment, ranged from 1.1 to 1.5 ha.

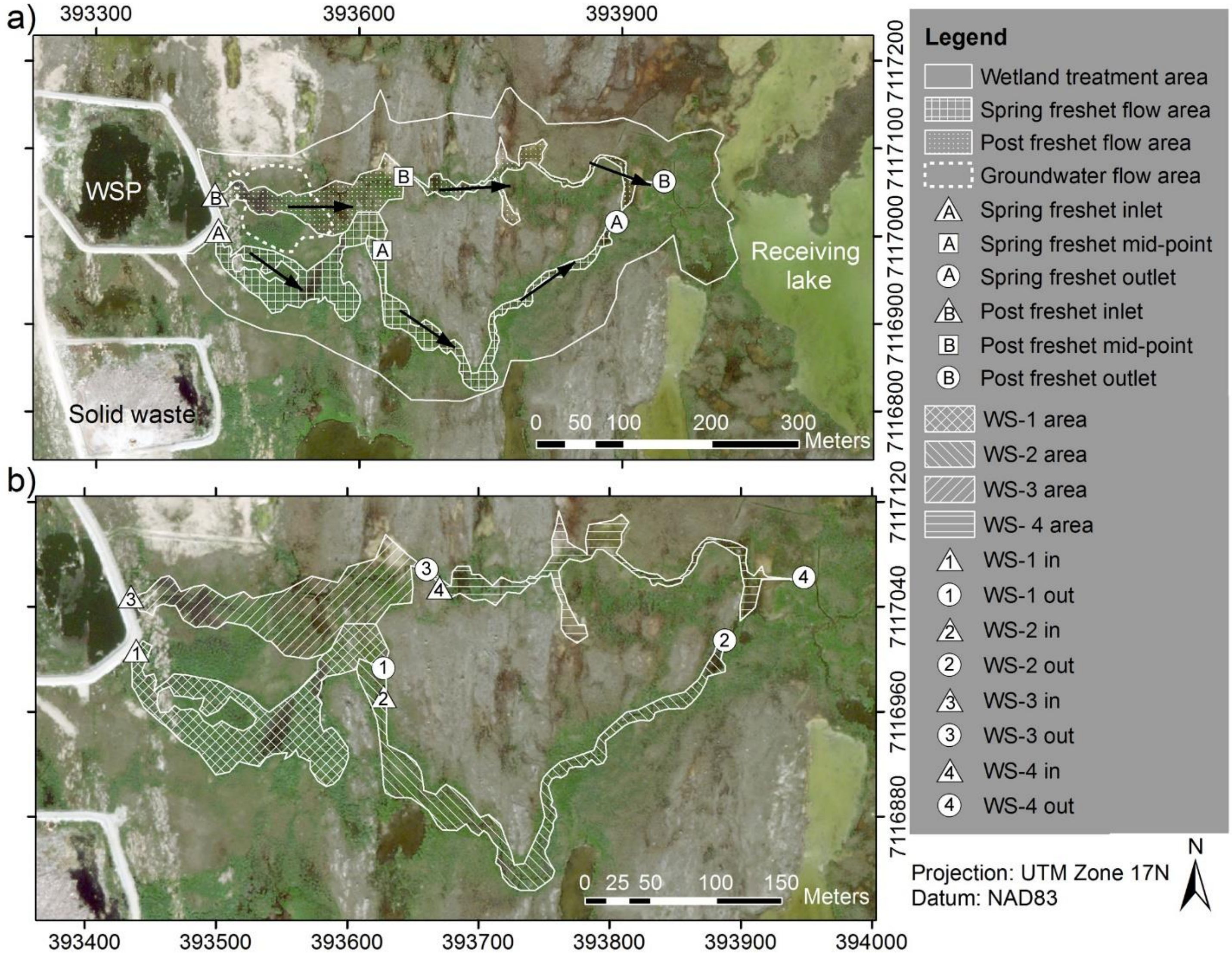



FIGURE 4. (A) PLAN VIEW OF THE WASTEWATER TREATMENT SYSTEM IN CORAL HARBOUR WITH ARROWS TO DENOTE THE DIRECTION OF EFFLUENT FLOW, AND (B) THE WETLAND SEGMENTS (WS) WHERE EACH TRACER TEST WAS CONDUCTED (SOURCE: HAYWARD AND JAMIESON, 2015).

### *2.4.2 Kugaaruk*

The hamlet of Kugaaruk (68° 32’ 05” N, 089° 49’ 29” W) has an estimated population of 771 (Statistics Canada, 2012). The site-specific study on the Kugaaruk WTA was conducted from September 6 to 11, 2012; and August 21 to 28, 2013. Average air temperatures range from –30 °C and –37 °C in January, and from 14 °C and 5 °C in July. Precipitation averages 117 mm as rainfall, and 1460 mm as snow, for a total of 261 mm of precipitation (Government of Canada, 2014b). Approximately 76 $m^3$/d (27 588 $m^3$/year) of primarily domestic municipal wastewater is generated daily (NWB, 2011a). Pump trucks are used to transport the wastewater from individual houses and establishments to the wastewater treatment facility located approximately 1 km south of the hamlet. Figure 5a shows the wastewater treatment facility which consists of a WSP (surface area of water approximately 1.2 ha) with a decant cell (755 $m^2$) and a tundra WTA (0.65 ha). There is a liner keyed into the berm perimeter of the WSP.

