Literature Review of Wastewater Treatment Design and Performance in the Far North

SUBMITTED TO:

Community and Government Services
Government of Nunavut

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Executive Summary

The Canadian Council of Ministers of the Environment developed the Municipal Wastewater Effluent Strategy in 2009. The Strategy aims to provide a harmonized national framework for managing wastewater. It was identified that the Far North, due to its extreme climatic conditions and remoteness, would require careful consideration in order to produce a viable means to improve human and environmental health protection. The North was therefore given a 5-year window to conduct research in order to develop feasible standards and an approach that will protect human and environmental health. The objectives of this report are to provide a snapshot of the current regulatory framework and types of systems that exist in the North, conduct a literature review on the performance of existing systems in cold climates, and provide a summary and gap analysis of the current modeling approaches used for lagoon and wetland design in cold climates.

Wastewater treatment in Nunavut is currently regulated through different forms of legislation and enforcement is conducted through various federal agencies, with Aboriginal Affairs and Northern Development Canada (AANDC) as the main enforcement body. Wastewater facilities must apply for a Water License through the Nunavut Water Board, which specifies treatment performance, monitoring requirements and any site-specific criteria. The majority of systems in Canada's Far North are considered very small, or small systems, and most consist of waste stabilization pond (WSP) or lake treatment with or without a wetland system. Very few mechanical plants exist as the capacity challenges that go along with operating and maintaining these systems in the North does not make them viable. The discharge from treatment systems varies from continual seasonal discharge to annual decant.

A review of the scientific literature and engineering consultant reports dealing with WSP and treatment wetland performance in Canada's North and other cold climate regions showed that treatment can be highly variable. WSP and treatment wetlands provide wastewater treatment through both physical and biological processes that will be affected by extreme cold temperatures and long winters. Cold temperatures and ice cover reduce biological activity and degradation processes within the WSP and wetland environment. Ice cover will also reduce the active volume that is available for treatment within the WSP environment, and frozen wetlands and receiving waters can prevent wastewater discharge during the winter months. Treatment performance is site specific and may depend on a number of factors including the type of system (natural or engineered, single or multiple cell, facultative, aerobic, or anaerobic), location (latitude) and timing of spring break-up and fall freeze-up, system operation (timing of decant, or continuous), and the monitoring period over which the samples were collected. Very little peer-reviewed literature has been produced documenting passive system treatment performance in arctic climates. The majority of performance data has been produced and reported by engineering consultants. The performance assessment typically has consisted of limited grab sampling, with little documentation of some key system characteristics required to put the data in context.

Design guidelines and approaches for modeling the treatment performance of passive systems specifically operating in arctic regions have yet to be produced. Engineers have been applying

models developed and validated in non-arctic regions to design northern wastewater treatment systems. These models have not been validated for arctic conditions. For both WSP and wetlands, a variety of performance modeling approaches have been developed, ranging from simple empirical equations to complex process-based computer simulation models. In practice, steady state rational-based models, utilizing first order reaction kinetics, have been typically applied for both WSP and wetland design in North America. Challenges associated with applying these models to the design of arctic systems are identified in this review. The application of these models to unsteady state systems, and selection of appropriate treatment rate constants, are key research needs.

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1.0 Introduction

In 2009, the Canadian Council of Ministers of the Environment (CCME) released a national Strategy for managing municipal wastewater effluent (MWWE). In the development of the Strategy, it was recognized that little information exists on the performance of wastewater treatment systems operating in Canada's Far North, and the risk they pose to human and environmental health (CCME, 2009). Northern provinces and territories were provided a five-year window to conduct research on northern wastewater management. The primary objectives of the research are to develop a better understanding of the performance of wastewater treatment systems currently used in the North, what factors affect effluent treatment, and to develop appropriate effluent quality criteria. Environment Canada has developed the Wastewater System Effluent Regulations (WSER) based on the CCME Strategy, and it is anticipated that the WSER will come into force in late 2011/2012.

Key to the development of wastewater management policies for Canada's Far North is knowledge related to the performance of passive wastewater treatments in these extreme climates. Waste Stabilization Ponds (WSPs) are the most common form of municipal wastewater treatment in Canada's Northern Territories (Heinke et al. 1991), and natural wetlands are being increasingly relied upon for further effluent polishing. Mechanical wastewater treatment plants are used in only a few communities in the North. Unfortunately, design guidelines for northern wastewater treatment systems, and published, peer reviewed studies on system performance, are currently lacking.

The majority of available information related to northern wastewater system design and performance has been produced by engineering consultants and published in the form of "grey" literature. Although these are not peer-reviewed studies, they do contain useful information related to the performance, and challenges, associated with designing passive wastewater treatment systems in Canada's Far North. To date, this information has not been synthesized. As well, a considerable body of research has been produced on the design and performance of passive wastewater treatment systems in non-arctic regions. Many of these studies have been conducted on systems operating in "cold" regions, and design methodologies and performance assessments produced for these systems would presumably have relevance to the design of systems operating in arctic regions.

