Treatment Performance of Municipal Wastewater Stabilization Ponds in Nunavut

Prepared for:
Community and Government Services (CGS)
Government of Nunavut
P.O. Box 1000 STN 700
4th Floor, W.G. Brown Building
Iqaluit, NU X0A 0H0

September 18, 2015

Prepared by:
Centre for Water Resources Studies
Dalhousie University
1360 Barrington St. D514
Halifax, NS B3H 4R2

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This document "*Treatment performance of municipal wastewater stabilization ponds in Nunavut*" was prepared by Dr. Rob Jamieson Canada Research Chair in Cold Regions Ecological Engineering, Jennifer Hayward, Joanna Poltarowicz, Colin Ragush, and Jordan Schmidt at the Centre for Water Resources Studies (CWRS) at Dalhousie University.

Further information in regards to this document may be obtained by contacting:

Centre for Water Resources Studies
Dalhousie University
1360 Barrington St. D514
Halifax, NS B3H 4R2
902.494.6070
water@dal.ca

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 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 of Pond Inlet, Clyde River, Kugaaruk, and Grise Fiord in Nunavut. Thank you to the Nunavut Research Institute for providing laboratory space at the Northern Water Quality Laboratory in Iqaluit, NU. Thank you to Colin Saunders, Pat Fuentes, and David Boyle for their provision of logistical support during the fieldwork. 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.

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List of Abbreviations

%	Percent
°C	Degree Celsius
APHA	American Public Health Association
BOD	Biochemical Oxygen Demand
BOD_5	Five-day Biochemical Oxygen Demand
$CBOD_5$	Five-day Carbonaceous Biochemical Oxygen Demand
CFU/100mL	Colony Forming Units per 100 mL
CGS	Community and Government Services
CWRS	Centre for Water Resources Studies
d	Day
DL	Detection limit
DNA	Deoxyribonucleic acid
DO	Dissolved Oxygen
E. coli	*Escherichia coli*
e.g.	*Exempli gratia*
EC	Environment Canada
et al.	*Et alii*
GCL	Geosynthetic Clay Liner
GN	Government of Nunavut
ha	Hectare
HDPE	High Density Polyethylene
i.e.	*Id est*
Inc.	Incorporated
Kg	Kilogram
km	Kilometre
L	Litre
m	Metre
m^2	Square metre

m^3	Cubic metre
MA	Massachusetts
mg	Milligram
mL	Millilitre
mm	Millimetre
MPN/100mL	Most probable number per 100 mL
N	North
n	Sample Number
NH_3-N	Un-ionized Ammonia
NPS	National Performance Standards
NS	Nova Scotia
NTC	No Template Control
NU	Nunavut
NWB	Nunavut Water Board
NY	New York
OH	Ohio
QC	Quebec
Q-PCR	Quantitative Polymerase Chain Reaction
TAN	Total Ammonia Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solids
W	West
WSER	Wastewater Systems Effluent Regulations
WSP	Wastewater Stabilization Pond
WTA	Wetland Treatment Area
WWTP	Wastewater Treatment Plant
μg	Microgram

Executive Summary

The majority of small remote communities in the Canadian Arctic Territory of Nunavut utilize waste stabilization ponds (WSPs) for municipal wastewater treatment because of their relatively low capital and operational costs, and minimal complexity. New national effluent quality regulations have been implemented in Canada, but not yet applied to Canada's Arctic due to uncertainty related to the performance of current wastewater treatment systems. Waste stabilization pond treatment performance is impacted by community water use, pond design, and climate. The greatest challenge Arctic communities experience when using passive wastewater treatment technologies is the constraints imposed by the extreme climate, which is characterized as having long cold winters with short cool summers that can be solar intense.

This study characterized the level of oxygenation and treatment performance within WSPs used in the Canadian Arctic. WSP systems used in this extreme climate function as controlled discharge storage ponds, where biological treatment processes are constrained to relatively short time periods (approximately 60 d) when air temperatures average between 7-10 ^{o}C. The removal of carbonaceous biochemical oxygen demand ($CBOD_5$), total suspended solids (TSS), nutrients (ammonia-nitrogen, total nitrogen, phosphorus) and bacteria were measured during this study. This study took place during the summer treatment periods (late June until early September) from 2011-2014 in four Nunavut communities; Pond Inlet, Clyde River, Kugaaruk and Grise Fiord .

Monitoring results show that WSPs in their current single cell design, can achieve greater than 80% removal of $CBOD_5$ and TSS, but are challenged to produce effluent quality that meets secondary wastewater treatment standards (< 25 mg/L for $CBOD_5$ and TSS). WSP systems currently used in Nunavut can achieve modest levels of treatment for total ammonia nitrogen (10 - 50% removal) and total phosphorus (30 - 60 % removal), but these removal rates are highly dependent on algae growth. The presence of near-neutral pH conditions in the majority of the WSPs resulted in relatively low concentrations of un-ionized ammonia (< 1.25 mg/L for NH_3-N) in final effluents.

Current design guidelines for facultative WSPs in cold climates need to be revised, as the facultative WSPs in this study were primarily anaerobic throughout the majority of the treatment seasons monitored. These systems are effective for the removal of suspended solids, but are challenged to meet secondary wastewater treatment objectives for the removal of oxygen demanding material, due to reduced biological treatment rates associated with low temperatures and near-anaerobic conditions. A possible strategy for improving treatment is the use of multi-cell pond arrangements employing a combination of deep, anaerobic cells, and shallow facultative cells receiving lower organic loading rates.

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 five day carbonaceous oxygen demand ($CBOD_5$) and total suspended solids (TSS), and 1.25 mg/L for un-ionized ammonia (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 report "*Treatment Performance of Municipal Wastewater Stabilization Ponds in Nunavut"* presented herein has been assembled from the research findings obtained during the grace period. It is intended that this treatment performance review will provide the data necessary to enable: (i) an assessment of the treatment performance of existing systems in use in northern regions, and (ii) an understanding of the driving factors influencing the treatment performance of these systems. These two research outcomes will help to develop performance standards appropriate for Canada's Far North. Additionally, the research outcomes will eventually help to inform and optimize the design of new systems.

This document has been prepared 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 research programs at the wastewater stabilization pond (WSP) sites described within this document. The studies took place during the summer treatment seasons from 2011 to 2014. This document summarizes the treatment performance findings from the studies. The studies were led by Dr. Rob Jamieson Associate Professor and Canada Research Chair in Cold Regions Ecological Engineering at Dalhousie University.

Readers looking for further technical information on wastewater stabilization ponds in Nunavut should refer to:

- Ragush, C.M., Schmidt, J.J., Krkosek, W.H., Jamieson, R.C., & Gagnon, G.A., under review. *The performance of municipal stabilization ponds in the Canadian Arctic.*
- Schmidt, J.J., Ragush, C.M., Krkosek, W.H., Gagnon, G.A., & Jamieson, R.C., under review. *Characterizing phosphorus removal in passive arctic waste stabilization ponds.*

1.0 Introduction

1.1 Purpose

This document provides a review of the treatment performance of wastewater stabilization ponds (WSPs), also referred to as sewage lagoons, in Nunavut. Until recently, there has been a lack of information on the performance expectations and treatment mechanisms of WSPs in Canada's Far North (Krkosek et al., 2012, Johnson et al., 2014). This document aims to summarize the performance of select existing WSPs in Nunavut. The performance findings are compared to the southern Wastewater Systems Effluent Regulations (WSER) implemented by Environment Canada (EC), as well as, current Nunavut Water Board (NWB) treatment standards, to provide context. In addition, the driving factors affecting the treatment performance of the systems will be identified. Identification of the driving factors affecting treatment performance will eventually help to inform best management practices for system upgrades and the configuration and operation of new systems.

This document has been developed to provide a summary of the treatment performance of select WSPs in Nunavut for municipal infrastructure managers in the Community and Government (CGS) department in the Government of Nunavut (GN). The results may also be helpful for territorial and federal regulators to inform the establishment of performance standards. The data presented within this document is also meant to inform the formation of best management practices for operation and design of system upgrades. This document is a summary of performance findings and does not specifically address recommended best management practices for WSPs or design configurations. These recommendations will be presented as a separate document on WSP design guidelines.

1.2 Wastewater treatment in Nunavut

There are many challenges associated with wastewater treatment in Canada's Far North. These challenges include: geographically isolated communities with relatively small population sizes, limited capital funding, lack of skilled personnel, extreme cold temperatures, short summer periods of ice-free pond cover and permafrost (Miyamoto and Heinke, 1979, Krkosek et al., 2012). Furthermore, it is difficult to attract, train, and retain skilled personnel. Conventional wastewater treatment plants (WWTPs) have repeatedly been cited as an inappropriate option for 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 and similar arctic regions (Yates et al., 2012, Krkosek et al., 2012, Jensen et al., 2013, Hayward et al., 2014, Chouinard et al., 2014b).

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. However, there still are circumstances where a conventional mechanical WWTP may be necessary when land availability and site topography are restrictive (Johnson et al., 2014). 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 (Hayward et al., 2014). This ice-free period is termed the treatment season which represents when the water temperatures are high enough to encourage biological treatment processes.

Municipal wastewater treatment in Nunavut consists of a combination of methods as shown in Figure 1. Further detail on the specific types of systems in each hamlet are provided in Appendix I. There are twenty-five communities located in Nunavut, and of these, sixteen systems use a WSP or un-engineered "lake lagoon" in combination with a tundra wetland treatment area (WTA). The tundra WTAs are typically non-engineered wetland systems, that are distinctively different from natural tundra wetlands, in terms of their hydrology, nutrient availability, vegetation and organic loading (Chouinard et al., 2014a, Hayward et al., 2014). Further improvements in effluent water quality have been demonstrated in these WTAs (Hayward et al., 2014, Yates et al., 2012, Doku and Heinke, 1995, Dubuc et al., 1986). To a lesser extent un-engineered lake lagoons are used instead of WSPs. There are only three hamlets that use mechanical WWTPs in Nunavut (Johnson et al., 2014).

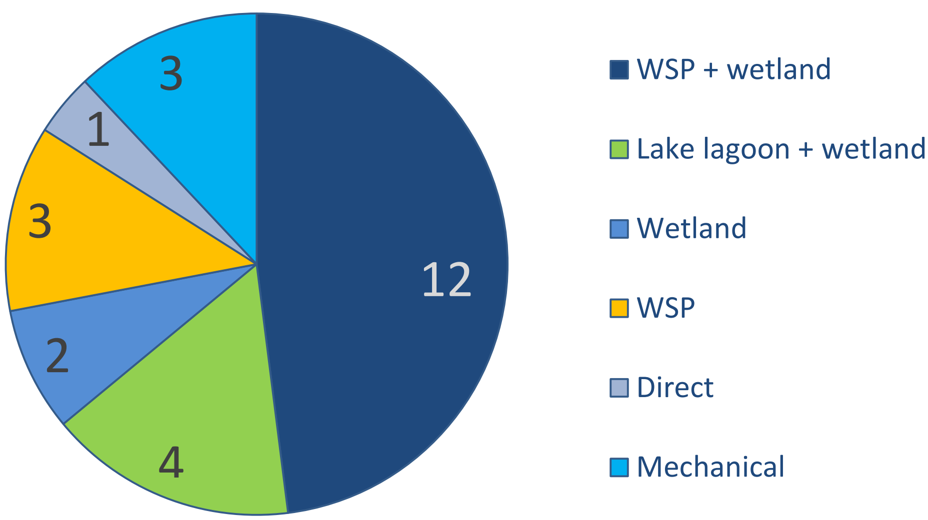

FIGURE 1. TYPES OF WASTEWATER TREATMENT SYSTEMS IN NUNAVUT.

Many hamlets in Nunavut use wastewater holding tanks to temporarily store wastewater at each house and building. Vacuum pump trucks are then used to collect the wastewater every 1 to 3 days from each house and building (Daley et al., 2014). Following collection, the wastewater is transported via the pump trucks and discharged into the wastewater treatment system. A water consumption value of 100 L/capita/day is typically used as a design drinking water provision rate in the hamlets (Daley et al., 2014). Nunavut's water use is much lower than the Canadian national average of 329 L/capita/day (Environment Canada, 2015). Therefore, the raw wastewater effluent produced is higher in strength compared to southern Canadian effluent (Schmidt et al., under review). Less commonly, heated piped systems are used to convey water and wastewater.

1.3 Wastewater stabilization ponds

Most commonly, wastewater stabilization ponds in Nunavut are designed as controlled discharge single-cell retention ponds with storage capacities to accommodate wastewater accumulated over an entire one year period. Wastewater is stored frozen for most of the year with discharge typically occurring at the end of the ice-free treatment season. Occasionally, additional WSPs cells are incorporated into the design of the treatment systems. These additional cells may be operated in series or parallel. A decant cell, which is a smaller and more shallow version of a WSP, is sometimes used to distribute effluent over a wide area into down gradient tundra wetland treatment areas. The WSPs are commonly rectangular in shape with granular material used to construct trapezoidal berms. The inner core of the berm may be constructed of low permeability granular material and designed to be frozen year-round to prevent unplanned seepage. Some sites feature a high density polyethylene liner (HDPE) to retain the wastewater within the pond.