The WSP is typically decanted with a pump and generator into the decant cell twice for a period of several days between July and October. The decant cell retains the effluent temporarily. Throughout decanting, effluent seeps out through the toe of the decant cell berm, into a channel which flows into the WTA. The wetted area of the WTA was 0.56 ha. The effluent discharges from the WTA into a coastal marine receiving environment.

The upstream section of the WTA is characterized by fractured bedrock outcrops and channelized flow, the middle segment is characterized by braided flow through a hummocky sedge area, and the downstream segment of the wetland is characterized by both surface and subsurface flow in a few channels with cobbles and boulders, algae deposits, mosses and some sedges. Figure 5a shows two inlets because there was effluent seeping from the toe of the berm in two locations. Topography in the WTA from the wetland inlet to the outlet is characterized by a 10% downward slope from south-east to north-west across the site.

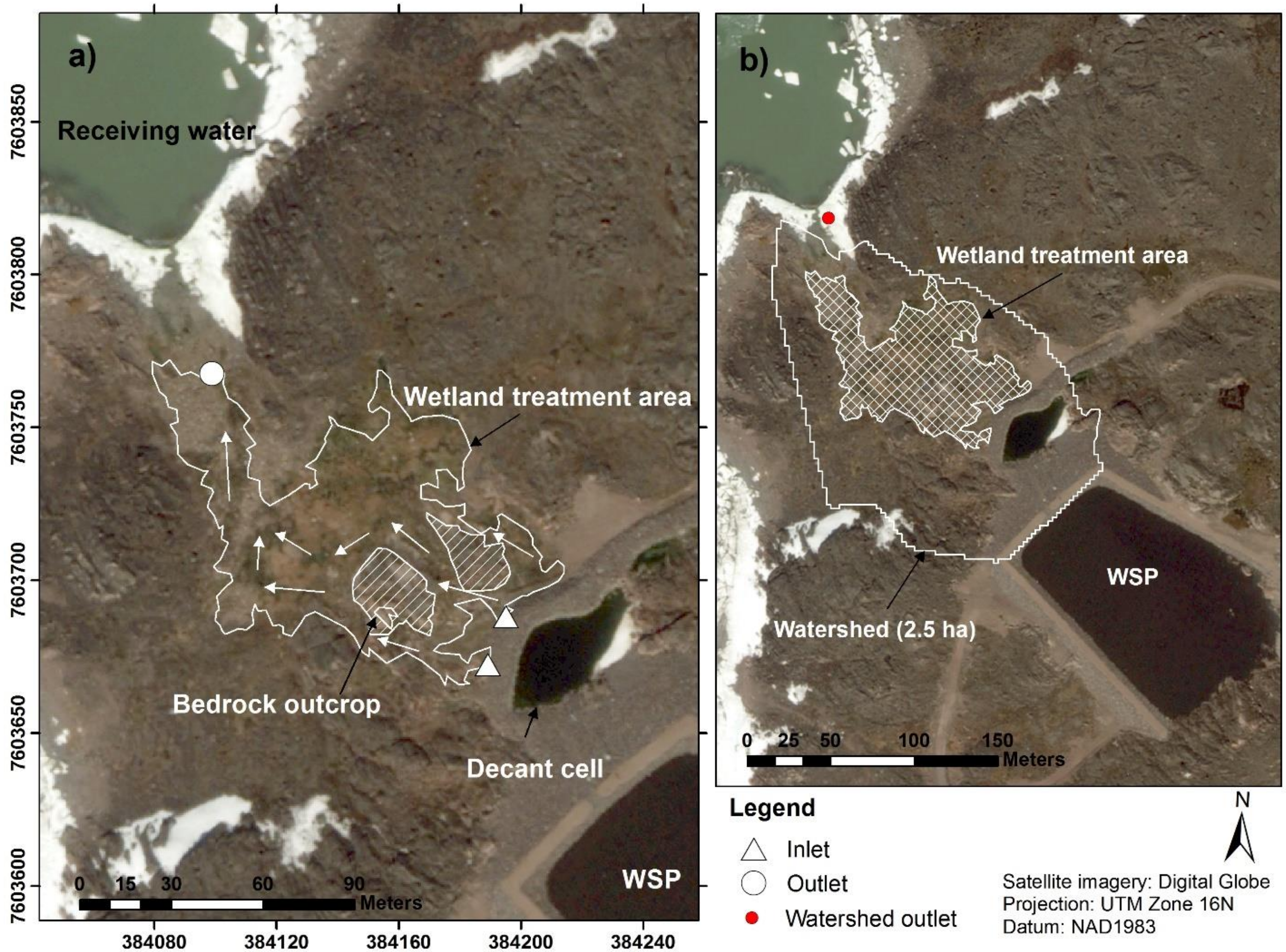



FIGURE 5. PLAN VIEW OF THE WASTEWATER TREATMENT SYSTEM IN KUGAARUK WITH WHITE ARROWS TO DENOTE THE DIRECTION OF EFFLUENT FLOW, AND (B) THE WTA SHOWN AS THE CROSS HATCHED AREA AND THE WATERSHED DELINEATION OF THE HYDROLOGIC CONTRIBUTION TO THE WTA.