The objectives of this literature review were to review and summarize: (i) the current regulatory environment for wastewater management in Canada's Far North and how it compares to other circumpolar nations, (ii) the types of systems currently used for wastewater treatment in these regions and their operating characteristics and challenges, (iii) northern wastewater system performance data that has been produced through non-peer reviewed studies, (iv) peer-reviewed literature related to WSP and wetland performance in cold regions, and (v) design guidelines and performance modeling approaches for WSPs and wetlands, and their applicability to northern regions. Throughout the review, primary knowledge gaps are identified to help guide future research efforts in this area.

Several reviews and synthesis reports have previously been produced on aspects on northern wastewater management. Our goal here was not to duplicate these publications. Where appropriate, we summarize key findings from these reports, and refer the reader to the original document for further details.

2.0 Regulatory Atmosphere

The regulatory approach that currently exists in Nunavut has been thoroughly described by Wooten et al. (2008) as part of a Nunavut Regional Impact Analysis in response to the CCME MWWE Strategy prepared for Inuit Tapiriit Kanatami, and Nunavut Tunngavik Inc.. The following sections provide a brief summary (as taken from Wooten et al. 2008) of the key organizations, and their roles and responsibilities with respect to wastewater management in Nunavut.

The Territory and the Government of Nunavut (GN) were established in 1999 as a result of the Nunavut Land Claims Agreement (NLCA). The territory spans two million km^2, and is one-fifth the size of Canada. The NLCA provides a self-governance model and led to the establishment of several key bodies with Inuit representation that are responsible for governing water resources. Article 13 in the NLCA led to the development of the Nunavut Surface Water Rights Tribunal Act, which created and gave regulatory powers to the Nunavut Water Board (NWB). There is no direct federal legislation that deals with wastewater treatment and discharge, yet there are several different legislations that deal with various aspects of the discharge of municipal wastewater.

2.1 Federal Government

The federal agencies responsible for administering legislation pertaining to wastewater include Aboriginal Affairs and Northern Development Canada (AANDC), Environment Canada (EC) and Fisheries and Oceans Canada (DFO).

2.1.1 Aboriginal Affairs and Northern Development Canada

AANDC serves as the main enforcement body responsible for regulatory compliance of wastewater and they also issue inspection reports on non compliance.

2.1.2 Department of Fisheries and Oceans

DFO works through the Fish and Habitat Management Program to enforce the fisheries act, namely *Subsection 36(3)* which states that no one shall deposit or permit the deposit of a deleterious substance of any type in water frequented by fish. The *Fisheries Act* allows for the establishment of federal regulations under subsection 36(5) of the Act, or under another federal Act, that would permit the discharge of deleterious substances to levels set out in the regulations.

2.1.3 Environment Canada

Environment Canada is developing the Wastewater Systems Effluent Regulation, which is the regulatory document involved in implementing the CCME MWWE Strategy. Environment Canada has no enforcement or compliance roles with respect to wastewater in Nunavut.

2.2 Inuit Representation

2.2.1 *Nunavut Tunngavik Inc.*

Nunavut Tunngavik Inc. (NTI) is an Inuit organization that manages all Inuit owned land in Nunavut and ensures that aspects of the NLCA are carried out taking into account the best interests of Inuit, and also ensures that federal and territorial governments fulfill their obligations.

NTI does not have jurisdiction for water on municipal lands; therefore, NTI does not have any involvement in the regulation or issuance of municipal water licenses. However, they do have exclusive rights to the quantity and quality of water flowing through, in or on Inuit Owned lands.

2.3 Government of Nunavut

There are several departments within the government of Nunavut that have responsibilities related to water and wastewater management.

2.3.1 Community and Government Services (CGS)

CGS works in partnership with community governments to assist with capacity building to meet the needs of residents. They are responsible for core municipal operation, infrastructure development, and land development. Several departments including Capital Planning and Technical Services, Community Development and Community Infrastructure have components that deal with wastewater. Through these programs, CGS develops capacity to build and operate services, and protect public health as it relates to municipal infrastructure. With the exception of a few communities, CGS is not responsible for the operation or maintenance of wastewater systems in the municipalities.

2.3.2 Department of Environment (DOE)

The DOE has an environmental protection program that reviews environmental assessments of proposed developments. DOE is involved in the review of water licenses.

2.3.3 Department of Health and Social Services (DHSS)

In addition to general public health components, the DHSS also guides regional health officers in disease prevention programs for environmental factors including drinking water and sanitation practices. DHSS is responsible for the analysis of drinking water quality but have no role in wastewater management. DHSS can provide comments during the water license process, and they can become involved when there is a health risk in place.

2.4 Institutions of Public Government

2.4.1 Nunavut Water Board (NWB)

The goal of the NWB is to conserve and utilize waters in Nunavut in a way that provides the greatest benefit to residents of Nunavut and Canadians in general. Members of the NWB are split equally between Inuit and government, and they are responsible for managing inland waters, not marine areas. The NWB has the power to issue, amend, renew or cancel licenses for inland water use. The NWB follows the *Fisheries Act* sections 36(3) and 36(5) when issuing water licenses. The board has full licensing power but no legislative enforcement power. Legislative enforcement is the responsibility of AANDC.