The wastewater can be discharged manually in a controlled manner which is referred to as a "decant" hereafter. Whereas, some WSPs have an uncontrolled discharge of wastewater with exfiltration through a berm structure. Some of the WSPs are designed with a decant pipe and control valve built directly into the berm structure. These decant pipes are rarely used due to issues associated with pipe freezing and potential for rust formation. Typically, the WSPs discharge out to either tundra wetland treatment areas or directly to the receiving water, which is usually marine. In many cases, decants are performed with a pump and generator used to lift wastewater effluent from the WSPs to the discharge areas. In some cases, gravity siphons have been established to decant effluent from WSPs. The timing of decanting is usually towards the end of the treatment season in August or September, just prior to freeze-up, to maximize the treatment potential. There are circumstances where an early decant may be necessary when the capacities of the WSPs have been reached prematurely. Additionally, some WSPs may discharge wastewater through exfiltration earlier in the treatment season.

Currently, the regulation of the performance of the WSPs is set by the Nunavut Water Board (NWB). The treatment requirements for the effluent discharged from WSPs typically consists of maximum concentrations of 120 mg/L for five-day biochemical oxygen demand (BOD_5), 180 mg/L for TSS, $1x10^6$ CFU/100 mL for fecal coliforms, and a pH between 6 and 9 (Nunavut Water Board, 2010, Nunavut Water Board, 2009a, Nunavut Water Board, 2009b). The compliance monitoring is conducted by Aboriginal Affairs and Northern Development Canada (AANDC).

Many of the WSPs are 2 to 5 m in depth. However, some are more or less deep, depending on site constraints and geology. The depth of wastewater has the greatest impact on the type of treatment occurring in the WSP (Ragush et al., under review). Ponds that are deep (i.e., > 2 m) are generally anaerobic due to limited mixing of the water column and air exchange with the pond surface. Deep ponds promote anaerobic biological activity where complex organic chemicals are metabolized to relatively inert gases. Whereas, shallow ponds (i.e., < 2 m) have the tendency to promote aerobic or facultative conditions. This is due to a large surface area to volume ratio and increased light penetration of the water column. Solar radiation of the upper layer of the water column promotes growth of algae which oxygenate this layer. Facultative pond conditions are characterized by a stratified water column, whereby the uppermost layer at the surface is aerobic, the intermediate layer is aerobic and/or anaerobic, while the bottom layer is anaerobic.

WSPs have been studied extensively in southern climates (Finney, 1980, USEPA, 1983). However, there are fundamental differences between WSPs operating in southern versus northern climates. The WSPs in Nunavut are subjected to extreme cold temperatures, with a short 3 to 4 month treatment season, when significant biological activity can occur. Additionally, the photoperiod in Nunavut is extremely long during the treatment season, with some communities subjected to near 24 hour daylight around the summer solstice. The long photoperiod may be advantageous to promote aerobic pond conditions with growth of algae.

There have been a few notable studies that were conducted on WSPs in Northern Canada which have demonstrated the potential viability of WSPs and passive treatment technology in the Arctic. The systems that were studied were located in Northern Alberta where a database of approximately 200 systems was analyzed (Prince et al., 1995), in Northern Northwest Territories where a single-cell WSP was studied (Miyamoto and Heinke, 1979), and in Northern British Columbia where an aerated WSP was studied (Johnson and Sarson, 1997). In all of those systems, the WSPs were demonstrated to meet the southern standard WSER of 25/25 mg/L for five-day carbonaceous biochemical oxygen demand ($CBOD_5$) and total suspended solids (TSS), and 1.25 mg/L for un-ionized ammonia nitrogen (NH_3-N) most of the time (Ragush et al., under review). Guidelines on the design of WSPs in northern Canada were presented by Heinke et al. (1991). Smith and Emde (1999) described WSPs as an effective and inexpensive treatment technique for Canada's northern communities. The existing literature has demonstrated a promising potential for successful use of WSPs in Northern environments.

However, there are still knowledge gaps in the treatment performance of WSPs operating in Nunavut. Little is known about the treatment mechanisms in the WSPs (Krkosek et al., 2012). Furthermore, the influence of environmental, design configuration, and operational factors on the overall performance is unknown. This information is needed to inform the development of appropriate regulations and establishment of design standards that will ensure adequate treatment of wastewater, to protect human health and the environment, prior to discharge into receiving environments.

1.4 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 CGS department of the Government of Nunavut. A focus area of the broader infrastructure research program was to conduct research on the WSPs in Nunavut due to their prevalence in Nunavut (e.g., 15 out of 25 systems use WSPs).

Comprehensive studies were conducted on the WSPs in the hamlet communities of Pond Inlet, Clyde River, Kugaaruk, and Grise Fiord, Nunavut (Figure 2). The study sites were chosen to represent a wide geographic range to capture conditions in western and eastern Nunavut, as well as, low and high latitudes. The four study sites enabled an intersystem assessment of treatment performance. These systems were not assessed during the winter because it is generally accepted that very little treatment would occur during this period. Furthermore, discharges of effluent do not occur during the winter period when the ponds are frozen.

The research program on the WSPs was conducted with the objectives of achieving an:

(i) Assessment of the treatment performance of WSPs used in Nunavut, and
(ii) Identification of the driving factors affecting the treatment performance of WSPs in this region.

The WSPs at the study sites were assessed by monitoring biogeochemical parameters *in-situ* and assessment of key treatment performance parameters. These long-term studies provide the first multi-seasonal intersystem study of WSPs in Northern Canada, and as such, provides unique insight into the environmental factors affecting their treatment performance.

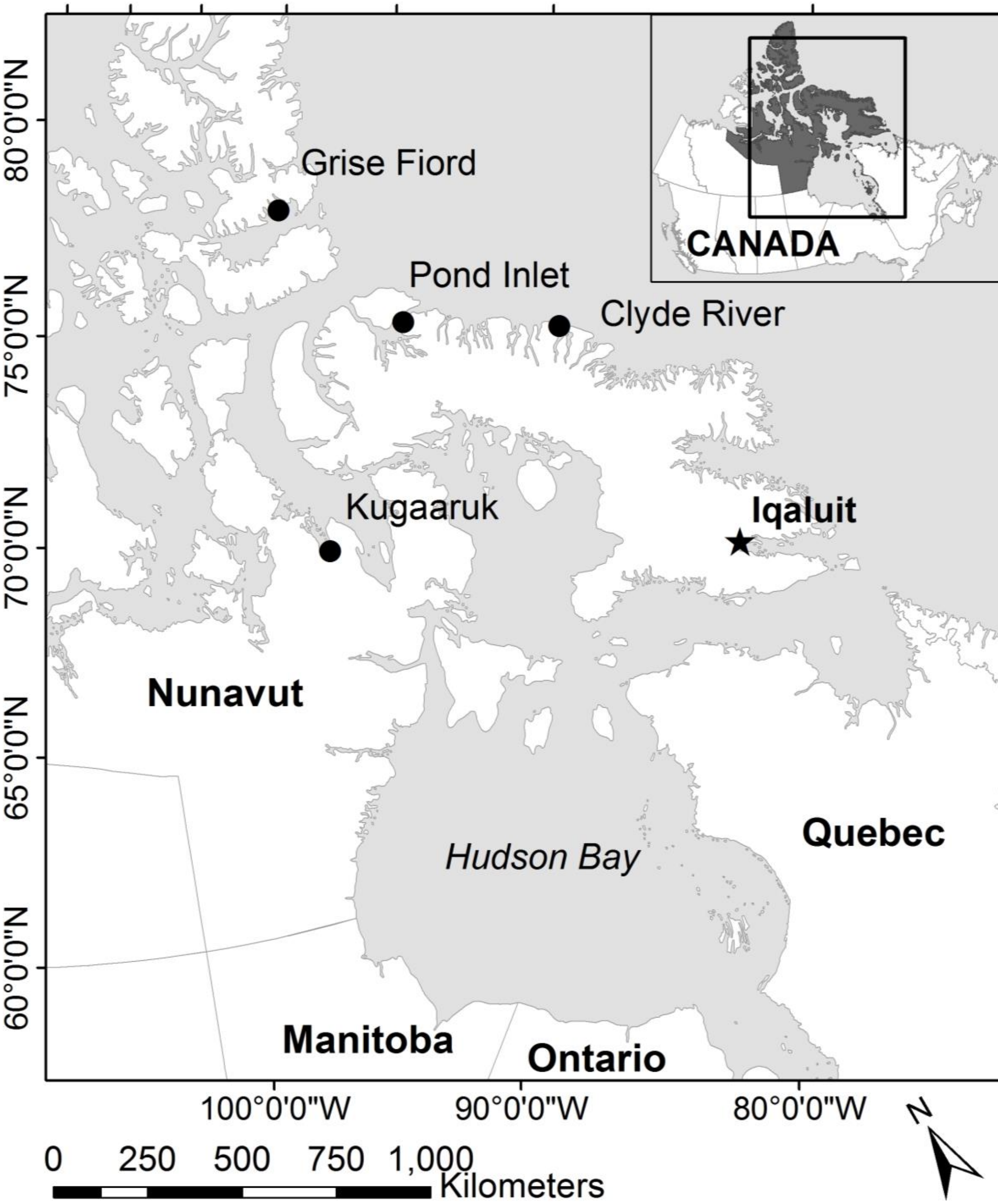

FIGURE 2. SITE LOCATOR MAP FOR THE COMPREHENSIVE SITE-SPECIFIC STUDIES ON THE WSPS IN POND INLET, CLYDE RIVER, KUGAARUK, AND GRISE FIORD, NUNAVUT.

2.0 Methodology

2.1 Site descriptions

2.1.1 Pond Inlet

The hamlet of Pond Inlet (72° 41’ 57” N, 077° 57’ 33” W) has an estimated population of 1612 (Nunavut Bureau of Statistics, 2013). Average air temperatures range from –30°C to –37°C in January, and from 11°C to 3°C in July. Precipitation averages 91 mm as rainfall, and 1319 mm as snow, for a total of 189 mm of precipitation annually (Government of Canada, 2015a). Approximately 114 m^3/d (41 046 m^3/year) of primarily domestic municipal wastewater is generated in Pond Inlet (Nunavut Water Board, 2014a). Pump trucks are used to transport the wastewater from individual houses and establishments to a single-cell WSP lined with a geomembrane (Figure 3a). The WSP is located approximately 1.4 km to the east of the hamlet (Figure 3b).

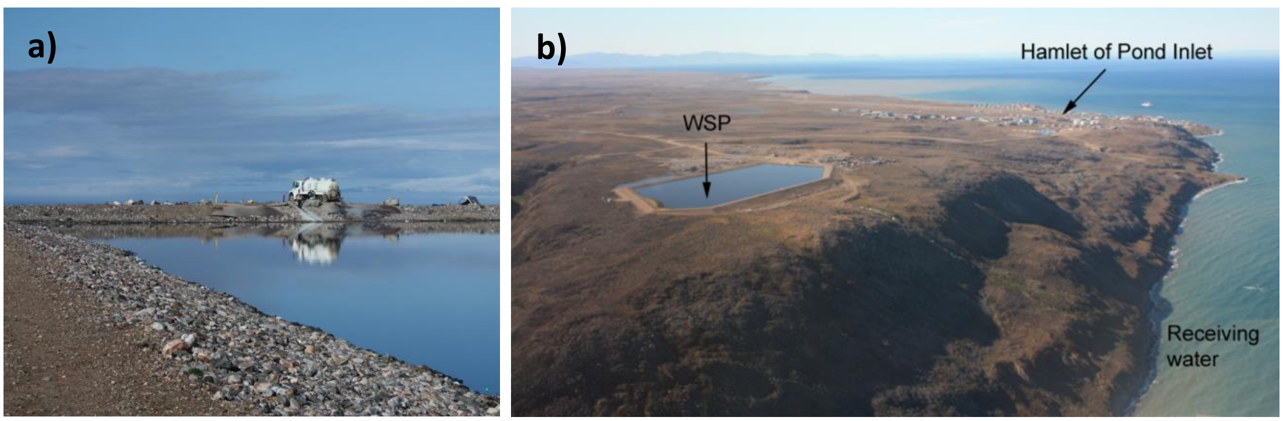

FIGURE 3. (A) PHOTOGRAPH OF A TRUCK DISCHARGE AT THE INLET OF THE WSP IN POND INLET, NU TAKEN ON AUGUST 19, 2010, AND (B) AN AERIAL PHOTOGRAPH OF THE WSP SHOWING THE LOCATION OF THE HAMLET OF POND INLET, NU TAKEN ON AUGUST 26, 2010.

The WSP was constructed in 2006. The surface area of the pond is close to 4 ha, with an approximate volume of 80 000 m^3. The average depth of the WSP in Pond Inlet is 1.6 m during the treatment season. The organic loading rate of the WSP is approximately 15 kg/ha/d. A manual decant of the WSP is performed annually for a period of three weeks in September or early October. A pump powered by a generator is used to lift the wastewater from the WSP to the discharge channel. The discharge channel is approximately 275 m in length and descends steeply from the berm of the WSP in a perpendicular direction towards the marine receiving environment (Figure 4).