### *2.4.3 Grise Fiord*

The hamlet of Grise Fiord (76° 25’ 03” N, 082° 53’ 38” W) has an estimated population of 130 (Statistics Canada, 2012). The site-specific study was conducted in Grise Fiord from July 27 to July 31, 2011. There is no weather station in Grise Fiord and therefore the closest station in Resolute was used (74° 43’ 01” N, 94° 58’ 10” W). Average air temperatures in Resolute range from –29 °C and –35 °C in January, and from 7 °C and 2 °C in July. Precipitation in Resolute averages 60 mm as rainfall, and 1112 mm as snow, for a total of 161 mm of precipitation (Government of Canada, 2014c).

Approximately 13 $m^3$/d (4656 $m^3$/year) of primarily domestic municipal wastewater is generated daily (NWB, 2011b). Pump trucks collect and transport wastewater from individual houses and establishments to the wastewater treatment facility located approximately 670 m to the north-west of the hamlet. The wastewater treatment facility consists of an unlined single cell WSP which is decanted bi-annually with a siphon to a tundra WTA (0.54 ha). The WTA in Grise Fiord is shown in plan view in Figure 6a. Typically, the decant lasts for 3 to 4 days.

The effluent flow in the WTA was mostly characterized by surface flow. Braided flow was observed near the outlet, however most of the flow was centralized in one main outlet channel. The WTA discharges to a coastal marine receiving environment. The decanted effluent flows into a channel at the south-west corner of the WSP. The WTA commences after approximately 150 m of channel flow. The vegetation in the WTA is characterized predominately by *Nodding Saxifrage* and *Poa Arctica*. The active layer depth ranges from 20 to 90 cm. Topography is characterized by a downward slope of approximately 11% from the inlet channel to the wetland outlet.