2.4.2 Nunavut Impact Review Board (NIRB)

The NIRB was created by the Nunavut Land Claims Agreement. The NIRB screens project proposals to determine the potential impacts on the Nunavut Settlement Area, and they conduct environmental and socio-economic assessments and monitoring when required.

2.4.3 Nunavut Planning Commission (NPC)

The NPC was also created by the Nunavut Land Claims Agreement. The NPC is responsible for land use planning in Nunavut and some aspects of environmental monitoring and reporting. The NPC works closely with the NWB. There is no legislation currently governing NPC.

2.5 Municipalities

Municipalities in Nunavut are responsible for the provision of water and sewer services to their communities. In general, municipalities are responsible for ensuring compliance with NWB licenses.

2.6 NWB Water License Process

A Water License is required for any party that uses more than 50 cubic metres of water per day. The NWB uses site-specific information to determine effluent water quality limits for each application. (Ferguson Simek Clark Engineers and Architects, 2000). The general water license process is depicted in Figure 2.1.

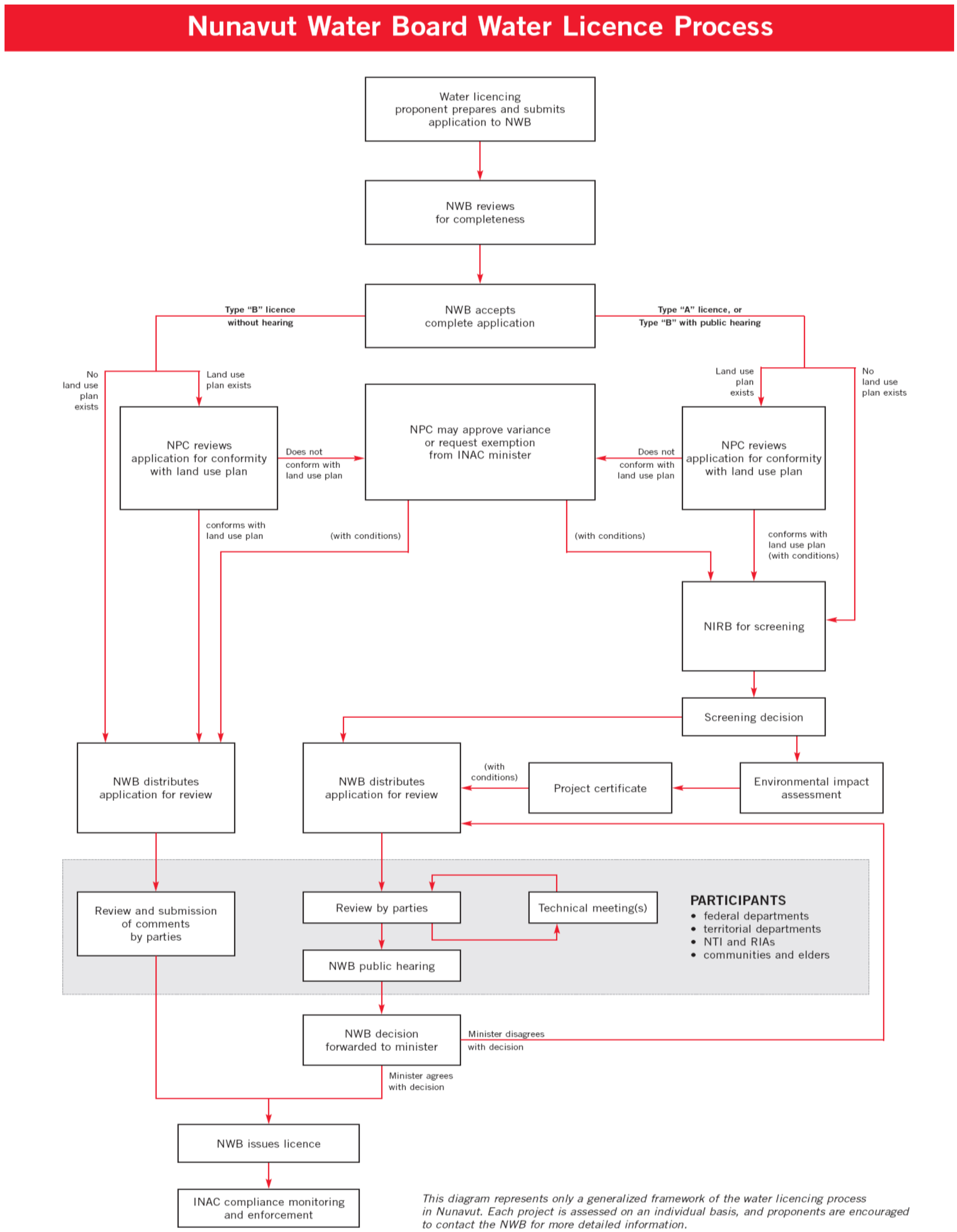

Figure 2.1 – Nunavut Water Board License Process (Wooten et al., 2008)

2.7 Effluent Water Quality

The specified effluent water quality varies across systems due to specifications in the NWB water license. The requirements vary from 100 -180 mg/L total suspended solids, 80-120 mg/L BOD_5 and 10^4-10^6 CFU/100mL fecal coliforms at the point of discharge (Wooten et al., 2008).