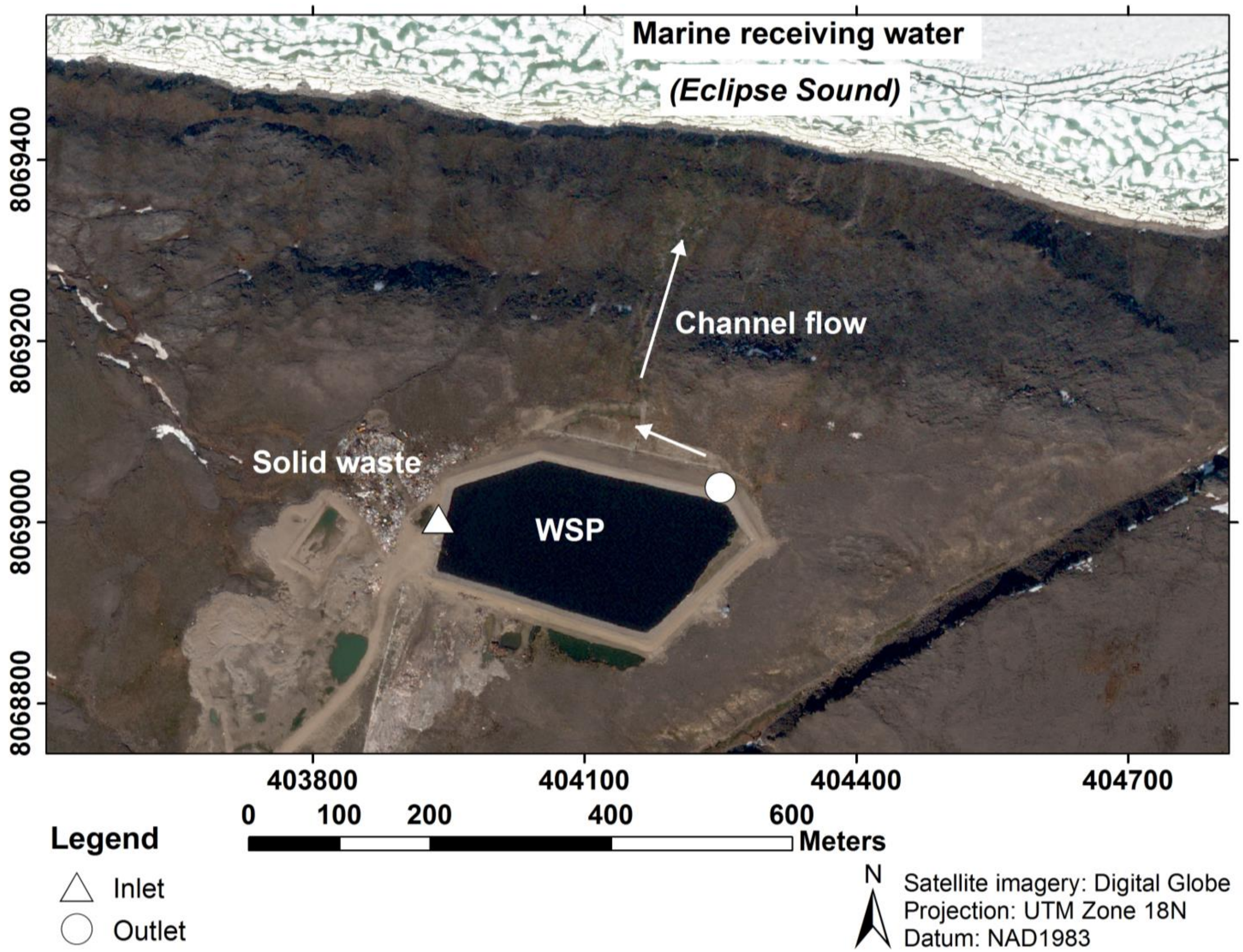

FIGURE 4. SATELLITE IMAGE OF THE WSP IN POND INLET, NU ACQUISITIONED ON JULY 2, 2012. ARROWS DENOTE THE DIRECTION OF EFFLUENT FLOW DURING THE DECANT.

2.1.2 Clyde River

The hamlet of Clyde River (70° 28′ 26″ N, 68° 35′ 10″ W) has an estimated population of 1004 (Nunavut Bureau of Statistics, 2013). Average air temperatures range from –25°C to –33°C in January, and from 9°C to 1°C in July. Precipitation averages 63 mm as rainfall and 1947 mm as snow (Government of Canada, 2015b). Approximately 93 m^3/d (34 011 m^3/year) of primarily domestic municipal wastewater is generated in Clyde River (Nunavut Water Board, 2014b). Pump trucks transport the wastewater from individual houses and establishments to a two cell WSP system (Figure 5a and Figure 5b). The WSPs are located approximately 1.1 km to the south west of the hamlet.

The two cell WSP system consists of cell 1 and cell 2 (Figure 5a), constructed in 1976 and 2011, respectively. Cell 1 was renovated in 2011 with the installation of a geosynthetic clay (GCL) liner into half of the berm and removal of sludge. The entire berm of the cell 2 is keyed-in with a GCL. The bottom of the WSPs are both unlined. The cells are operated in semi-parallel with both cells receiving raw wastewater from the pump trucks. Periodically, the wastewater is transferred from cell 1 to cell 2, when cell 1 is full. Cell 1 has an approximate surface area of 0.6 ha, an average operating depth of 1.1 m and volume of 6600 m^3, during the treatment season. Cell 2 has a surface area of 1.5 ha, an operating depth of 2.3 m and volume of 35 000 m^3, during the treatment season. The areal organic loading rates for cell 1 and cell 2 are 57 kg/ha/d and 11 kg/ha/d, respectively.

The decant takes place over a few week period towards the end of the treatment season in September. The decant is performed with a pump powered by a generator. The decant effluent is discharged into a vegetated filter strip (23 ha) prior to flowing into the marine receiving environment (Patricia Bay) (Figure 6).

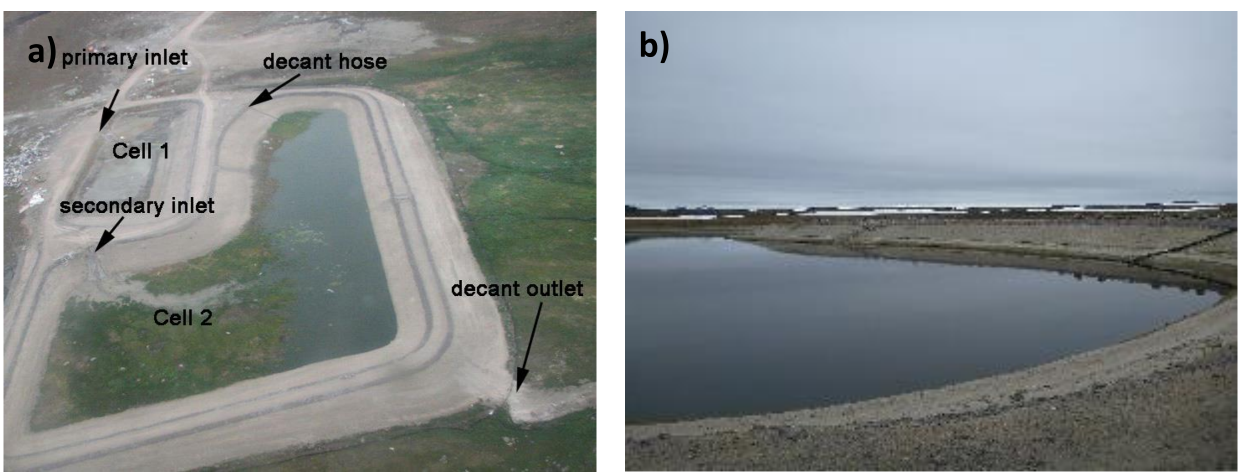

FIGURE 5. (A) AN AERIAL PHOTOGRAPH OF THE TWO CELL WSP SYSTEM IN CLYDE RIVER, NU (DATE UNKNOWN), AND (B) PHOTOGRAPH OF CELL 2 TAKEN ON JULY 5, 2012.

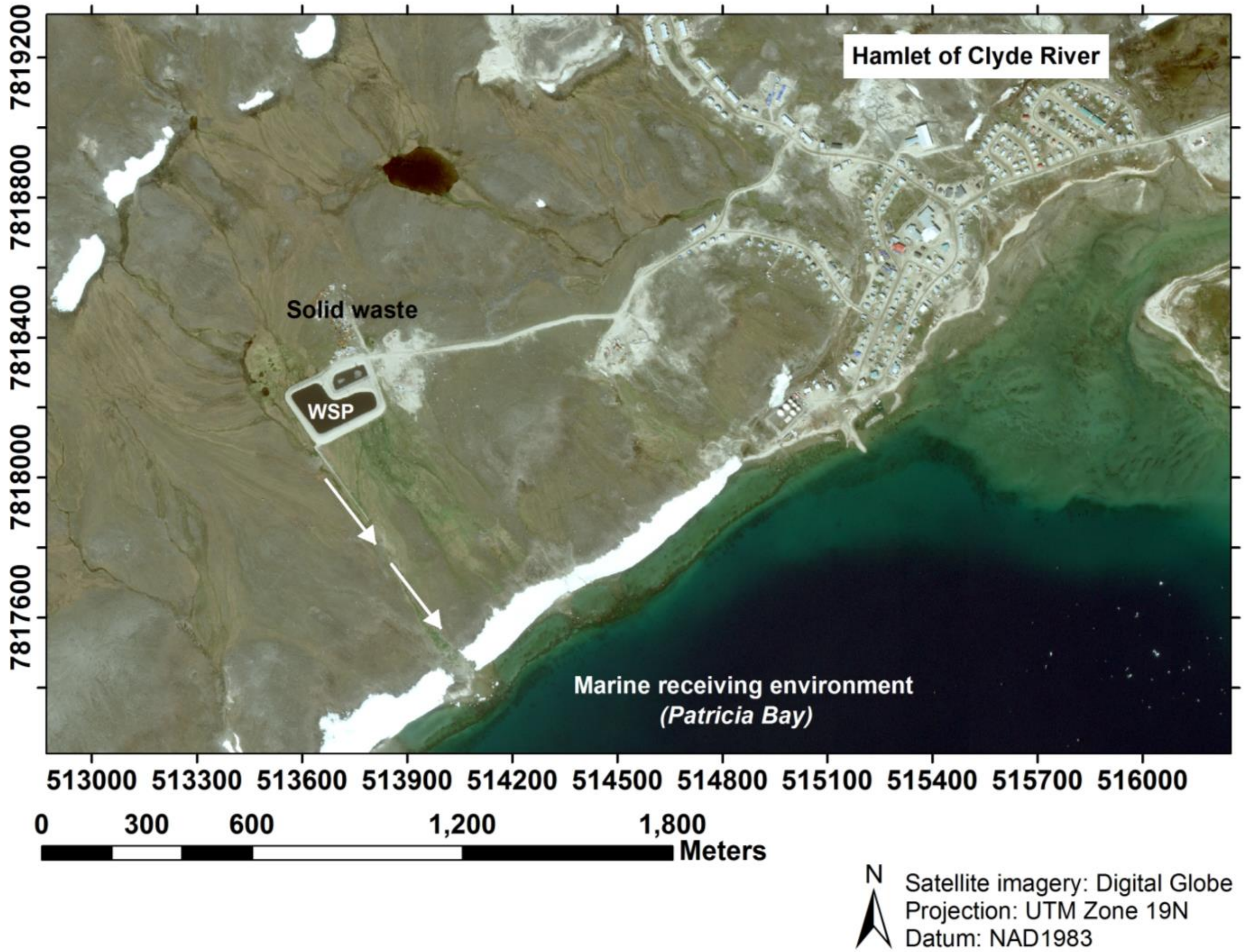

FIGURE 6. SATELLITE IMAGE OF THE WSP AND HAMLET OF CLYDE RIVER ACQUISITIONED ON JULY 17, 2012. ARROWS DENOTE THE DIRECTION OF EFFLUENT FLOW DURING THE DECANT.

2.1.3 Kugaaruk

The hamlet of Kugaaruk (68° 32′ 05″ N, 089° 49′ 29″ W) has an estimated population of 878 (Nunavut Bureau of Statistics, 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, 2014c). Approximately 76 m^3/d (27 588 m^3/year) of primarily domestic municipal wastewater is generated daily (Nunavut Water Board, 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 7a and Figure 7b shows the wastewater treatment facility which consists of a WSP (1 ha), with a decant cell (755 m^2), and a tundra wetland treatment area (0.7 ha).

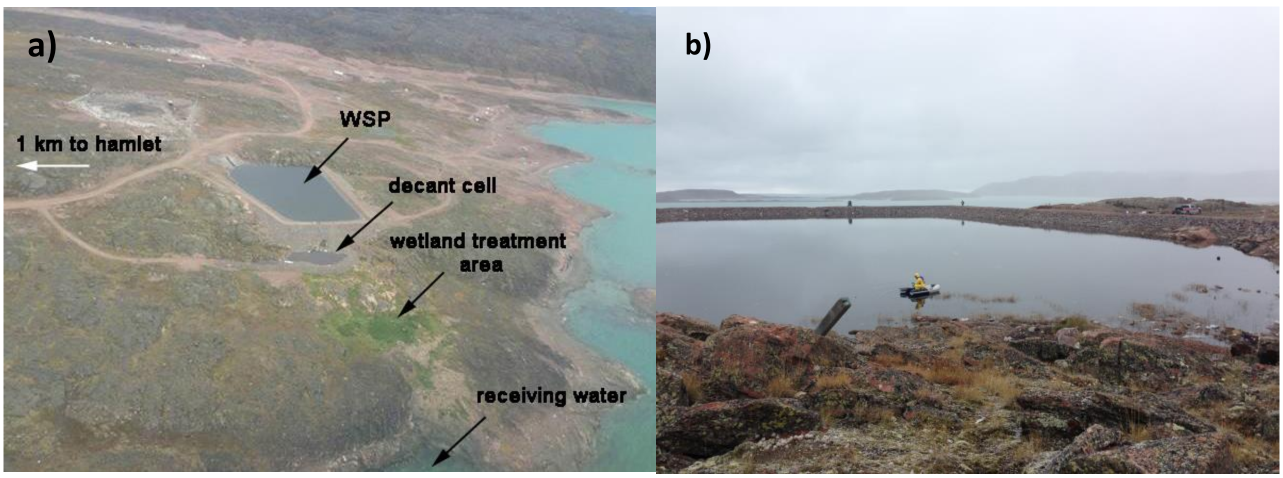

FIGURE 7. (A) AN AERIAL PHOTOGRAPH OF THE WSP AND WETLAND TREATMENT AREA IN KUGAARUK, NU TAKEN ON AUGUST 28, 2013, AND (B) PHOTOGRAPH OF WSP TAKEN FROM NEAR THE INLET IN KUGAARUK TAKEN ON AUGUST 27, 2013.