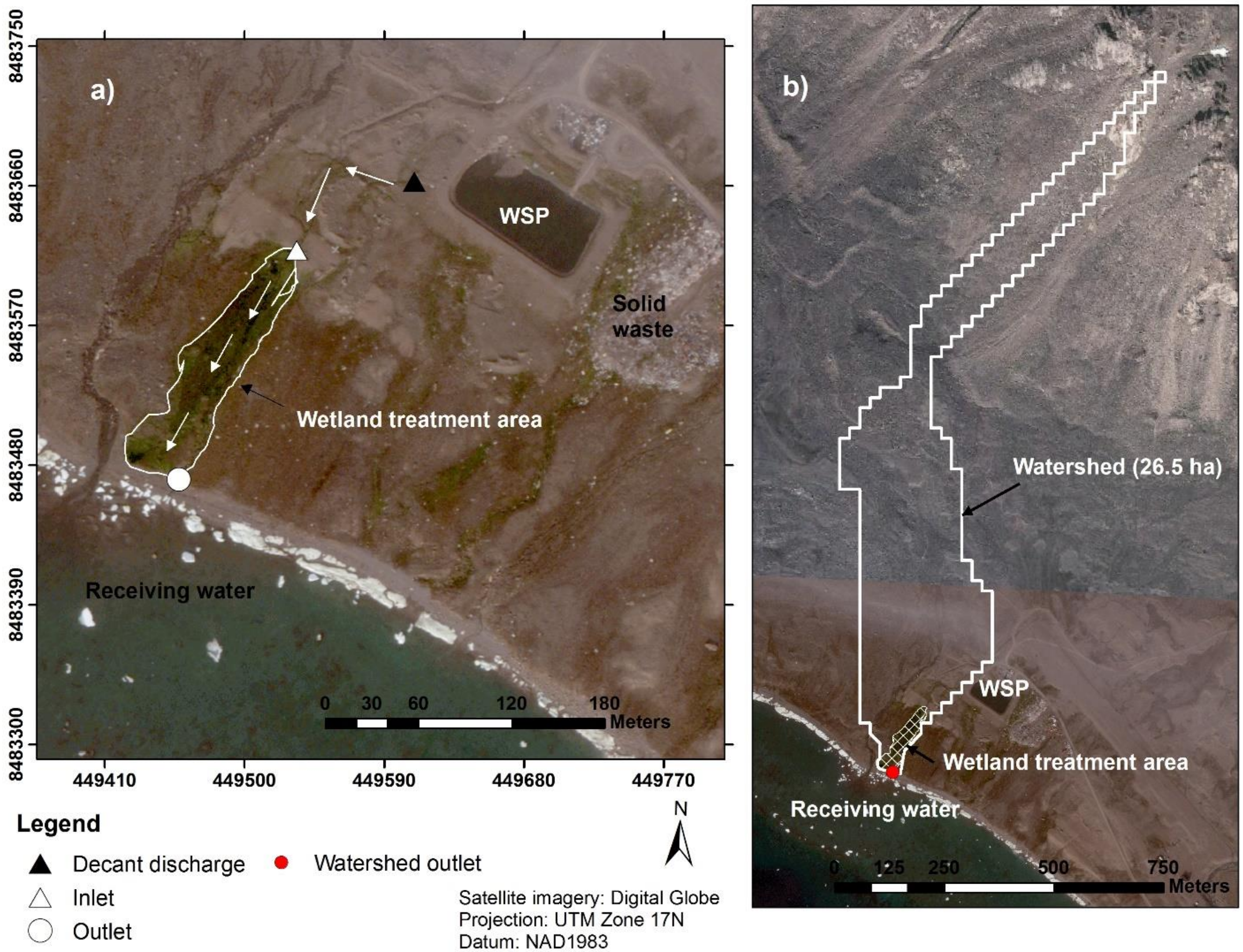



FIGURE 6. (A) PLAN VIEW OF THE WASTEWATER TREATMENT SYSTEM IN GRISE FIORD WITH WHITE ARROWS TO DENOTE THE DIRECTION OF EFFLUENT FLOW, AND (B) WATERSHED DELINEATION OF THE HYDROLOGIC CONTRIBUTION TO THE WTA.

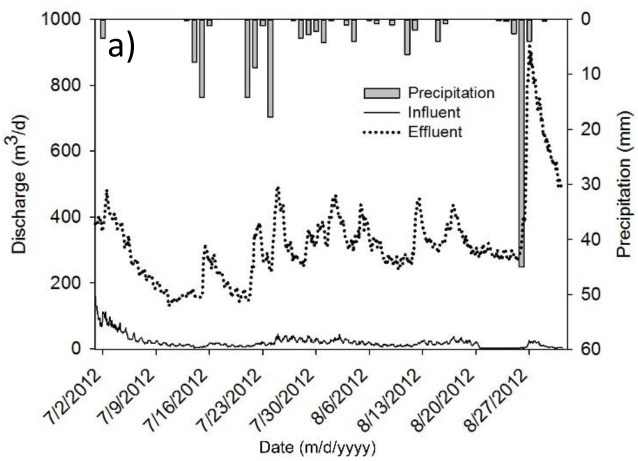
## 3.0 Results and discussion

### *3.1 Coral Harbour*

### *3.1.1 Hydrological setting*

#### *3.1.1.1 Influent and effluent flow*

Measurement of flow was performed on a regular basis at key points in the wetland including the inlet, outlet, and other areas where external hydrologic contributions from the watershed were suspected. Water level loggers were installed to continuously measure influent and effluent wetland flow to capture seasonal variability in flows. Figure 7a from Hayward et al. (2014) illustrates the influent and effluent flow continuously over the treatment season in 2012. Figure 7a indicates that external hydrologic contributions added a large amount of water to the wetland upstream of the outlet.



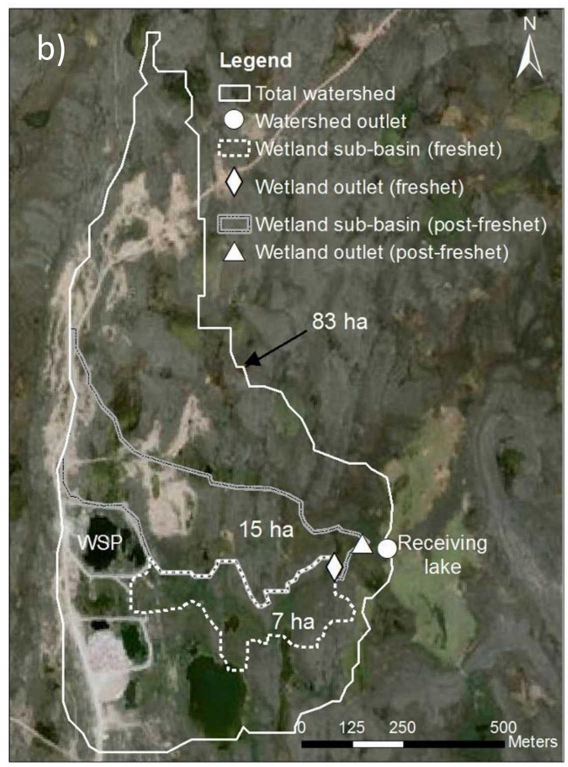




FIGURE 7. (A) WETLAND INFLUENT AND EFFLUENT HYDROGRAPHS WITH PRECIPITATION FOR JULY AND AUGUST 2012 IN CORAL HARBOUR (B) WATERSHED DELINEATION OF THE HYDROLOGIC CONTRIBUTION TO THE WETLAND OUTLET AT THE RECEIVING LAKE. THE WTA LIES WITHIN TWO SUB-BASINS WHERE EFFLUENT DISCHARGE DIRECTION VARIES SEASONALLY. THE OUTLETS FOR THE TOTAL WATERSHED AND SUB-BASINS ARE INDICATED. (SOURCE: HAYWARD ET AL., 2014).

#### *3.1.1.2 Hydraulic loading rates*

Areas of the WTA where effluent discharged varied seasonally, which accounted for the range of wetted areas observed. The 1.5 ha (14 620 $m^2$) spring freshet flow area is representative of where effluent was observed to discharge during spring freshet in June 2011 (Figure 4a). The 1.1 ha (10 646 $m^2$) post-freshet flow area represents where effluent was observed to discharge during the post-spring freshet (Figure 4a). The hydraulic loading rates (HLRs) onto the WTA over the two treatment seasons (total of 86 days), ranged from 0 to 8 cm/d (0 to 827 $m^3$/ha-d), with an average of 1 cm/d (97 $m^3$/ha-d). At times, the HLR was much greater than the recommended 2.5 cm/d from Alberta Environment (2000).