2.8 CCME Strategy

In 2009, the CCME released a national Strategy for improving municipal wastewater treatment facilities. Through the Strategy, facilities will be required to achieve minimum National Performance Standards and develop and manage site-specific Effluent Discharge Objectives (EDO). The Strategy provides considerations for the extreme climatic conditions and remoteness of Canada's Far North. A five-year window, which ends in February 2014, has been given to undertake research into factors affecting performance of wastewater systems in northern conditions. Through this research, specific Northern criteria will be developed, including: Northern Performance Standards, initial risk level criteria and timelines for implementation, adaptation of an environmental risk assessment approach for the Far north and adaptation of monitoring and reporting requirements (CCME, 2009).

2.8.1 National Performance Standards

The Strategy has identified the following as the National Performance Standards:

- Carbonaceous Biochemical Oxygen Demand ($CBOD_5$)-25 mg/L
- Total Suspended Solids (TSS) – 25 mg/L
- Total Residual Chlorine (TRC) – 0.02 mg/L

Risk assessments must be carried out on each system and based on the outcome of the risk assessment, a timeline for compliance is given.

2.8.2 Effluent Discharge Objectives

Effluent Discharge Objectives are to be developed for each system through site-specific Environmental Risk Assessments within 8 years of the Strategy being adopted, in order to provide adequate protection for human health and the receiving environment. The procedure for carrying out the Environmental Risk Assessments include initial characterization of the effluent followed by an assessment of the receiving water to determine whether or not the levels in the effluent produce a risk to the receiving environment. If there are substances present at a level that is not protective of human or environmental health, then specific EDOs for those substances would be developed. EDOs may be more stringent than the National Performance Standards based on the risk assessment.

Technical Supplement 2 of The Strategy outlines the framework and guidance for Environmental Risk Management, which is a decision making process that takes site specific factors into account for quality of effluent in order to determine the required level of protection of the environment and human health. In order to determine EDOs for a specific site, it is necessary to determine environmental quality objectives (EQOs). EQOs can be developed through several different approaches including chemical/physical/pathogenic, toxicological, and biological indicators. Mixing zones may also be used to establish EQOs on a site specific basis because end-of-pipe concentrations may not be representative of overall concentration of a substance in the receiving water body. Mixing zones can be used to back calculate from EQOs to EDOs taking into account the assimilative capacity of the water body. The extent of mixing zones can be calculated using modeling approaches such as PLUME and CORMIX, which are commonly used by the United States Environmental Protection Agency.

The use of site specific risk assessments to determine EQOs and EDOS will be an important component for developing Northern performance standards, as they can be used to demonstrate what quality of effluent would be required to minimize impacts to environmental and human health.

2.8.3 Compliance Monitoring and Reporting

The Strategy outlines monitoring requirements based on the size of the facility (Table 2-1). In Nunavut the majority of communities are considered very small systems with Iqaluit falling in the small category. However, the waste composition of northern wastewater will be considerably different than southern Canada due to the quantity of water used. Northern trucked water systems use on average 90- 100 L/per person/day (Heinke et al., 1991) compared to over 300 L/per person/day used in piped water systems in the rest of Canada (Environment Canada, 2011), and so the strength of the wastewater will be quite different. Also, there is very little industrial and no agricultural input for northern systems.

Table 2-1: Monitoring Requirements as per the CCME Strategy

Facility Size and flow rate	Total Residual Chlorine	$CBOD_5$, TSS,	Acute Toxicity	Chronic Toxicity
Very Small (<500 m^3/day)	Daily	Monthly	n/a	n/a
Small (500-2500 m^3/day)	Daily	Monthly	n/a	n/a

According to the Strategy, for jurisdictions that have a devolution agreement in place, it is the jurisdiction that determines who is responsible for conducting compliance monitoring, and all analysis is to be done in an accredited laboratory. In Nunavut, which does not have a devolution agreement in place, regular monitoring would have to be done by municipalities, while compliance and enforcement monitoring would be the responsibility of AANDC. Due to the remoteness, climate and resource capacity, meeting monthly monitoring requirements will be a serious challenge. Communities do not currently have the capacity to do onsite testing and there is no accredited laboratory in the region. Samples would have to be sent to Yellowknife or Ottawa for analysis, which is a serious challenge both financially and logistically due to scheduled flight times and delays.

Currently, monitoring and reporting requirements do not apply to Nunavut, however it will be an integral part of development of Northern specific criteria at the end of the 5-year window.

2.8.4 Governance

The Strategy states that for the Northwest Territories and Nunavut, agreements are to be developed taking into account the respective roles of regulatory bodies. The agreements are to address the implementation of standards over time, regulatory reporting, public reporting and other management activities such as inspections and enforcements.