The WSP was constructed in 2008 and has a liner keyed into the berms (Figure 7b). The volume of the WSP is 54 000 m^3. The average operating depth is comparatively deep at 5.4 m during the treatment season. The average organic loading rate is 28 kg/ha/d. The WSP is typically decanted with a pump and generator into the decant cell periodically between July and October. The decant cell retains the effluent temporarily. Throughout decanting, effluent seeps out the toe of the permeable decant cell berm into a channel, which flows into the tundra wetland treatment area. The wetted area of the tundra WTA is 0.56 ha. The effluent discharges from the WTA area into a coastal marine receiving environment (Pelly Bay) (Figure 8).

In Kugaaruk, there are two compliance points regulated by the NWB. The first represents the effluent decant from the WSP which is set at 120 mg/L for BOD_5, 180 mg/L for TSS, $1x10^4$ CFU/100 mL for fecal coliforms and a pH between 6 and 9. The second compliance point at the end of the tundra WTA must have maximum concentrations of 45 mg/L for BOD_5, 45 mg/L for TSS, $1x10^4$ CFU/100 mL for fecal coliforms, and a pH between 6 and 9 (Nunavut Water Board, 2007).

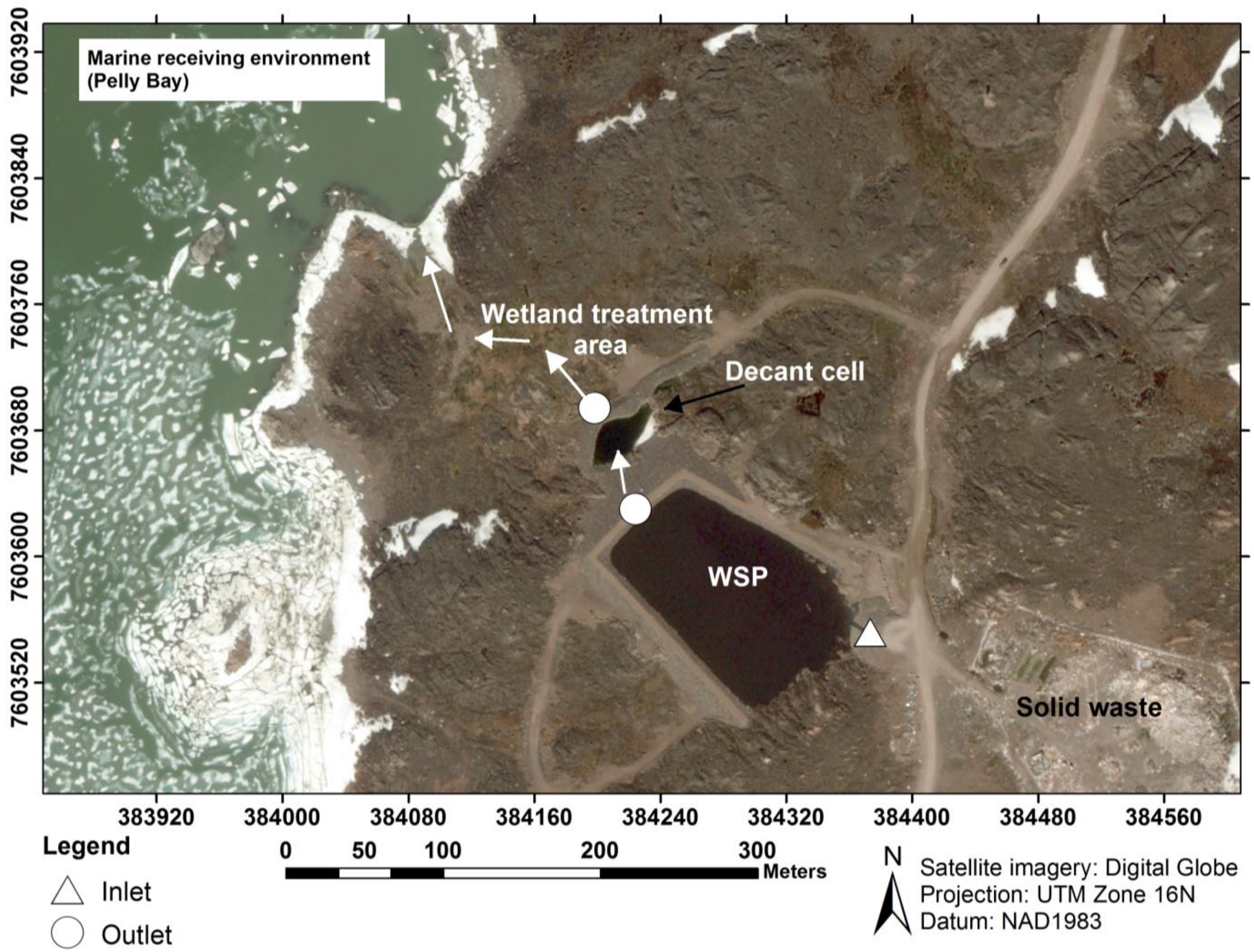

FIGURE 8. SATELLITE IMAGE OF THE WSP IN KUGAARUK, NU ACQUISITIONED ON JULY 3, 2012. ARROWS DENOTE THE DIRECTION OF EFFLUENT FLOW DURING THE DECANT.

2.1.4 Grise Fiord

The hamlet of Grise Fiord (76° 25′ 03″ N, 082° 53′ 38″ W) has an estimated population of 157 (Nunavut Bureau of Statistics, 2013). 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, 2014d). Approximately 13 m^3/d (4656 m^3/year) of primarily domestic municipal wastewater is generated daily (Nunavut Water Board, 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 (Figure 9a and Figure 9b).

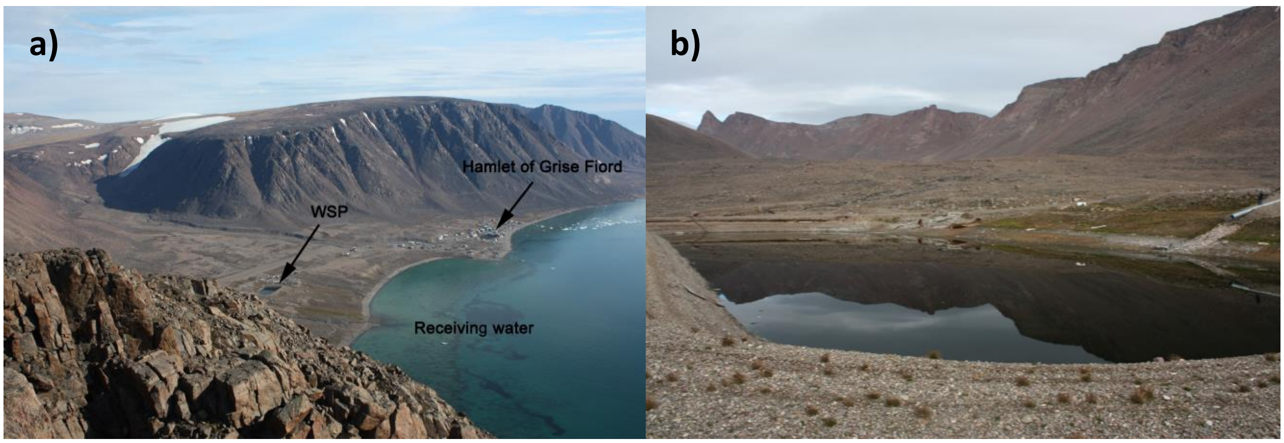

FIGURE 9. (A) OVERHEAD VIEW PHOTOGRAPH OF THE WSP SHOWING THE LOCATION OF THE HAMLET OF GRISE FIORD, NU TAKEN ON AUGUST 16, 2010, AND (B) PHOTOGRAPH OF WSP WITH THE INLET SHOWN ON THE RIGHT TAKEN ON AUGUST 17, 2010.

The wastewater treatment facility consists of an unlined single cell WSP (0.4 ha) (Figure 9b). The WSP is decanted bi-annually with a siphon to a small tundra wetland treatment area (0.5 ha). The WTA discharges to a marine receiving environment (Jones Sound) (Figure 10). Typically, the decant lasts for 3 to 4 days. The WSP was constructed in 1997 and has a volume of 6000 m^3. The WSP has an operating depth of approximately 1.5 to 2 m, during the treatment season. The organic loading rate onto the WSP is approximately 25 kg/ha/d.

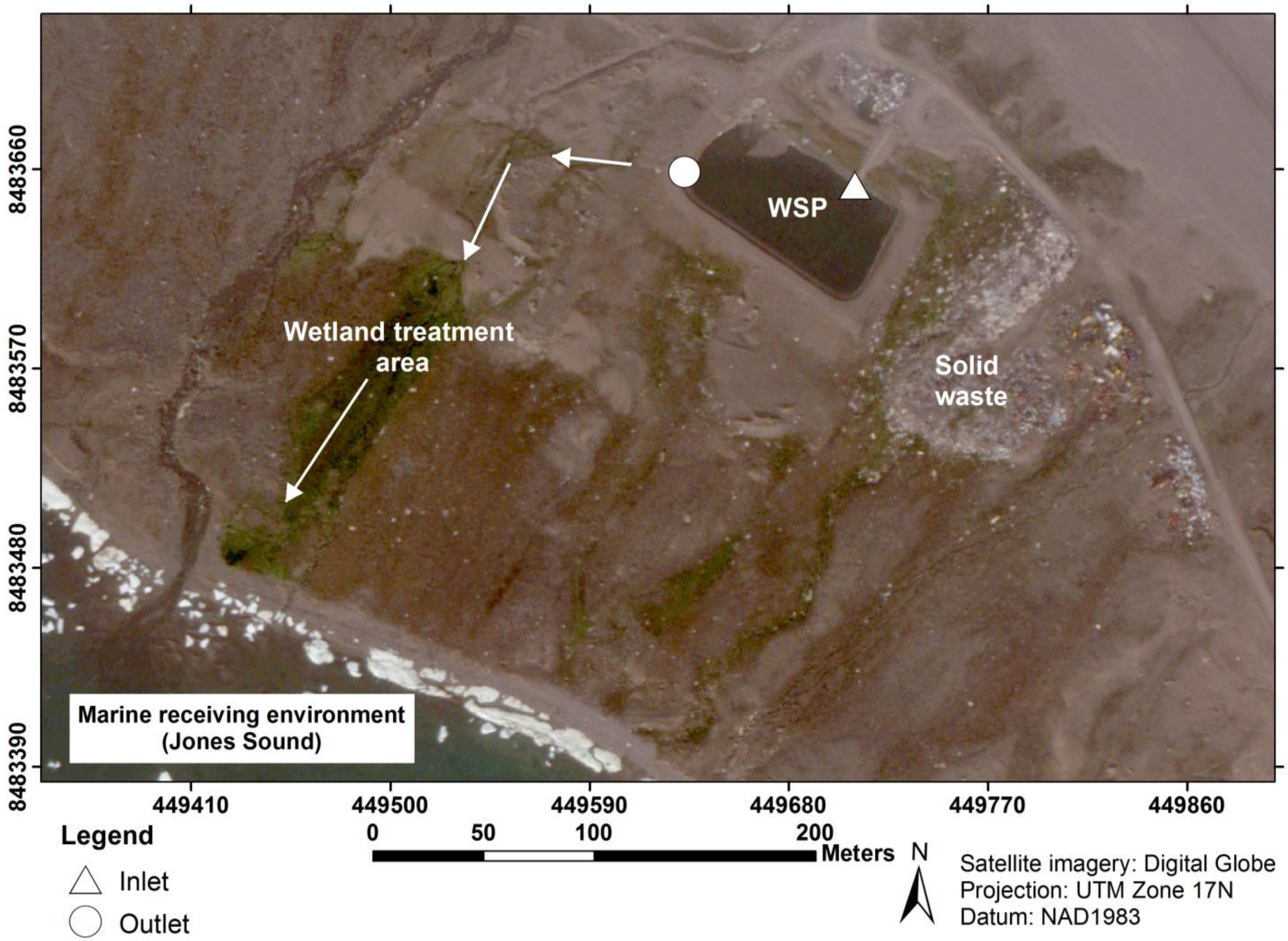

FIGURE 10. SATELLITE IMAGE OF THE WSP IN GRISE FIORD, NU ACQUISITIONED ON AUGUST 5, 2013. ARROWS DENOTE THE DIRECTION OF EFFLUENT FLOW DURING THE DECANT.

2.2 Data collection strategy

The data collection strategy consisted of multiple site visits during the treatment seasons between 2011 and 2014. Site reconnaissance was conducted in 2010; however, data collection took place primarily after 2010. Winter monitoring was not conducted because it is generally accepted that no appreciable treatment occurs during the period when the ponds are frozen. The sites were difficult to access and had high associated travel costs, therefore not all of the sites were visited the same number of times. The schedule of each of the site visits and a description of the site activities is shown in Table 1. The timing of the site visits fell into three ranges during the treatment season consisting of the: start (June 16 – July 8); middle (July 18 – August 9); and end (August 22 – September 16). The start of the treatment season coincides with the WSP thawing; often there is still ice coverage during this period. The middle of the treatment season is typically characterized by the warmest temperatures and hence greatest possibility for biological treatment. The end of the treatment season is associated with the decanting of the WSPs prior to freezing.