#### *3.1.1.3 Hydraulic retention times*

Hydraulic tracer tests were conducted in the WTA at key times during the treatment season. Rhodamine WT dye was used as the tracer for the tests, and it provided a visual indicator of the direction of flow and extent of the wetted area. The tracer also facilitated the quantitative determination of hydraulic retention time (HRT). The HRTs were determined to range from 11 hours to 1.4 days during the spring freshet, and up to 14 days, during the post-spring freshet. The spring freshet HRT was short compared to other northern Canadian treatment wetlands (Hayward et al., 2014). It is recommended that natural wetlands receiving wastewater should have an HRT of 14 to 20 days (Alberta Environment, 2000).

#### *3.1.1.4 Watershed delineation*

The watershed delineation of the WTA was determined with a desktop analysis of low (30 m) and high (10 m) spatial resolution topographic data. The watershed delineation of the WTA is shown in Figure 7b by Hayward et al. (2014). The entire watershed contributing water to the final outlet is 83 ha, while the 7 and 15 ha sub-basins, show the area where water is seasonally drained towards the outlets. Figure 7b supports the observation of seasonal variability in hydrologic response of the WTA. For this wetland, the watershed has the potential to add large quantities of non-effluent contributions to the WTA, which dilutes the effluent.

### ***3.1.2 Treatment performance***

Seven rounds of treatment performance samples were collected to assess the conditions across the entire treatment season. Each round of treatment performance samples consisted of raw wastewater samples, an influent, a mid-point, and an effluent sample.

The treatment performance data is summarized in Table 2. The reductions of contaminants from raw concentrations are provided for both the wetland influent and effluent. The overall removal includes WSP and wetland treatment, but also dilution due to external hydrologic contributions from the watershed. For all of the sampling events, the wetland effluent met the EC WSER for southern systems. In some instances, the wetland influent did not meet the EC WSER for southern systems. There was considerable variability in treatment performance over the course of the treatment season. Minimal treatment was observed during the spring freshet when the HRTs were short. Maximum treatment was observed during the post-freshet when HRTs were maximized. There was also a positive relationship observed between algal growth at the inlet during the post-spring freshet and the influent TSS and VSS concentrations.

TABLE 2. SUMMARY OF TREATMENT PERFORMANCE RESULTS FROM CORAL HARBOUR (HAYWARD ET AL., 2014).

| Parameter | Influent | | Effluent | | *n* |
|---|---|---|---|---|---|
| | Mean conc. ± st. dev. | Reduction from raw | Mean conc. ± st. dev. | Reduction from raw | |
| $CBOD_5$ (mg/L) | 91* ± 32 | 75.4% | 8 ± 9 | 96.9% | 7 |
| *E. coli* (MPN/100mL) | $4.3x10^5$ ± $7.4x10^5$ | 2.9 log | $3.4x10^3$ ± $6.9x10^3$ | 5.9 log | 7 |
| TSS (mg/L) | 90* ± 49 | 77.1% | 9 ± 8 | 97.7% | 7 |
| VSS (mg/L) | 83 ± 49 | 76.1% | 6 ± 6 | 98.0% | 7 |
| TN (mg/L) | 35 ± 7 | 64.2% | 6 ± 9 | 93.2% | 5 |
| TAN (mg/L) | 20 ± 10 | 66.8% | 3 ± 5 | 93.2% | 14 |
| $NH_3$-N (mg/L) | 0.6 ± 0.7 | 39.6% | 0.3 ± 0.3 | 76.8% | 14 |
| TP (mg/L) | 3 ± 0.6 | 74.2% | 0.7 ± 1 | 93.5% | 5 |
| Temperature (°C) | 8.2 ± 4.3 | | 12.5 ± 5.9 | | 36 |
| DO (mg/L) | 4.2 ± 3.9 | | 12.7 ± 2.5 | | 36 |
| pH | 7.9 ± 0.4 | | 8.6 ± 0.4 | | 36 |
| Sp. Cond. (µS/cm) | 592 ± 137 | | 423 ± 112 | | 36 |

*Exceedance of the Environment Canada WSER standard for southern systems of 25/25 for $CBOD_5$ and TSS, and 1.25 mg/L for $NH_3$-N.

### 3.1.3 Model and rate constants

#### *3.1.3.1 Modified tanks-in-series*

A modified TIS model was used to represent the treatment performance of the wetland. The modeling technique and results are described in detail in Hayward and Jamieson (2015). The tracer tests provided important model parameterization data. The WTA was sectioned into wetland segments (WS) representing the upstream and downstream sections of the wetland as shown in Figure 4b. Division of the wetland into segments ensured that the effluent tracer concentrations were within the detection range of the measurement instrument. That also allowed for determination of rate constants representative of the upstream and downstream sections of the WTA. Compartmentalization of each WS was optimized with four TIS for WS-1, five TIS for WS-2, two TIS for WS-3, and three TIS for WS-4 (Figure 4b).