2.9 Wastewater Systems Effluent Regulations

The CCME Strategy is being developed into a regulation by Environment Canada through the *Fisheries Act*. A draft regulation was published in the Canada Gazette in March 2010 (Government of Canada, 2010). The Wastewater Systems Effluent Regulations (WSER) will apply to any wastewater system that has a capacity to deposit a daily effluent volume of 10 m^3 or more from the final discharge point. As previously mentioned, the average water consumption (and thus wastewater production) is estimated to be 100 L per day per capita for Trucked systems in Nunavut, which means the regulations would be applicable to any community in Nunavut with a population greater than 1000 people. According to a report by the Nunavut Bureau of Statistics (2010), there were 11 communities (of a total of 25) in Nunavut with an estimated population of >1000 people in 2010. It is projected that most communities in Nunavut will experience population growth and by 2021, it is projected that 14/25 communities will have more than 1000 people. The WSER also states that systems in the Northwest Territories, Nunavut and Northern Quebec and Newfoundland Labrador are exempt from the regulations while research is conducted to set appropriate standards for these regions, as detailed in the CCME Strategy.

The effluent quality standards set out in the WSER are the same as for the CCME Strategy with the addition of an ammonia nitrogen requirement.

- Average (Quarterly or monthly) Carbonaceous Biochemical Oxygen Demand ($CBOD_5$)-25 mg/L
- Average (Quarterly or monthly) Total Suspended Solids (TSS) – 25 mg/L
- Average (Quarterly or monthly) Total Residual Chlorine (TRC) – 0.02 mg/L
- Maximum un-ionized ammonia of 1.25 mg/L, expressed as nitrogen at 15°C.

If a system does not meet the effluent quality standards, they may apply for a transitional authorization, which would outline operational conditions and a risk based timeline to meet the national standards. High risk systems will be given a 10 year timeline for compliance, medium and low risk systems will have 20 and 30 years, respectively.

2.9.1 Effluent Monitoring

The owner of a wastewater system must determine the actual volume of waste discharged in a given year. For systems discharging < 2,500 m^3/day, grab or composite samples must be taken on a monthly basis. 2,500 m^3/day corresponds to a Northern community population of 25,000, and so all systems would fall into this category. These samples must be analyzed for CBOD, TSS, TRC and NH_3-N according to established methods.

In addition to samples for national performance standards, samples must also be taken quarterly for systems with flow rates between 2,500 and 17,500 m^3/day for acute lethality. However, there is no mention of acute lethality sampling for smaller systems (< 2,500 m^3/day).

2.9.2 Environmental Effects Monitoring

The percentage of effluent in the receiving water within 100 m of the discharge point must be determined. If it is determined that >10% of the volume at this point is effluent, then an environmental effects monitoring study must be conducted, which consists of both water quality monitoring as well as biological monitoring studies.

Effluent Effects monitoring could last up to 13 years or four cycles, depending on initial results. If no impacts are demonstrated in two consecutive assessments, no further environmental effects monitoring would be required.

Water quality monitoring of the following parameters in the exposure area must be conducted: temperature, pH, dissolved oxygen, conductivity (for fresh water), total ammonia, nitrate, nitrite, total phosphorus, alkylphenol ethoxylates, ethinylestradiol, 17β-estradiol and estrone. Water quality samples in the exposure area must be taken twice per year (at least one month apart) and during biological studies.

Biological monitoring studies consist of both benthic invertebrate and fish population studies. For the benthic invertebrate sampling, analysis should include: total benthic invertebrate density, the evenness index, taxa richness and similarity index, and total organic content and grain size analysis of the sediment. For the fish studies, analysis should include: indicators of growth, of reproduction, of condition and survival.

Prior to biological monitoring studies, a site characterization must be conducted which includes a description of the mixing of effluent with the receiving water within the exposure area, description of anthropogenic or other factors that may contribute to results, description of the treatment system and any other additional information.

2.10 Regulatory Atmosphere for other Circumpolar Nations

A literature and government document review was performed in order to investigate the regulatory framework associated with wastewater management in Arctic regions outside of Canada. This information on wastewater regulation in combination with published literature reporting on the treatment performance associated with wastewater systems in these cold climate regions (Section 4.0) should provide insight and knowledge as to possible solutions that could be applied in Canada's North.