TABLE 1. SCHEDULE OF SITE VISITS FOR DATA COLLECTION FOR THE WSP STUDIES.

Study site	Year	Dates of site visit	Description of WSP activities		
			Deploy sondes	Performance sampling	Retrieve sondes
Pond Inlet	2011	Jul 24 - 26	X	X	
		Sep 10 - 14		X	X
	2012	Jul 5 - 8	X	X	
		Aug 4 - 9		X	
		Sep 3 - 7		X	X
	2013	Jun 16 - 19	X	X	
		Jul 18 - 22		X	
		Sep 9 - 12		X	X
	2014	Jun 29 – Jul 2	X	X	
		Jul 28 – Aug 1		X	
		Sep 10 – 16		X	X
Clyde River	2012	Jul 5	X	X	
		Sep 7		X	X
	2013	Jun 25	X	X	
		Jul 25		X	
		Sep 5		X	X
	2014	Jun 26	X	X	
		Sep 8		X	X
Kugaaruk	2012	Jul 3 - 5	X	X	
		Sep 4 - 11		X	X
	2013	Jun 17 - 18	X	X	
		Aug 22 - 28		X	X
Grise Fiord	2011	Jul 27 - 31		X	

2.3 Water quality measurement

The biogeochemistry of the WSPs was important to characterize because it provides an indication of the treatment mechanisms that may be occurring, as well as, the oxygen state of the WSPs. The water quality parameters of temperature, pH, specific conductivity and dissolved oxygen (DO) provided an indication of the biogeochemical environment of the WSPs. The water quality parameters were measured electrochemically with multi-parameter sondes.

2.3.1 Discrete measurement

Discrete measurement of the biogeochemistry of the samples were performed with handheld YSI 600 multi-parameter sondes (YSI Inc., Yellow Springs, OH). Each of the handheld sondes was calibrated for dissolved oxygen at the beginning of each day of the fieldwork. Each of the handheld sondes was calibrated for pH and conductivity at a minimum of once per site visit as per the manufacturer's specifications. Discrete measurement of samples were performed on the raw wastewater samples directly from the pump trucks at the WSPs. As well, discrete samples were recorded within the WSPs from an inflatable boat. At times, the discrete samples were collected from the edges of the WSPs with a sample pole collector or as grab samples.

2.3.2 Continuous monitoring

Continuous monitoring of the water quality of the WSPs over entire treatment seasons was conducted at the Pond Inlet, Clyde River, and Kugaaruk sites. The continuous monitoring was performed with YSI 6-series and EXO multi-parameter sondes installed *in situ* in the WSPs (YSI Inc., Yellow Springs, OH). Prior to deployment, the sondes were calibrated as per the manufacturer's specifications. The multi-parameter sondes were programmed to collect data on the water quality parameters on an hourly basis. The sondes were deployed in the WSPs at the start of the treatment season in mid-to-late June or early July, and retrieved prior to freeze-up, in late August or September. The *in situ* sondes were suspended from buoys at the water surface and therefore were measuring at depths of approximately 30 cm. The buoys were deployed near the middle of the WSPs and anchored with weights.

In addition, dissolved oxygen was measured on an hourly basis with ROX DO probes (YSI, Yellow Springs, OH) at different depths in the water column as a validation for the *in situ* sonde data. The water temperature, depth and light were measured on an hourly basis at different depths in the water column with HOBO temperature and light pendants, and HOBO water level loggers with temperature (Onset Computer Corporation, Cape Cod, MA).

2.4 Treatment performance assessment

2.4.1 Sample collection

The treatment performance samples were collected raw from the trucks with sample bottles attached to a sample pole. The raw wastewater samples were collected as they were discharging from the trucks to the WSPs. Treatment performance samples were also collected from multiple locations within the WSPs. Consistent sampling locations were used for each site visit. Sampling of the WSP was conducted from an inflatable boat when possible. When sampling from the boat was not possible due to weather and time constraints, alternatively the samples were collected from the shore of the WSP with a fully extended subsurface pole sampler (Environmental Remediation Equipment, Inc., Montreal, QC). Occasionally, an acrylic bacon bomb sampler (Koehler Instrument Company, Inc., Bohemia, NY) was used to collect samples at various depths. At times, surface samples were collected as grab samples due to logistical challenges.

Each WSP was sampled at three to five different locations to examine spatial variability. The WSPs in Pond Inlet and Kugaaruk each had five sample locations consisting of the four corners and the middle. The WSP in Clyde River was sampled in two locations, in cells 1 and 2, respectively. While, the WSP in Grise Fiord was sampled in each of the four corners. All of the samples were collected in clean, Milli-Q rinsed, polypropylene 500 mL and 1 L bottles. All of the samples were stored chilled in sample coolers with ice packs.

2.4.2 Sample analysis

After collection, the treatment performance samples were transported in chilled coolers by aircraft to analytical laboratories. The samples that were collected in Pond Inlet and Clyde River were analyzed in the Northern Water Quality Laboratory at the Nunavut Research Institute in Iqaluit, NU. The samples collected from Kugaaruk were transported to Yellowknife and analyzed by Taiga Environmental Laboratory, an accredited laboratory. Due to the remote geographic location of Grise Fiord, for this site, the samples were processed in a temporary laboratory space. The treatment performance samples from the WSP and raw from the truck were analyzed within their respective holding times for $CBOD_5$, TSS, *Escherichia coli (E. coli),* total ammonia nitrogen (TAN), NH_3-N and total phosphorus (TP). The samples were analyzed according to APHA (2012) or the manufacturer's specifications.

The samples collected for human bacterial pathogens were stored chilled for a maximum of 48 hours in a cooler while being transported to the water quality laboratory at Dalhousie University in Halifax, NS. Duplicate wastewater samples (10 mL each) from each WSP sampling site and raw sewage samples were subjected to an initial pathogen enrichment step using standard protocols by Stea (2013) for Rappaport-Vassiliadis for *L. monocytogenes*, *Campylobacter, Salmonella* and *Escherichia coli* O157:H7, respectively. Following enrichments, 2 mL from each of the enrichment broths were pooled into a 15 mL sterile test tube and the cells pelleted by centrifugation at 3200 x g for 10 minutes. DNA was extracted from the cell pellet using the Powersoil MoBio kit (MoBio, Carlsbad, CA) following the manufacturer's instructions. The quantitative polymerase chain reaction (Q-PCR) methods used TaqMan probes to ensure the specificity of the signal from the pathogens. All assays were carried out on a StepOne Plus Q-PCR thermocycler (Life Technologies, Carlsbad, CA) using previously developed methods (Stea, 2013). Positive (extracted DNA from control strains) and no template control (NTC) samples were also analyzed. The results from this testing are reported as pathogen presence or absence in 10 mL of wastewater samples (Huang et al., 2014).

2.4.3 Statistics and calculations

Sample T-tests were used to compare sample populations at a confidence level of 95%. Samples corresponding to a site and sampling period (i.e., start, middle, and end) were pooled. The samples were pooled because there were no significant statistical differences between sampling year or spatial locations of sample points in the WSPs.

The percent reductions presented in the treatment performance assessment were calculated by using the following equation:

$$\% \, reduction = \frac{\left(C_{raw} - C_p\right)}{C_{raw}} \cdot 100 \quad \text{[Eq. 1]}$$

where C_{raw} is the raw treatment performance parameter concentration taken as the mean (mg/L or MPN/100mL), and C_p is the treatment performance parameter concentration in the pond (mg/L or MPN/100mL). The log reductions for *E. coli* were calculated with mean values for raw wastewater according to Equation 2.

$$log \, reduction = log(C_{raw}) - log(C_p) \quad \text{[Eq. 2]}$$

3.0 Results

3.1 Biogeochemistry

The general water quality parameters of temperature, pH, and DO provide insight into the biogeochemical processes within the WSPs. The DO is also indicative of the oxygen state of the WSPs, in particular whether they functioning as aerobic, facultative, or anaerobic. A summary of the general water quality characteristics over the study period is shown in Table 2.

TABLE 2. SUMMARY OF GENERAL WATER QUALITY CHARACTERISTICS OVER THE STUDY PERIOD FOR THE STUDY SITES. THE AVERAGE VALUES AND RANGE (MINIMUM TO MAXIMUM) FOR TEMPERATURE, PH AND DO ARE SHOWN. UNLESS OTHERWISE STATED, THE DATA IS REPRESENTATIVE OF HOURLY CONTINUOUS MONITORING DATA (TABLE FROM RAGUSH ET AL., UNDER REVIEW).

Location	Year	Temperature (°C)	pH	Dissolved Oxygen (mg/L)
Pond Inlet	2011	8.7 (1.9 – 12.7)	8.0 (7.2 – 9.0)	5.7 (<DL[b] – 29.0)
	2012	11.0 (5.2 – 19.0)	7.6 (7.3 – 7.8)	<DL
	2013	7.9 (0.8 - 18.0)	7.5 (7.1 – 7.7)	0.3 (<DL – 13)
	2014	10.5 (4.0 – 21.5)	7.8 (7.6 – 8.0)	0.1 (<DL – 0.9)
Clyde River (Cell 1)	2012	-	7.2[a]	1.6[a]
	2013	7.9 (0.6 – 17.5)	7.5 (7.2 – 7.7)	<DL
	2014	7.2 (0.0 – 16.2)	7.3 (6.9 – 7.6)	0.0 (<DL – 0.9)
Clyde River (Cell 2)	2012	8.6 (3.9 – 13.3)	7.4[a]	3.5[a]
	2013	8.0 (2.7 – 13.9)	7.4 (7.2 – 7.6)	0.0 (<DL – 1.1)
	2014	7.9 (0.7 – 12.7)	7.4 (7.3 – 8.0)	<DL
Kugaaruk	2012	11.2 (7.7 – 17.2)	7.6 (7.4 – 7.8)	0.2 (<DL – 0.4)
	2013	9.6 (0.4 – 20.9)	7.2 (6.8 – 7.4)	0.8 (<DL – 2.8)
Grise Fiord	2011	14.2[a]	10.8[a]	23.8[a]

[a] Averages from discrete samples taken during field visits and not from continuous data.
[b] Detection limit = 0.1 mg/L

3.1.1 Water temperature

The temperature of the pond water is an important parameter because many chemical and biological processes are affected by temperature. It has been demonstrated that biological activity is appreciably reduced at water temperatures below 10°C (Bartsch and Randall, 1971; Lettinga et al., 2001). There was a temperature profile with depth observed in the WSPs. High water temperatures were present near the surface and colder waters were observed at depth. An average temperature of 8°C throughout the depth of the water column over the treatment season was observed. The surface water temperatures reached 15 to 20°C for a limited period of time during the treatment season (Table 2). The high temperatures occurred when there was low cloud cover and subsequent warming of the ponds by sunlight. The window of time during the treatment season when the surface water temperatures of the ponds are above 10°C is important because that is when biological treatment can occur. Shallow ponds are more conducive to warmer water temperatures. This tendency is because the light can penetrate proportionally more of the water column. This is significant because the ponds can be optimized to promote biological activity simply with shallow operational water depths.

3.1.2 pH

The pH of the WSPs over the study period are tabulated in Table 2. The pH's were observed to be neutral to slightly basic and had a slight tendency to rise as the treatment season progressed, and peak in the middle of the summer in late July. The increase in pH is an effect of algae consuming carbon dioxide and changing the carbonate – bicarbonate equilibrium (Talling, 1976; Ragush et al., under review). In 2011, there were observations of very high pH values of 9 and 10.8 in the Pond Inlet and Grise Fiord WSPs respectively (Table 2). During this period in 2011, the WSPs in Pond Inlet and Grise Fiord were observed to have extensive algae blooms throughout the water column, which is the reason for the high pH values observed.

3.1.3 Dissolved oxygen

Table 2 shows that the dissolved oxygen concentrations were minimal to undetectable in Pond Inlet, Clyde River and Kugaaruk during the 2012 to 2014 treatment seasons. This meant that the WSPs were anaerobic during this time due to limited algae growth and oxygenation and consumption of available oxygen by aerobic bacteria. Whereas, the Pond Inlet and Grise Fiord WSPs were supersaturated with oxygen during the 2011 treatment season, with maximum DO concentrations of up to 29 mg/L. This observation suggests that the WSPs can operate as aerobic when specific climatic and operational conditions are occurring.

3.2 Treatment performance assessment

In this section, the treatment performance results are compared to the existing NWB treatment objectives and the southern WSER to provide context. The treatment performance data is presented in tables that were populated from the studies by Ragush et al., (under review) and Schmidt et al., (under review).

3.2.1 Raw wastewater quality

The raw wastewater quality has an influence on the performance of the WSPs. Tables 4 – 6 summarize the raw wastewater quality measured over multiple site visits. When compared to literature values, the raw wastewater strengths are within or above the composition of typical medium to high strength wastewater suggested in Tchobanoglous et al. (2003) (Table 3). Rates of per capita residential water use in Nunavut are based on a design standard of 100 L/capita·day (Daley et al., 2014). This water usage rate is only approximately one-third of the Canadian average of 274 L/capita·day (Daley et al., 2014). This difference in water usage results in less dilution and higher concentrations of contaminants in municipal wastewater in Nunavut compared to other regions in Canada.