The HRT was determined from the tracer tests and this parameter was used as model input. The number of tanks (*N*) was required to parameterize the TIS model. The *N* for each WS was determined from the least squares fit of the gamma model to the residence time distribution from each tracer test. Hydrological data such as the flows and water depths measured at the inlet, mid-point, and outlet, were used as model input. Treatment performance data was used to parameterize the influent, effluent, and the background concentrations.

#### *3.1.3.2 Rate constants*

The first order areal rate constants (*k*) were determined for each WS by setting up a modified TIS model in Microsoft Excel for each WS studied. A universal *k* for each WS was obtained by setting the effluent model concentration to equal to the effluent concentration observed in the field data. The rate constants were normalized to 20°C ($k_{20}$). These values for $k$ were compared to existing literature values in terms of percentiles for treatment wetlands operating across North America that were assembled by Kadlec and Wallace (2009).

In comparison to the rate constant databases in Kadlec and Wallace (2009), the minimum $k_{20}$ for $CBOD_5$ was below the 5th percentile, the $k_{20}$ for *E. coli* and TAN was within the 40th percentile, and the $k_{20}$ for TN fell below the 10th percentile. The rate constants that were determined are summarized in Table 3. Dilution from external hydrologic contributions accounted for 33% of the contaminant reductions observed (Hayward and Jamieson, 2015). For this wetland, a conservative selection of rate constants would be the low percentiles of rate constants derived from wetlands in non-arctic contexts (Hayward and Jamieson, 2015).

TABLE 3. FIRST ORDER AREAL RATE CONSTANTS FOR THE WTA IN CORAL HARBOUR (HAYWARD AND JAMIESON, 2015).

| Parameter | Mean $k_{20}$ (m/y) | Min. $k_{20}$ (m/y) | Percentile min. | Max. $k_{20}$ (m/y) | Percentile max. |
|---|---|---|---|---|---|
| $CBOD_5$ | 60 | 4.4 | 5th | 120 | 70th |
| *E. coli* | 391 | 78 | 40th | 887 | 90th |
| TN | 11 | 2.7 | 10th | 20 | 60th |
| TAN | 31 | 12 | 40th | 64 | 80th |

## 3.2 Kugaaruk

### 3.2.1 Hydrological setting

#### 3.2.1.1 Influent and effluent flow

The effluent flow rate was measured at the inlet, mid-point and outlet of the WTA. There were a few areas at the toe of the decant cell where seepage from the unlined WSP was suspected due to a 10 m elevation difference between the WSP and the WTA, and the presence of standing water. Subsurface flow was confirmed within the wetland with flow measurement, which indicated that the surface flow was highest at the mid-point, during the August 2013 decant. The discrepancy indicated that additional effluent was likely entering and exiting the wetland by subsurface flow. The influent flow ranged from 3 to 58 $m^3$/d during the 5 day decant period of 2013. The effluent flow ranged from 10 to 48 $m^3$/d during the decant period of 2013. Whereas, a range of flows from 82 to 223 $m^3$/d were observed in an intermediate sample point during the decant period of 2013.

#### 3.2.1.2 Hydraulic loading rates

The hydraulic loading rate onto the Kugaaruk WTA (5641 $m^2$) ranged from 0.06 – 1 cm/d (6 – 103 $m^3$/ha-d) during the 4 day decant monitoring. This HLR was within the recommended range from Alberta Environment (2000) of 2.5 cm/d.

#### *3.2.1.3 Hydraulic retention times*

Tracer tests were conducted to determine the HRT of the WTA during the August 2013 decant. Separate tracer tests were conducted to assess different segments of the wetland. RWT dye tracer was used for the tracer tests of the wetland segments, because they were anticipated to have relatively short HRTs, and were characterized mostly by surface flow. Sodium bromide was used for the tracer test of the entire wetland treatment area from the decant cell to the outlet, because the tracer had to sit for an extended period of time in the decant cell, and flow through porous media in the berm. The middle segment of the wetland had an HRT of approximately 5 hours. The HRT from the inlet area near the decant cell berm to the outlet was greater than 10 hours. The HRT from the decant cell to the outlet was approximately 6 days. These HRTs were shorter than the recommended 14 to 20 day range for natural wetlands receiving wastewater (Alberta Environment, 2000).

#### *3.2.1.4 Watershed delineation*

The watershed delineation of the WTA was determined with a desktop analysis of low (20 m) and high (5 m) spatial resolution topographic data. The watershed area contributing to the WTA is only 2.5 ha (Figure 5b). The WTA is bounded closely along the length by topographic divides. As a result of the topography on site, there is little potential for dilution from external hydrologic contributions.

### ***3.2.2 Treatment performance***

Table 4 summarizes the performance data for Kugaaruk. The reductions of contaminants from raw concentrations are provided for both the wetland influent and effluent. Nine raw samples were collected from separate pump trucks. In total, three rounds of treatment performance samples were collected from the inlet and outlet. Two of the sets of treatment performance samples collected from the inlet and outlet were 4 hour composite samples.