Wastewater regulation and treatment performance in other cold climate regions ranges from little to no treatment or regulation (ex. Greenland) to strict regulation and treatment performance standards (ex. The European Union). This review will help us understand the regulatory framework surrounding the management of wastewater systems under similar climate conditions where proven technologies and treatment systems have the ability to meet strict effluent discharge criteria. Although these regions may have a similar climate compared to Nunavut and the rest of the Canadian North, we must consider the differences in population densities, and therefore community capacity and accessibility. Nunavut communities have relatively small population densities, limited community capacity, and can only be accessed by air or sea. Small population densities mean that wastewater discharges may not pose as significant a risk to the surrounding ecosystem compared to urban centers. However, limited community capacity and accessibility means that wastewater technologies and treatment processes that are often applied to urban populations may not be feasible for remote communities in Canada's North. Risk and feasibility must be considered when developing Northern specific guidelines for wastewater discharge in Canada. Rural and remote regions of Northern Europe (for example) are typically serviced by on-site or individual wastewater systems, which may be a more economical option for these countries, but may also present cost and management issues within the Canadian Arctic due to accessibility and reduced or inconsistent community capacity. The remainder of this section will summarize the regulatory framework including wastewater discharge criteria (where available) for Arctic regions outside of Canada, including: Alaska, Greenland, Northern Europe (Iceland, Finland, Sweden, and Norway), and Russia.

2.10.1 Alaska

The Alaska Department of Environmental Conservation (DEC; Division of Water) regulates domestic wastewater treatment and disposal in Alaska under the DEC's Wastewater Treatment and Disposal Regulation (18 AAC 72). The DEC's Domestic/Municipal Wastewater Program ensures protection of the environment and public heath through a number of services including: domestic wastewater discharge permitting, and technical assistance for both the permitting process and wastewater treatment optimization (Alaska DEC, 2011). Permitting, compliance, and enforcement are managed by the Alaska Pollutant Discharge Elimination System (APDES) with direction from the US EPA's National Pollutant Discharge Elimination System (NPDES). The Alaska DEC's Wastewater Treatment and Disposal Regulations were developed as a requirement under the US EPA's Clean Water Act. The state has legal authority over issuing and enforcing permits for wastewater discharges issued under the Clean Water Act (Alaska DEC, 2011). The Alaska DEC Wastewater Treatment and Disposal Regulation (18 AAC 72) describes the requirements associated with the installation and management of various types of wastewater systems including holding tanks, pit privies, on-site septic systems, sewer discharges, sludge disposal, and operator certification (Alaska DEC, 2011). Minimum treatment requirements for domestic wastewater under the DEC Regulation include secondary treatment for surface discharges, and primary treatment for subsurface discharges, however, reduced levels of treatment may be considered if the applicant can prove that the reduced treatment will protect public health, public and private water systems, and the environment. Effluent discharge criteria are defined on a case by case basis, depending on the nature of the wastewater discharge and sensitivity of the receiving water environment (Alaska DEC, 2011).

There are a number of stakeholders involved with wastewater management in Alaska besides the US EPA and DEC including the Alaska Water and Wastewater Management Association (AWWMA), The Water Environment Federation (WEF), and the American Water Works Association (AWWA). AWWA and/or WEF members also receive membership with the AWWMA. AWWMA provides programs and services involving networking opportunities, professional development including education and training, peer recognition, and wastewater products and services (AWWMA, 2011).

2.10.2 Greenland

Each municipality is responsible for the disposal of wastewater and solid waste in Greenland. Most towns have insulated sewers (buried or above ground) that transport wastewater to an ocean outfall. At the time of this report (2010) no treatment facilities had yet been established in Greenland (Government of Greenland, 2010).

2.10.3 Northern Europe: European Union (EU)

The European Commission regulates wastewater treatment and disposal within the EU countries under the Urban Waste Water Treatment Directive (91/271/EEC; European Commission, 1998). The Urban Waste Water Treatment Directive requires a minimum of secondary treatment for populations exceeding 2000; effluent discharge requirements are summarized in Table 1. Although wastewater discharge criteria (Table 1) are set at the national level within the EU, the municipal government typically has ownership, and therefore is legally responsible for wastewater system permitting, management, and compliance (Marques, 2010). Wastewater is managed though several agencies and organizations within the EU including the European Environment Agency (EEA), the European Commission, the EUREAU European Federation of National Associations of Water and Wastewater Services, WISE (Water Information System for Europe), and other local government organizations within each country (EEA, 2010; European Commission, 2011; EUREAU, 2011; WISE, 2011; Marques, 2011).

The Urban Waste Water Treatment Directive was implemented between 1998 and 2005. In 2010 the EEA released an assessment report in order to answer a specific policy question: Is the Urban Waste Water Directive (91/271/EEC) being implemented in Member States? The EEA found that within Northern Europe (Finland, Sweden, and Norway) 80% of wastewater receives tertiary treatment; while in Iceland 50% of wastewater receives primary treatment where the other 50% receives no treatment. Connection to Urban Waste Water Treatment Plants is influenced by the ratio of rural/urban population and an increasing number of individual wastewater treatment systems (septic systems) in rural areas (EEA, 2010).

2.10.4 Russia

It was not possible to find any recent resources describing Russia's wastewater management structure or requirements. A publication by the United Nations Environment Programme from 2000 (UNEP, 2000) describes the country as having great challenges in water management due to stringent standards that are difficult to implement and enforce. In 2000, the majority of wastewater discharged to freshwater systems had to meet water quality standards for fisheries. These standards were BOD_{20} – 3 mg/L, NH_4 – 0.39 mg/L, oil products 0.05 mg/L and phosphate 0.15 mg/L. It was not possible to find any current sources, and there was no information provided on northern systems in particular.