TABLE 3. TYPICAL COMPOSITION OF DOMESTIC WASTEWATER FROM TCHOBANOGLOUS ET AL. (2003).

Parameter	Strength[a] Medium	High
BOD_5 (mg/L)	190	350
TSS (mg/L)	210	400
Fecal coliform (# per 100 mL)	$10^4 - 10^6$	$10^5 - 10^8$
TAN (mg/L)	25	45
TP (mg/L)	7	12

[a] Strength is based on an approximate flow of wastewater of 460L/capita·day and 240 L/capita·day, for medium and high strength respectively.

Table 4 shows the $CBOD_5$, and TSS concentrations observed in the raw wastewater samples. The average raw wastewater $CBOD_5$ concentrations for all the study sites were greater than the high strength range from Tchobanoglous et al. (2003). The average raw $CBOD_5$ concentrations for the Pond Inlet and Grise Fiord systems were higher at 525 and 632 mg/L $CBOD_5$, than the Clyde River and Kugaaruk systems, which were 367 and 371 mg/L respectively. The average TSS concentration for all the study sites, except Grise Fiord which was above, fell within the medium to high strength range from Tchobanoglous, et al. (2003). Grise Fiord had the highest TSS concentrations in the raw wastewater; however the sample size was only three.

TABLE 4. RAW WASTEWATER QUALITY FOR $CBOD_5$, AND TSS. THE MINIMUM AND MAXIMUMS ARE THE LIMITS OF THE 95% CONFIDENCE INTERVAL.

Location	*n*[a]	$CBOD_5$ (mg/L)			TSS (mg/L)		
		min.	mean	max.	min.	mean	max.
Pond Inlet	23	436	525	614	272	326	380
Clyde River	15	300	367	434	211	273	335
Kugaaruk	8	321	371	421	227	272	317
Grise Fiord[b]	3	504	632	871	380	665	1036

[a] n is sample number.

[b]Insufficient number of samples to calculate a representative confidence interval, therefore actual minimum and maximums used.

The raw wastewater quality in terms of *E. coli* concentrations is shown in Table 5. The majority of the values for *E. coli* fall within the range typical of fecal coliforms in high strength domestic wastewater suggested in Tchobanoglous et al. (2003). All of the sites had similar concentrations for *E. coli* except Grise Fiord. For example, the raw wastewater had a one to two order magnitude lower concentration of *E. coli.* It should be noted that the sample size in Grise Fiord only consisted of three samples.

TABLE 5. RAW WASTEWATER QUALITY FOR *E. COLI.*

Location	*n*	Min. *E. coli* (MPN/100 mL)	Mean *E. coli* (MPN/100 mL)	Max. *E. coli* (MPN/100 mL)
Pond Inlet	31	4.18E+06	2.66E+07	2.32E+08
Clyde River	15	1.01E+06	1.09E+07	1.37E+08
Kugaaruk	5	2.42E+06	1.11E+07	9.80E+07
Grise Fiord	3	1.32E+05	4.98E+05	1.30E+06

Table 6 shows that the TAN values in the raw wastewater were all above the high strength range from Tchobanoglous et al. (2003). All of the WSPs had similar comparable TAN concentrations in the raw wastewater. Finally, the TP concentrations were greater than the high strength values from Tchobanoglous et al. (2003) for all the sites except Kugaaruk. In particular, the Pond Inlet system had the highest average TP concentrations in the raw wastewater at 16.3 mg/L TP. The higher strength raw wastewater poses more challenges for treatment performance because loading rates of wastewater constituents are high.

TABLE 6. RAW WASTEWATER QUALITY FOR TAN, NH_3-N AND TP. THE MINIMUM AND MAXIMUMS ARE THE LIMITS OF THE 95% CONFIDENCE INTERVAL.

Location	*n*	TAN (mg/L)			NH_3-N (mg/L)			TP (MPN/100mL)		
		min.	mean	max.	min.	mean	max.	min.	mean	max.
Pond Inlet	23	94	107	120	1.3	1.6	1.9	14.6	16.3	18.0
Clyde River	15	87	103	119	0.5	0.6	0.8	12.1	14.8	17.5
Kugaaruk	8	83	94	105	1.7	2.3	2.8	9.1	11.4	13.7
Grise Fiord[a]	3	76	113	135	1.7	3.3	5.4	8.9	12.9	15.2

[a] Insufficient number of samples to calculate a representative confidence interval, therefore actual minimum and maximums used.

3.2.2 Five-day carbonaceous biochemical oxygen demand

Table 7 summarizes the treatment performance data of the WSPs for $CBOD_5$. In all cases the concentrations observed in the WSPs were above 25 mg/L for $CBOD_5$. Furthermore, the WSPs could not always meet the 120 mg/L standard for BOD_5 set by the NWB. In particular, cell 1 in Clyde River has the highest $CBOD_5$ concentrations throughout the treatment season with the lowest percent removals ranging from 16 to 42%. This was attributed to the sludge accumulation and high areal biochemical oxygen demand (BOD) loading rate. The accumulated sludge creates conditions where organics can be released back into the water column.

Generally, the WSPs removed progressively more $CBOD_5$ over the course of the treatment season. The slight increase in $CBOD_5$ removal would likely be attributed to warmer pond water temperatures as the treatment season progressed which would promote biological activity. At the start of the treatment season, no biological activity would be expected in the WSPs, and $CBOD_5$ removal observed would be attributed to settling.

By the end of the treatment season, the WSPs in Pond Inlet, Grise Fiord, and cell 2 in Clyde River removed more $CBOD_5$ (e.g., 71 – 88%) than the Kugaaruk system (e.g., 57 – 62%). This difference may be attributed to the difference in operating depths; for instance the Pond Inlet, Clyde River, and Grise Fiord systems range from 1.5 to 2.3 m, while the Kugaaruk WSP is 5.4 m deep.

TABLE 7. SUMMARY OF $CBOD_5$ CONCENTRATIONS, PERCENT REDUCTION FROM RAW AND NUMBER OF SAMPLES (*n*). THE MINIMUM AND MAXIMUMS ARE THE LIMITS OF THE 95% CONFIDENCE INTERVAL.

Location	Sampling period	Sampling year (s)	*n*[a]	$CBOD_5$ (mg/L and % reduction) min.	mean	max.
Pond Inlet	Start	2012 - 2014	22	182 (65%)	217 (59%)	252 (52%)
	Middle	2011 - 2014	25	142 (73%)	154 (71%)	166 (68%)
	End	2011 - 2014	28	108 (79%)	118 (78%)	128 (76%)
Clyde River (Cell 1)	Start	2012 - 2014	8	214 (42%)	255 (31%)	296 (19%)
	Middle	2013	3	254 (31%)	281 (23%)	308 (16%)
	End	2012 - 2014	10	215 (41%)	239 (35%)	263 (28%)
Clyde River (Cell 2)	Start	2012 - 2014	8	96 (74%)	119 (68%)	142 (61%)
	Middle	2013	4	67 (82%)	93 (75%)	119 (68%)
	End	2012 -2014	10	58 (84%)	82 (78%)	106 (71%)
Kugaaruk	Start	2012 - 2013	8	120 (68%)	133 (64%)	146 (61%)
	End	2012 - 2013	12	142 (62%)	150 (60%)	158 (57%)
Grise Fiord	Middle	2011	4	76 (88%)	94 (85%)	112 (82%)

[a] Sample number based on the minimum number of samples obtained, there may be instances where additional samples were obtained.

3.2.3 Suspended solids

The treatment performance results for total suspended solids is presented in Table 8. At times, cell 2 in Clyde River and the Kugaaruk WSP could meet the southern WSER treatment standard of 25 mg/L for TSS. All of the systems, except for Grise Fiord, could meet the 180 mg/L standard typically set by the NWB at all observed times. The Grise Fiord system was exceptional because there was an algae bloom in the WSP during the sampling period in 2011. The presence of algae in the water sample results in high concentrations of TSS (Williamson and Swanson, 1979). Therefore, the Grise Fiord WSP had comparatively higher concentrations of TSS in the raw wastewater ranging from 380 to 1036 mg/L. Optimization of treatment in WSPs with the promotion of algae growth will likely require considerations for tail-end removal of TSS.

The Pond Inlet WSP had percent removals ranging from 67 – 89%, and it did not perform as well as the Clyde River (cell 2) and the Kugaaruk systems, which had percent removals ranging from 85 – 92%. The Pond Inlet WSP was slightly shallower at 1.6 m, whereas the Clyde River (cell 2) and the Kugaaruk system, were 2.3 m and 5.4 m deep respectively. It is hypothesized that WSPs with deep operational depths encourage settling of suspended solids because there would be less re-suspension of deposited solids. There is also less algae growth in the deeper WSP systems.

There is no apparent trend showing temporal differences in TSS concentrations during the treatment season which would suggest that the settling process occurs consistently over the treatment season. An exception is in Pond Inlet where the concentrations increased slightly over the treatment season, which may be influenced by the 2011 treatment season. During this year, elevated algae growth occurred in the WSP, which would have elevated the TSS concentrations by the middle to end of the season.

TABLE 8. SUMMARY OF TSS CONCENTRATIONS, PERCENT REDUCTION FROM RAW AND NUMBER OF SAMPLES (*n*). THE MINIMUM AND MAXIMUMS ARE THE LIMITS OF THE 95% CONFIDENCE INTERVAL.

Location	Sampling period	Sampling year (s)	*n*[a]	TSS (mg/L and % reduction) min.	mean	max.
Pond Inlet	Start	2012 - 2014	21	35 (89%)	46 (86%)	57 (83%)
	Middle	2011 - 2014	24	47 (86%)	59 (82%)	71 (78%)
	End	2011 - 2014	28	63 (81%)	86 (74%)	109 (67%)
Clyde River (Cell 1)	Start	2012 - 2014	8	34 (88%)	54 (80%)	74 (73%)
	Middle	2013	3	51 (81%)	65 (76%)	79 (71%)
	End	2012 - 2014	10	46 (83%)	58 (79%)	70 (74%)
Clyde River (Cell 2)	Start	2012 - 2014	8	21 (92%)	31 (89%)	41 (85%)
	Middle	2013	4	23 (92%)	28 (90%)	33 (88%)
	End	2012 -2014	10	23 (92%)	30 (89%)	37 (86%)
Kugaaruk	Start	2012 - 2013	8	21 (92%)	30 (89%)	39 (86%)
	End	2012 - 2013	12	21 (92%)	25 (91%)	29 (89%)
Grise Fiord	Middle	2011	4	212 (68%)	438 (34%)	664 (0%)

[a] Sample number based on the minimum number of samples obtained, there may be instances where additional samples were obtained.

3.2.4 Bacteria

The summarized performance data for bacteria was assessed with the fecal indicator bacteria *E. coli* (Table 9). The Grise Fiord WSP had higher removal of *E. coli* than the other ponds ranging from 2.4 to 4 log removal. It should be noted that the raw wastewater had two orders of magnitude less *E. coli* and there were only three samples for this site. It is hypothesized that algae growth in the Grise Fiord WSP may have led to an increase in pH and DO which contributes to relatively lower *E. coli* concentrations observed. The sudden decrease of the *E. coli* in a WSP in response to pH increases attributed to algal growth was also observed by Parhad and Rao (1974).

The poorest removal of *E. coli* was observed in cell 1 of the Clyde River system with log reductions ranging from -1.3 to 0.6 by the end of the treatment season. This means that more *E. coli* was noted in cell 1 than in the raw wastewater. Cell 1 likely had a BOD loading rate that was too high to facilitate treatment of *E. coli.* At the end of the treatment season, cell 1 in Clyde River did not meet the fecal coliform treatment standard of $1x10^6$ CFU/100mL regulated by NWB. Generally, the Pond Inlet and cell 2 of the Clyde River system performed similarly for *E. coli* removal with reductions ranging from 1.0 to 3.4 log over the treatment season. However, the Pond Inlet and Kugaaruk systems could not always meet the NWB fecal coliform standard of $1x10^6$ CFU/100mL. Whereas, cell 2 in Clyde River could meet this level of effluent quality. The deeper system in Kugaaruk did not perform quite as well as, the Pond Inlet, and cell 2 of the Clyde River system. This difference may be due to more biological activity, as well as, deeper light penetration of the water column with the shallower systems, which would act to reduce *E. coli* concentrations.

TABLE 9. SUMMARY OF *E. COLI* CONCENTRATIONS, LOG REDUCTIONS FROM RAW, AND NUMBER OF SAMPLES (*n*) FOR EACH SITE DURING THE SAMPLING PERIODS.