The wetland influent met the southern WSER for TSS and $NH_3$-N. The average influent $CBOD_5$ exceeded the southern WSER. The wetland effluent met the southern WSER during all sampling events. The WTA improved the water quality of the effluent prior to discharge into the receiving environment demonstrating that the HRT of the WTA was long enough to provide treatment of the wastewater.

Table 4. Summary of treatment performance results from Kugaaruk.

| Parameter | Influent | | Effluent | | |
|---|---|---|---|---|---|
| | Mean conc. ± st. dev. | Reduction from raw | Mean conc. ± st. dev. | Reduction from raw | *n* |
| $CBOD_5$ (mg/L) | 151* | 59% | 12 | 97% | 2 |
| *E. coli* (MPN/100mL) | 3.2E+05 ± 4.4E+05 | 1.8 log | 4.2E+03 ± 3.1E+03 | 3.7 log | 4 |
| TSS (mg/L) | 21 ± 3 | 92% | 10 ± 11 | 97% | 4-3 |
| VSS (mg/L) | 21 ± 4 | 91% | 10 ± 11 | 96% | 4-3 |
| TN (mg/L) | 81 ± 8 | 38% | 55 ± 8 | 58% | 4 |
| TAN (mg/L) | 82 ± 11 | 13% | 55 ± 13 | 41% | 4 |
| $NH_3$-N (mg/L) | 0.8 | 15% | 0.4 | 55% | 2 |
| $NO_3$-N (mg/L) | 0.09 | -40% | 0.15 | -121% | 2 |
| TP (mg/L) | 8.6 ± 1.3 | 24% | 4.9 ± 1.6 | 56% | 4 |
| Temperature (°C) | 5.2 ± 1.6 | | 3.0 ± 1.2 | | |
| DO (mg/L) | 2.0 ± 0.8 | | 4.9 ± 0.8 | | |
| pH | 7.5 ± 0.3 | | 7.4 ± 0.1 | | |
| Sp. Cond. (µS/cm) | 1145 ± 188 | | 848 ± 193 | | |

* Exceedance of the Environment Canada WSER standard for southern systems of 25/25 for $CBOD_5$ and TSS, and 1.25 mg/L for $NH_3$-N.

## 3.3 Grise Fiord

### *3.3.1 Hydrological setting*

#### *3.3.1.1 Influent and effluent flow*

Flows were measured at the WTA inlet, intermediate sample points, and at the outlet, over the five day decant period in 2011. The influent flows ranged from 921 – 1479 $m^3$/d and the effluent flows ranged from 516 – 1132 $m^3$/d. It would be expected that the inlet flows would be lower than the outlet flows, however subsurface flow was possible near the outlet.

#### *3.3.1.2 Hydraulic loading rates*

The hydraulic loading rates onto the WTA of Grise Fiord (5417 $m^2$) ranged from 17 – 27 cm/d (1700 $m^3$/ha-d – 2730 $m^3$/ha-d) which are excessively high. The recommended maximum value for an HLR onto a natural wetland receiving wastewater is 2.5 cm/d (Alberta Environment, 2000).

#### *3.3.1.3 Hydraulic retention times*

Tracer tests were conducted with sodium bromide to determine the HRTs of the WTA. During the August 2011 decant, the HRT of the main channel in the WTA was only 20 minutes. The HRTs in the two smaller channels were 90 and 140 minutes. These HRTs are extremely short in comparison to other treatment wetlands. For instance, Alberta Environment (2000) suggested an HRT range of 14 to 20 days for natural wetlands receiving wastewater. Therefore, very little treatment would be possible in this WTA due to the short HRTs.

#### 3.3.1.4 Watershed delineation

There was a defined external hydrologic contribution near the wetland inlet that diluted the effluent stream by 20% to 40%. The watershed of the WTA was delineated to better understand external hydrologic contributions to the WTA. The watershed contributing to the WTA was approximately 26.5 ha in area. The estimate is approximate as the delineation was based on 23 m spatial resolution elevation data.

### 3.3.2 Treatment performance

To quantify the treatment performance of the WTA, two 4 hour composite samples of the WSP decant, at the wetland inlet and outlet, were taken during the first and third (last) days of decant. Three raw wastewater samples were taken directly from trucks discharging into the WSP. Table 5 shows the average water quality parameters for the wetland influent and effluent, and the percent reductions from raw wastewater. The reductions of contaminants from raw concentrations are provided for both the wetland influent and effluent. The overall removal includes WSP and wetland treatment, but also dilution due to the confluence of decant water with an existing stream, as shown in Figure 6b.

The influent decant water from the WSP did not meet the EC WSER southern systems requirements. The wetland effluent also did not meet the WSER for southern systems for $CBOD_5$ and TSS. However, the wetland effluent did meet the WSER for southern systems for $NH_3$-N. The HRTs were fairly short, and therefore limited treatment would be occurring in the WTA, which is confirmed with the performance results.