Table 2-2: Summary of Wastewater Regulators in Arctic Regions outside of Canada

State, Country	Regulatory Agency	Domestic Wastewater Effluent Discharge Criteria	Website
Alaska, USA	Department of Environmental Conservation US EPA	Case by case (site specific)	http://www.dec.state.ak.us/water/wwdp/ http://water.epa.gov/polwaste/wastewater/index.cfm
European Union	European Commission European Environment Agency	25 mg/L BOD_5 125 mg/L COD 35 mg/L TSS	http://ec.europa.eu/environment/water/water-urbanwaste/legislation/directive_en.htm http://www.eea.europa.eu/
Greenland	Municipal Governments Government of Greenland	None to date	http://uk.nanoq.gl/

2.10.5 Summary

Within Northern Europe, Alaska, and **Russia** there are a number of government and private industrial organizations involved in wastewater management and regulation. Wastewater regulation and effluent discharge criteria are typically determined or recommended at the national level but most local/municipal governments take ownership of the wastewater systems and are therefore responsible for permitting, management, and compliance. The specific framework may vary between regions, but generally where regulations exist a minimum level of secondary treatment is required.

3.0 Northern Wastewater Treatment

The following sections provide a summary of 72 wastewater treatment facilities in Nunavut, Nunavik, and the Northwest Territories. This summary was completed based on data compiled by Environment Canada from 2007-2009 through available literature and field work and is a best approximation of current conditions although some communities may have upgraded their systems since compilation of this data.

3.1 Community population

The CCME MWWE Strategy has categorized systems based on their flow rates:

- Very Small <500 m^3/day
- Small 500-2,500 m^3/day
- Medium 2,500-17,500 m^3/day
- Large 17,500-50,000 m^3/day

As previously mentioned, the water consumption for communities in the North on trucked water delivery is known to be around 100 L/per person/day (Heinke et al., 1991), less than a third of the national average. This would correspond to approximately 100 L/per person/day of wastewater volume of as the majority of water is used within the home, as there are no lawns or gardens. There is no agriculture or industry in the majority of Northern communities and thus wastewater would be almost entirely residential in origin, which is quite different than wastewater composition in the south that would have a combination of residential and industrial waste. Based on community populations from the 2006 census, the vast majority of communities will be considered very small systems with Iqaluit and Yellowknife being the only communities to fall into the small category. Figure 3-1 presents community population by region in the North.

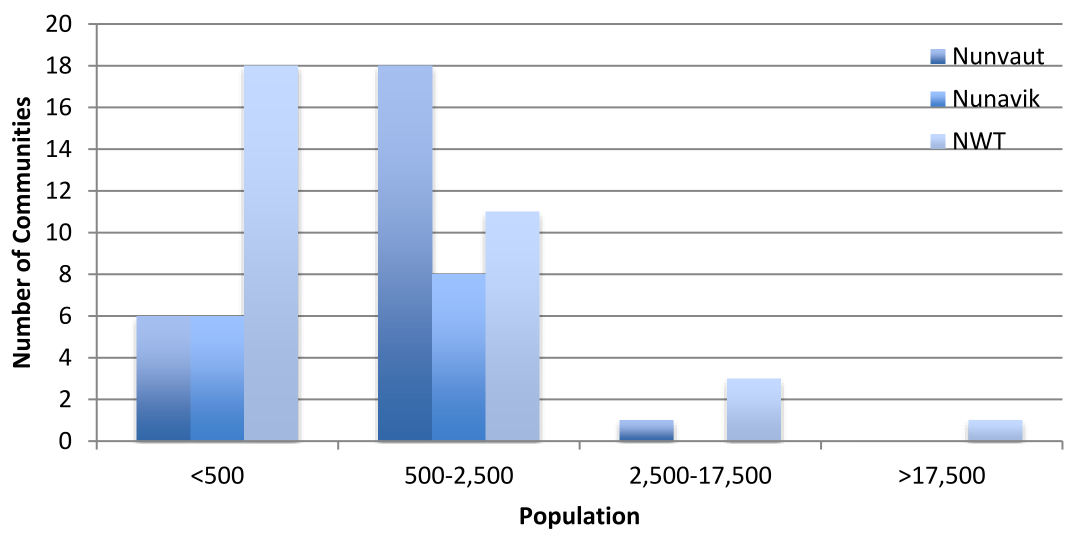

Figure 3-1: Population distribution of communities in Nunavut, Nunavik and the Northwest Territories.

3.2 Types of Wastewater Systems

Most wastewater systems in Nunavut, Nunavik and the NWT are either WSP or lake systems. Only 5 of 72 systems are mechanical plants. Figures 3.2 and 3.3 show the distribution of system type. In this instance, WSP refers to an engineered system while lake refers to a natural water body.