Location	Sampling period	Sampling year (s)	*n*	*E. coli* (MPN/100 mL and log reduction)		
				min.	mean	max.
Pond Inlet	Start	2012 - 2014	26	1.06E+04 (3.4)	3.03E+05 (1.9)	9.75E+05 (1.4)
	Middle	2012 - 2014	28	2.50E+04 (3.0)	1.77E+05 (2.2)	1.07E+06 (1.4)
	End	2012 - 2014	26	2.39E+05 (2.0)	6.77E+05 (1.6)	2.60E+06 (1.0)
Clyde River (Cell 1)	Start	2012 - 2014	13	8.78E+04 (2.1)	2.42E+05 (1.7)	5.75E+05 (1.3)
	Middle	2013	4	1.61E+04 (2.8)	7.56E+04 (2.2)	9.10E+05 (1.1)
	End	2012 - 2014	10	2.56E+06 (0.6)	6.04E+06 (0.3)	2.20E+08 (-1.3)
Clyde River (Cell 2)	Start	2012 - 2014	12	6.92E+04 (2.2)	2.11E+05 (1.7)	4.75E+05 (1.4)
	Middle	2013	3	2.88E+04 (2.6)	1.21E+05 (2.0)	2.93E+05 (1.6)
	End	2012 -2014	12	6.10E+03 (3.3)	2.34E+04 (2.7)	9.09E+04 (2.1)
Kugaaruk	Start	2012 - 2013	8	1.73E+05 (1.8)	3.52E+05 (1.5)	6.13E+05 (1.3)
	End	2012 - 2013	16	7.89E+04 (2.1)	2.14E+05 (1.7)	1.41E+06 (0.9)
Grise Fiord	Middle	2011	3	5.20E+01 (4.0)	2.09E+02 (3.4)	2.18E+03 (2.4)

In addition to the basic assessment of fecal indicator bacteria, a pathogen analysis was conducted on the Clyde River two cell system by Huang et al. (2014). The preliminary study aimed to characterize the presence/absence of human bacterial pathogens present in each of the WSP cells. This included an assessment for the presence/absence of *Listeria monocytogenes*, *E. coli* O157:H7, *Campylobacter* spp. and *Salmonella* spp., *L. monocytogenes,* and *E. coli* O157:H7. Table 10 shows the presence and absence of the pathogens that were assessed in the raw wastewater and within the cells of the WSPs.

TABLE 10. PRESENCE OR ABSENCE OF HUMAN BACTERIAL PATHOGENS IN THE CLYDE RIVER SYSTEM IN 2013 (ADAPTED FROM HUANG ET AL., 2014).

Sample location	Sampling period		
	Start	Middle	End
Raw from truck	L+C+S+E[a]	L+E	L+C+S+E
Cell 1	L+C+S+E	L+E	L+C+S+E
Cell 2	L+C+S+E	L+E	L+C+S+E

[a] L: *Listeria monocytogenes,* C: *Campylobacter* spp., S: *Salmonella* spp., and E: *E. coli* O157:H7.

The preliminary study showed that the Clyde River system had human bacterial pathogens present within both cells of the WSP. There was presence of *Campylobacter* spp., *Salmonella* spp., *E. coli* O157:H7 and *Listeria monocytogenes* at the end of the treatment season (i.e., decant period) in cell 2 in 2013. Huang et al. (2014) hypothesized that the middle of the treatment season had preferable conditions for pathogen removal due to higher pond water temperatures and UV disinfection.

3.2.5 Nitrogen

Table 11 summarizes the treatment performance of the WSPs for TAN. Cell 1 in Clyde River had the poorest removal of TAN with percent removals ranging from -32 to 26%. The negative removals are indicative that the TAN concentrations measured in the WSP were higher than those observed in the raw wastewater on average. The Kugaaruk system also demonstrated poor removal of TAN over the course of the treatment season with a 5 to 16% removal of TAN at the end of the treatment season. The Grise Fiord WSP had the best removals of TAN which ranged from 90 to 97%. It is hypothesized that the Grise Fiord system had high removal of TAN as a result of volatilization of ammonia resulting from the high pH (i.e., > 9) which was observed to coincide with the algae growth in the WSP. For the other WSPs, the removal of TAN was variable ranging from 0 to 61% and did not show major trends.

TABLE 11. SUMMARY OF TAN CONCENTRATIONS, PERCENT REDUCTION FROM RAW AND NUMBER OF SAMPLES (*n*). THE MINIMUM AND MAXIMUMS ARE THE LIMITS OF THE 95% CONFIDENCE INTERVAL.

Location	Sampling period	Sampling year (s)	*n*[a]	TAN (mg/L and % reduction)		
				min.	mean	max.
Pond Inlet	Start	2012 - 2014	19	85 (21%)	96 (10%)	107 (0%)
	Middle	2011 - 2014	29	83 (22%)	94 (12%)	105 (2%)
	End	2011 - 2014	28	63 (41%)	72 (34%)	81 (24%)
Clyde River (Cell 1)	Start	2012 - 2014	8	90 (13%)	113 (-10%)	136 (-32%)
	Middle	2013	3	76 (26%)	89 (14%)	102 (1%)
	End	2012 - 2014	10	89 (14%)	97 (6%)	105 (-2%)
Clyde River (Cell 2)	Start	2012 - 2014	8	52 (50%)	57 (45%)	62 (40%)
	Middle	2013	4	40 (61%)	45 (56%)	50 (51%)
	End	2012 -2014	10	65 (37%)	73 (29%)	81 (21%)
Kugaaruk	Start	2012 - 2013	8	48 (49%)	56 (40%)	64 (32%)
	End	2012 - 2013	12	79 (16%)	84 (11%)	89 (5%)
Grise Fiord	Middle	2011	4	3.1 (97%)	7.4 (93%)	11.7 (90%)

[a] Sample number based on the minimum number of samples obtained, there may be instances where additional samples were obtained.

Table 12 summarizes the NH_3-N observed in the WSPs. In most of the cases during the studied treatment seasons, the WSPs met the southern WSER standard of 1.25 mg/L NH_3-N. Of importance to this parameter is the pH of the WSPs during the measurement of the un-ionized ammonia, which was mostly in the neutral range. The only exception was the Grise Fiord WSP where concentrations of NH_3-N above the southern WSER were observed. During the sampling period in Grise Fiord, the algae growth increased the pH to basic conditions, which converts all the ammonium nitrogen to un-ionized ammonia form. The conversion of the ammonium nitrogen to ammonia nitrogen is beneficial to encourage the volatilization of ammonia, which removes nitrogen from the water column. Conversely, this is problematic for decant effluent quality because the un-ionized ammonia form of nitrogen could reach concentrations greater than 1.25 mg/L NH_3-N.

TABLE 12. SUMMARY OF NH_3-N CONCENTRATIONS, PERCENT REDUCTION FROM RAW AND NUMBER OF SAMPLES (*N*). THE MINIMUM AND MAXIMUMS ARE THE LIMITS OF THE 95% CONFIDENCE INTERVAL.

Location	Sampling period	Sampling year (s)	*n*[a]	NH_3-N (mg/L and % reduction)		
				min.	mean	max.
Pond Inlet	Start	2012 - 2014	19	0.31 (80%)	0.4 (75%)	0.49 (70%)
	Middle	2011 - 2014	25	0.6 (63%)	0.76 (53%)	0.92 (43%)
	End	2011 - 2014	28	0.32 (80%)	0.4 (75%)	0.48 (70%)
Clyde River (Cell 1)	Start	2012 - 2014	8	0.1 (83%)	0.15 (75%)	0.2 (67%)
	Middle	2013	3	0.11 (82%)	0.14 (77%)	0.17 (72%)
	End	2012 - 2014	10	0.14 (77%)	0.25 (58%)	0.36 (40%)
Clyde River (Cell 2)	Start	2012 - 2014	8	0.11 (82%)	0.14 (77%)	0.17 (72%)
	Middle	2013	4	0.09 (85%)	0.2 (67%)	0.31 (48%)
	End	2012 -2014	10	0.12 (80%)	0.21 (65%)	0.3 (50%)
Kugaaruk	Start	2012 - 2013	8	0.09 (96%)	0.12 (95%)	0.15 (93%)
	End	2012 - 2013	12	0.35 (85%)	0.44 (81%)	0.53 (77%)
Grise Fiord	Middle	2011	4	2.9 (12%)	7 (-112%)	11.1 (-236%)

[a] Sample number based on the minimum number of samples obtained, there may be instances where additional samples were obtained.

3.2.6 Phosphorus

The treatment performance of the WSPs for phosphorus is shown in Table 13. The treatment performance of the WSPs for total phosphorus was highly variable with observed effluent concentrations ranging from 3.1 to 11.2 mg/L TP. The Grise Fiord WSP performed the best for phosphorus treatment with percent removals ranging from 70 to 76%. It is hypothesized that the Grise Fiord system was better at removing phosphorus as a result of the algae presence during the sampling period. The algae would consume phosphorus as part of their life cycle and act as a sink for phosphorus at the end of their life cycle by deposition on the bottom of the WSP. Additionally, chemical precipitation of phosphorus can result from the high pH (i.e., > 9) caused by the algae growth. Cell 2 of the Clyde River system had the second best removals of phosphorus ranging from 42 to 72%. The poorest removals of phosphorus were observed in the Pond Inlet WSP with percent removals ranging from 31 to 44 %. It should be noted that the Pond Inlet system received the highest concentrations of phosphorus in the raw wastewater when compared to the other studied WSPs, which may explain the comparatively lower removals of phosphorus.

TABLE 13. SUMMARY OF TP CONCENTRATIONS, PERCENT REDUCTION FROM RAW AND NUMBER OF SAMPLES (*n*). THE MINIMUM AND MAXIMUMS ARE THE LIMITS OF THE 95% CONFIDENCE INTERVAL.

Location	Sampling period	Sampling year (s)	*n*	TP (mg/L and % reduction)		
				min.	mean	max.
Pond Inlet	Start	2012 - 2014	8	9.1 (44%)	9.5 (42%)	9.9 (39%)
	Middle	2011 - 2014	7	10.1 (38%)	10.4 (36%)	10.7 (34%)
	End	2011 - 2014	7	10.4 (36%)	10.8 (34%)	11.2 (31%)
Clyde River (Cell 1)	Start	2012 - 2014	4	8.7 (41%)	9.4 (36%)	10.1 (32%)
	Middle	2013	4	7.5 (49%)	7.6 (49%)	7.7 (48%)
	End	2012 - 2014	3	8.8 (41%)	8.9 (40%)	9 (39%)
Clyde River (Cell 2)	Start	2012 - 2014	4	4.2 (72%)	6.4 (57%)	8.6 (42%)
	Middle	2013	4	6.2 (58%)	6.3 (57%)	6.4 (57%)
	End	2012 -2014	2	5.8 (61%)	5.9 (60%)	6 (59%)
Kugaaruk	Start	2012 - 2013	4	6.6 (42%)	7.6 (33%)	8.6 (25%)
	End	2012 - 2013	4	7.9 (31%)	8.4 (26%)	8.9 (22%)
Grise Fiord	Middle	2011	4	3.1 (76%)	3.5 (73%)	3.9 (70%)

4.0 Discussion

4.1 Driving factors affecting treatment performance

There were a few driving factors that have been identified through this study which have been shown to affect treatment performance of the WSPs. These driving factors are discussed within the following sub-sections.

4.1.1 Raw wastewater quality

The raw wastewater quality has an impact on the performance of the WSPs. It has been demonstrated that the raw wastewater quality is higher in strength than raw wastewater in southern localities. This means that the systems have a tendency to become overloaded with contaminants, in particular with organic matter. Furthermore, the WSPs with the highest strength raw wastewater generally led to higher contaminant concentrations in the WSP effluent. This led to concentrations elevated above the southern WSER standard for $CBOD_5$, and in some cases for TSS in the WSPs, despite reductions of 52 – 88% for $CBOD_5$ (excluding cell 1 in Clyde River), and 62 – 92% for TSS (excluding Grise Fiord).

4.1.2 BOD loading rate

One of the challenges associated with treatment of high strength raw wastewater is the potential for overloading the WSPs with organic matter. Design recommendations for WSPs in arctic environments suggest a maximum BOD_5 loading rate of 22 kg/ha/day (Dawson, 1969, Heinke et al., 1991, Smith, 1986). Heinke et al. (1991) cautioned that organic loading rates above this recommended limit would result in reduced treatment performance. Based on these recommendations, the Pond Inlet and Clyde River (total pond area) WSPs are within the recommendations, while the Grise Fiord and Kugaaruk WSPs were above. A consequence of overloading WSPs with organic matter is the formation of anaerobic conditions.

Cell 1 in the Clyde River system was subject to BOD loading rates that were twice the recommended maximum BOD_5 loading rate. Accordingly, the water quality in cell 1 was lower than all the other sites. In most cases, the WSPs could not maintain a facultative state, and therefore this may be indicative that the BOD loading rates may require refinement.

4.1.3 Algae growth

The data has demonstrated that algae growth in WSPs has a large yet sporadic effect on water quality. The presence of algae blooms was observed in some of the WSPs that were studied (Figure 11a). Algae presence has advantages and disadvantages. Generally, the treatment performance of the WSPs improve in terms of $CBOD_5$, *E. coli*, TAN, and TP removal when algae is prevalent. Adverse effects of the algae growth in the WSPs include high concentrations of TSS and NH_3-N. Some of the negative implications can be mitigated in practice with using simple monitoring tools to time the decant to occur during optimal periods.

FIGURE 11. PHOTOGRAPHS OF A: (A) WATER SAMPLE WITH ALGAE FROM THE GRISE FIORD WSP TAKEN ON AUGUST 8, 2010, AND (B) TSS FILTER WITH RETAINED ALGAE TAKEN ON AUGUST 20, 2010.

The WSPs that had aerobic conditions as a result of the growth of algae tended to perform better for $CBOD_5$ and *E. coli* removal. For instance, the aerobic Grise Fiord system demonstrated 82 – 88% removal for $CBOD_5$, and 2.4 to 4 log removal of *E. coli*. Comparatively, the anaerobic Kugaaruk system demonstrated lower removals of 57 – 68% of $CBOD_5$, and 0.9 to 2.1 log removal of *E. coli*. In addition, TAN removal is encouraged by algae growth because the high pH's (i.e., > 9) encourage volatilization of ammonia. Therefore the TAN removal is high when algae growth is observed. The ponds that had algae growth also had greater reductions in phosphorus. This was likely attributed to two reasons. The algae consume the phosphorus and act as phosphorus sinks at the end of their life cycle. Also, the high pH produced as a result of algae growth and facilitates the chemical precipitation of phosphorus.