TABLE 5. SUMMARY OF TREATMENT PERFORMANCE RESULTS FROM GRISE FIORD.

| Parameter | Influent | | Effluent | | |
|---|---|---|---|---|---|
| | Mean conc. | Reduction from raw | Mean conc. | Reduction from raw | *n* |
| $BOD_5$ (mg/L) | 194* | 69% | 75* | 88% | 2 |
| *E. coli* (MPN/100mL) | $3.0 \times 10^1 \pm 2.5 \times 10^1$ | 4.5 log | $1.6 \times 10^2 \pm 2.4 \times 10^2$ | 3.7 log | 3 |
| TSS (mg/L) | 140 ± 106* | 79% | 230 ± 118* | 65% | 3 |
| TN (mg/L) | 23 | 72% | 8 ± 7 | 90% | 2-3 |
| TAN (mg/L) | 25 ± 17 | 77% | 14 ± 8 | 88% | 13 |
| $NH_3$-N (mg/L) | 3.2 ± 3.5* | 77% | 0.4 ± 0.2 | 88% | 13 |
| TP (mg/L) | 3.6 | 72% | 1.2 ± 0.9 | 91% | 2-3 |
| Temperature (°C) | 8.4 ± 3.8 | | 8.7 ± 1.3 | | 13 |
| DO (mg/L) | 10.8 ± 3.6 | | 11 ± 0.7 | | 13 |
| pH | 8.5 ± 1.2 | | 8 ± 0.3 | | 13 |
| Sp. Cond. (µS/cm) | 400 ± 120 | | 323 ± 66 | | 13 |

*Exceedance of the Environment Canada WSER standard for southern systems of 25/25 for $CBOD_5$ and TSS, and 1.25 mg/L for $NH_3$-N.

## 4.0 Summary of findings

The studies conducted at Coral Harbour, Kugaaruk, and Grise Fiord provided insight into the treatment performance of tundra WTAs. In summary, the studies demonstrated the following key findings:

i) **Comprehensive site-specific treatment performance, and hydraulic, hydrological and hydrogeological studies are recommended due to the unique attributes of the WTAs.**

Tundra WTAs are typically minimally or un-engineered systems which are different than conventional constructed treatment wetlands. The study sites were all unique in terms of treatment performance and hydrology, due to the natural physical attributes of the landscape, and operational differences in hydraulic loading. The hydrological and hydrogeological settings of the wetlands will influence the hydraulic retention times (HRTs) and amount of dilution from external hydrologic contributions. The timing and method of hydraulic loading may also influence the HRTs. Quantification of the HRTs, dilution effects and sample locations, requires detailed tracer studies, watershed delineations, flow monitoring, and in some cases, characterization of the wetland subsurface.

ii) **Temporal changes in treatment performance require special consideration.**

Seasonal variations in treatment performance may occur in some WTAs. Particularly, seasonal variability may be observed in wetlands with prolonged passive distribution of influent into the wetland. It is important to assess the WTA over a range of operating conditions, if they are suspected to change over the treatment season.

iii) **A modified Tanks-In-Series mass balance modeling approach can be used as a tool to predict performance expectations in tundra WTAs.**

The expected performance of a given WTA can be estimated with a modified TIS chemical reactor model adapted from the *P-k-C** method by Kadlec and Wallace (2009). The TIS model may need to be modified to account for external hydrologic contributions depending on the results from the comprehensive site-specific studies.

iv) **The initial assessment of rate constants fell within the low percentiles compared to literature for cold (non-arctic) climates.**

In the Coral Harbour, NU study, the minimum $k_{20}$ for $CBOD_5$ fell below the $5^{th}$ percentile, the $k_{20}$ for *Escherichia coli* (*E. coli*) and total ammonia nitrogen (TAN) was within the $40^{th}$ percentile, and the $k_{20}$ for TN fell below the $10^{th}$ percentile.

## 5.0 Conclusions

In conclusion, the tundra WTAs are a valuable resource that, with the appropriate management procedure, can be important part of the treatment train in Nunavut's municipal wastewater management strategy. Published literature to date has repeatedly shown that tundra WTAs produce water quality improvements. The site-specific research program conducted by CWRS has focused on identifying the specific elements required to develop an adequate understanding of the WTAs from a risk and engineering stand-point.

Some of the WTAs met the southern regulatory standards of 25/25 mg/L for $BOD_5$ and TSS, and 1.25 mg/L for $NH_3$-N. However, this was not consistent in all three of the WTAs studied. Due to the natural physical attributes that characterize each WTA, detailed site-specific studies are recommended to inform the performance estimates. Uncertainties in performance expectations may be minimized by collection of sufficient site specific data. The hydrological setting of the WTA will be very important to characterize to obtain an accurate understanding of dilution versus treatment. The comprehensive site-specific studies and ongoing monitoring programs will be costly; however, these studies will, in many cases, still be significantly more economical than conventional wastewater infrastructure with large associated capital and O&M costs. The WTAs will also be less prone to the operational failure observed with existing WWTP technology in northern communities.

A modified tanks-in-series model was demonstrated to well represent the internal hydraulics of tundra WTAs. Therefore, this type of model may be used as a design tool to predict treatment performance expectations in other tundra WTAs. Site-specific data will be required to parameterize the model. The initial determination of the first order rate constants for the Coral Harbour WTA indicated that the conservative rate constants fell within the low percentile values in comparison to literature from treatment wetlands across North America (i.e., <5 – 40 %). Further refinement of the rate constant estimates to improve design assumptions may be developed as more site-specific data becomes available with monitoring.

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