A disadvantage to having algae growth in the WSP is that the suspended solids concentrations are increased in conjunction with the growth of algae. For instance, an average TSS concentration of 438 mg/L was measured in the Grise Fiord WSP coinciding with the presence of an algae bloom. Whereas, the TSS in the other WSPs, where algae was mostly not present, ranged from an average of 25 to 86 mg/L for TSS. It will not be realistic to meet a stringent TSS treatment objective if the WSPs are experiencing substantial algae growth (Figure 11b). Another disadvantage of the algae proliferation is that the basic pH's convert all forms of the ammonia nitrogen to un-ionized ammonia (NH_3). This is potentially problematic if the un-ionized ammonia is not reduced to less than 1.25 mg/L NH_3-N prior to decant.

Simple tools such as using water quality multi-parameter sondes could be used to easily assess when to optimize decanting to avoid deleterious impacts to the receiving environment. For example, if the pH is measured to be above 8.5, and the DO is above 10 mg/L, then it may be prudent to delay decanting until the algae is no longer present, and accordingly the pH drops along with the DO. To further verify the presence of algae, chlorophyll analysis may be coupled with suspended solids analysis. When chlorophyll a concentrations are greater than 50 μg/L, the suspended solids exemption could be applied.

4.1.4 Water depth

The operating water depth was an important factor in the treatment performance of the WSPs. There are advantages to both shallow and deep WSP designs. The Pond Inlet and Grise Fiord WSPs were slightly shallower at 1.6 m, and 1.5 – 2 m respectively. Whereas the Clyde River (cell 2) and the Kugaaruk systems, were 2.3 m and 5.4 m deep respectively. The shallow ponds promoted biological activity and the deep ponds promoted settling of solids. A combination approach to WSP design may be preferential to optimize for the advantageous characteristics of both the shallow and deep conditions.

Based on the findings from these site-specific studies, a summary of overall expected water quality from one year detention WSPs in the arctic, based on the water depth, is presented in Table 14. In general, the shallow ponds had slightly lower $CBOD_5$ concentrations than the deeper ponds; while the deeper ponds performed better for TSS removal. Overall, the TAN removal was poor and primarily observed to occur in the shallow ponds. The un-ionized ammonia was below the WSER southern standards for the most part. The exception to this was when algae blooms were observed in some of the ponds.

TABLE 14. SUMMARY OF EXPECTED EFFLUENT QUALITY FROM THE WSPS.

Parameter	Shallow (< 2.5 m)	Deep (> 2.5 m)
$CBOD_5$ (mg/L)	80 – 120	120 – 160
TSS (mg/L)	50 – 100	25 – 50
TAN (% removal)	10 – 25	0
NH_3-N (mg/L)	< 1.25	<1.25

The shallower systems in Pond Inlet and Grise Fiord were the only WSPs that had algae growth and conversion to aerobic conditions. The shallow ponds tend to promote biological activity which improves the removal of $CBOD_5$, *E. coli*, and TAN. Potential problems arise from algae growth in shallow ponds, such as elevated TSS and NH_3-N concentrations, which may require mitigation.

The deeper systems in Clyde River (cell 2) and Kugaaruk did not show evidence of algae growth. There were advantages to the deep WSPs which consisted of settling of solids and less potential for the re-suspension of solids in the water column. The Kugaaruk WSP is especially deep and the treatment performance results showed no change in $CBOD_5$ and an increase in TAN over the treatment season. This indicated that minimal biological treatment was occurring over the treatment season in the deep ponds.

Optimization of the different treatment mechanisms occurring in arctic WSPs may be achieved by using a combination approach of both shallow and deep design aspects. For example, a deep long-term retention cell used in series with two shallow ponds optimized for algae growth. The deep cell would be useful to store wastewater over winter frozen period and would function as primary treatment for settling of solids. While, the shallow ponds would possess shorter retention times, and be used in parallel to promote biological activity, acting as secondary treatment.

4.1.5 Climate

The extreme climate in the arctic strongly influences the treatment performance of the WSPs in Nunavut. The average water temperature in the WSPs over the treatment season were below 10°C. The cold water temperatures limit the potential for biological treatment in the ponds. However, the long photoperiods in the treatment season are advantageous to warm the surface of the ponds to greater than 15°C for a period of weeks in the middle of the summer. These long photoperiods can encourage the formation of algae given sufficient days without cloud cover. The climatic conditions pose both challenges and opportunities for applying passive treatment technologies in Nunavut. The cold temperatures slow biological activity and hence many treatment processes. This is contradicted by long photoperiods which promote biological activity. The climatic conditions cannot be controlled, and therefore the WSPs should be optimized to capitalize on long photoperiods, and still obtain adequate treatment in low temperatures.

4.1.6 Maintenance and operation

The maintenance and operation of the WSPs plays an important role in the treatment performance of the WSPs. In terms of maintenance, sludge removal is an important aspect that can affect the treatment performance. Sludge releases organics, nutrients, and solids back into the water column after deposition, if disturbed by turbulence within the water column. For example, this was demonstrated with cell 1 in Clyde River, where accumulated sludge has compromised the treatment performance of the WSP. An important consideration for the management of these systems on the long term should consider a routine program to de-sludge the WSPs.

Operational aspects of the WSPs are also driving factors for treatment performance. As was previously mentioned the water depth in the WSPs can govern the types of treatment processes occurring within the WSPs. The operational water depth of the WSPs can be designed and managed to optimize for particular treatment processes. In addition, the timing of decants is an operational aspect that can be scheduled to ensure that maximum treatment is achieved and that deleterious impacts to the receiving water are minimized.

5.0 Conclusions

The WSPs demonstrated improvements in the effluent quality before discharge into the receiving environment or further treatment components. However, there are still system improvements that are needed to obtain performance results that are consistently within regulatory ranges. Treatment performance for each parameter was affected by a number of driving factors which included the: raw wastewater quality, BOD loading rate, algae growth, pond water depth, climate, and maintenance and operation. Design and operation of existing systems, upgrades and new WSPs should capitalize on the driving factors affecting treatment mechanisms to optimize overall treatment potential. The following list summarizes the main findings from the treatment performance assessments and provides a review of the supporting observations.

i) The southern WSER standards were not consistently met.

In comparison to the southern WSER standards, none of the WSPs could meet the 25 mg/L $CBOD_5$ at any time. At times, cell 2 in Clyde River and the Kugaaruk WSP could meet the southern WSER treatment standard of 25 mg/L for TSS. However, the majority of the time the WSPs are not able to obtain treatment to the southern WSER standard for TSS. In most of the cases during the studied treatment seasons, the WSPs met the southern WSER standard of 1.25 mg/L NH_3-N. The only exception was with the Grise Fiord WSP where concentrations of NH_3-N above the southern WSER were observed.

ii) **The typical NWB standards of 120 mg/L for BOD_5 and $1x10^6$ CFU/100mL for fecal coliform were not consistently met.**

The WSPs could not always meet the 120 mg/L standard for BOD_5 which is typically used by the NWB. The poorest removals were observed in the cell 1 of the Clyde River WSP where concentrations ranging from 214 to 308 mg/L of $CBOD_5$ were observed. The systems in Pond Inlet, Grise Fiord and cell 2 in Clyde River performed best for BOD removal with end of season concentrations ranging from 82 – 118 mg/L $CBOD_5$. Comparatively, the deeper system in Kugaaruk had end of season concentrations ranging from 142 – 158 mg/L $CBOD_5$.

Additionally, the WSPs could not consistently meet the fecal coliform standard. The WSP in Grise Fiord and cell 2 in Clyde River could meet the standard during the study periods. However, the remainder of the systems could not consistently meet the standard.

iii) The typical NWB standard of 180 mg/L for TSS was met the majority of the time.

At all observed times, all of the systems, except for Grise Fiord, could meet the standard of 180 mg/L for TSS set by the NWB. The Grise Fiord system had algae growth during the study period which artificially elevated the TSS levels.

iv) The raw wastewater quality is high in strength in comparison to southern Canada.

At all the study sites, the observed concentrations for $CBOD_5$ were above the high strength range from literature (i.e., 350 mg/L BOD_5). For TSS, all the systems except Grise Fiord, fell within the medium to high strength range from literature (i.e., 210 – 400 mg/L TSS). All of the study sites were above the high strength range in literature for TAN (i.e., 45 mg/L TAN). For TP, all of the systems except Kugaaruk, were greater than the high strength value for literature (i.e., 12 mg/L TP). Therefore, the removal of contaminants must be higher than southern systems to achieve an equivalent effluent quality. Additionally, the loading rates for some contaminants may be too high to facilitate optimized treatment if the influent quality is not adequately incorporated into design processes.

v) The areal BOD loading rates were too high for optimal treatment for some of the WSPs.

For instance, the Grise Fiord and Kugaaruk WSPs had BOD loading rates that were above the recommended range in literature of 22 kg/ha/d. This runs the risk of the formation of anaerobic systems due to the overloading of organic matter.

vi) Algae growth was a major driving factor affecting the treatment mechanisms.

However, this was a sporadic phenomenon and only observed in the Grise Fiord and Pond Inlet WSPs. The presence of algae growth in the WSPs had both positive and negative effects. Algae growth had the effect of creating aerobic pond conditions, and raising the pH of the pond water to the basic range. The TSS concentrations become elevated in conjunction with algae growth. Removal of TAN due to volatilization from basic pH conditions was observed as a result of algae growth. However, the remaining ammonia is in the un-ionized form which is deleterious to receiving waters. Removal of $CBOD_5$, *E.coli*, and TP were also observed to be improved with algae conditions in the ponds.

vii) The water depth was a major driving factor affecting the treatment mechanisms.

The WSPs with shallow pond depths (< 2 m) tended to favor aerobic pond conditions resulting from algae growth and biological removal of $CBOD_5$. Whereas, the pond systems with deep depths (2 – 5 m) showed improved removal of suspended solids. Shallow ponds generally had concentrations ranging from 80 – 120 mg/L for $CBOD_5$, and 50 – 100 mg/L for TSS. While the deeper systems generally had concentrations ranging from 120 – 160 mg/L for $CBOD_5$, and 25 – 50 mg/L for TSS. Both shallow and deep ponds did not perform well for TAN removal but the shallower ponds performed slightly better at 10 – 25% removal versus close to 0% removal for deep ponds. Both deep and shallow systems had NH_3-N concentrations below 1.25 mg/L with exception to when algae blooms were present. A possible strategy for improving treatment is the use of multi-cell pond arrangements employing a combination of deep, anaerobic cells, and shallow facultative cells receiving lower organic loading rates.

viii) The climate was a major driving factor for treatment performance.

Low water temperatures of less than 10°C on average over the treatment season slows biological productivity. The long photoperiods can be advantageous from a treatment standpoint to encourage warmer surface water temperatures (over 15°C) and promote biological activity from the solar radiation. Since the climate cannot be controlled, the systems should be designed to be robust enough to perform in low temperatures and capitalize on the long photoperiods.

ix) The maintenance and operation was an influential factor on the treatment performance.

The WSPs require maintenance and operation to maintain adequate treatment. For example, an accumulation of sludge was observed in cell 1 of the Clyde River WSP. In this instance, unfavorable levels of treatment were observed. The WSPs should undergo scheduled de-sludging maintenance on an as-need basis. Other operational factors are important such as the previously discussed operational depth. When algae blooms are present, the timing of the decant can be important to schedule in order to avoid discharge of pond water with high concentrations of TSS and NH_3-N.

Moving forward, the use of WSPs in the future may be informed with the findings from this comprehensive treatment performance assessment on WSPs in Nunavut. Knowledge of the main factors influencing treatment performance is critical to begin to assess optimal design and operation practices.

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Appendix I

Types of Wastewater Treatment Systems in Nunavut

TABLE A.1 TYPES OF WASTEWATER TREATMENT CONFIGURATIONS IN NUNAVUT COMMUNITIES.

Number	Community	Treatment configuration*
1	Arctic Bay	WSP + wetland**
2	Arviat	WSP + wetland
3	Baker Lake	WSP + wetland
4	Cambridge Bay	Lake lagoon + wetland
5	Cape Dorset	WSP + wetland
6	Chesterfield Inlet	Wetland
7	Clyde River	WSP + wetland
8	Coral Harbour	WSP + wetland
9	Gjoa Haven	WSP
10	Grise Fiord	WSP
11	Hall Beach	WSP + wetland
12	Igloolik	WSP + wetland
13	Iqaluit	Mechanical
14	Kimmirut	WSP + wetland
15	Kugaaruk	WSP + wetland
16	Kugluktuk	WSP + wetland
17	Pangnirtung	Mechanical
18	Pond Inlet	WSP
19	Qikiqtarjuaq	WSP + wetland
20	Rankin Inlet	Mechanical
21	Repulse Bay	Wetland
22	Resolute	Direct
23	Sanikiluaq	Lake lagoon + wetland
24	Taloyoak	Lake lagoon + wetland
25	Whale Cove	Lake lagoon + wetland

Totals	
WSP + wetland	12
Lake lagoon + wetland	4
Wetland only	2
WSP only	3
Direct	1
Mechanical	3
Sum	25

*The configuration was determined from the water licences available at the time of this reporting. This is our interpretation of the water licences and some deviances from this list may exist in reality.

**Some of the wetlands are identified but not formally recognized as part of the treatment configuration.