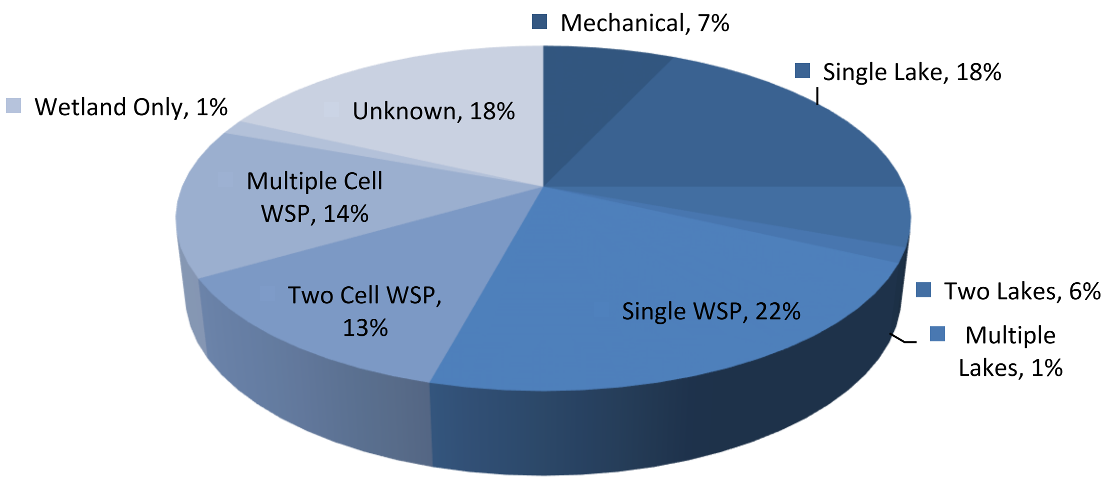

Figure 3-2: Pie chart showing distribution of wastewater system type in Nunavut, Nunavik and NWT.

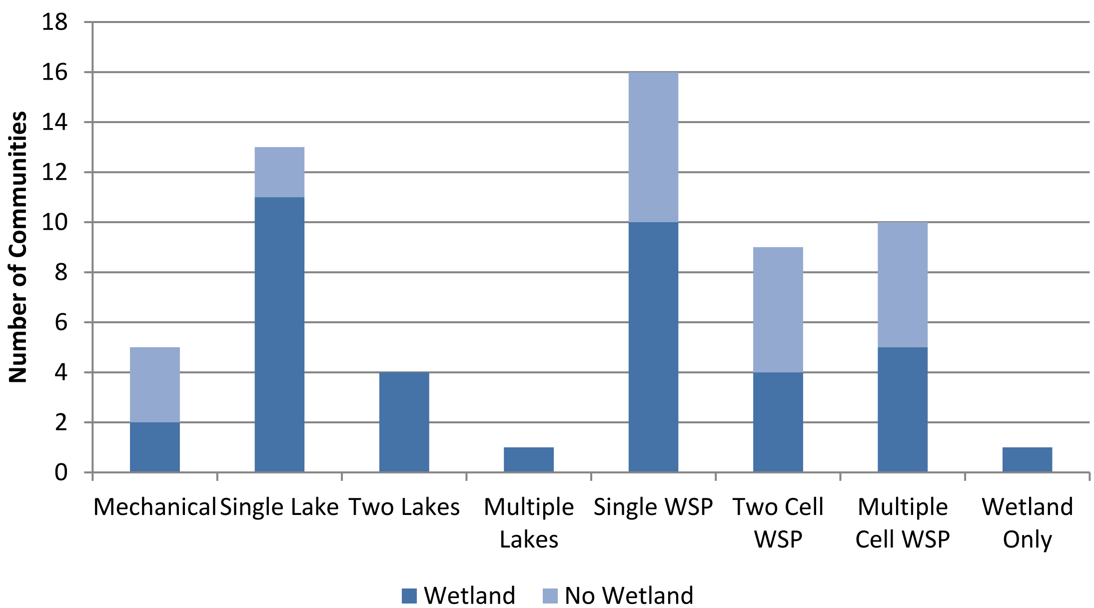

Figure 3-3: Distribution of system type and use of wetlands.

3.3 Loading Rates and Discharge Frequency

Both the areal and organic loading rates for the 72 northern systems are highly variable ranging 0.2 - 253.8 mm/day and 0.1 - 60.9 $gBOD/m^2/day$, respectively (Figure 3-4 and Figure 3-5). The majority of the high loading rate systems have a seasonally continuous discharge, whereas nearly 50% of the low loading rate systems are annual discharge only (Figure 3-6 Figure 3-7). In general the majority of systems with an annual decant discharge in late summer or fall, although data is not provided for all systems. Figure 3-8 shows the distribution of continuous versus annual discharge systems for the three different regions, indicating that system type varies with region as the NWT has a much larger percentage of continually discharging systems compared to Nunavut and Nunavik. There is not enough information at this point to determine whether this difference is due to climate and geography, performance or preference of engineering design firms. It is also not indicated whether the continuous discharge systems were designed to be continuously exfiltrating or whether they are failed permafrost berm systems.

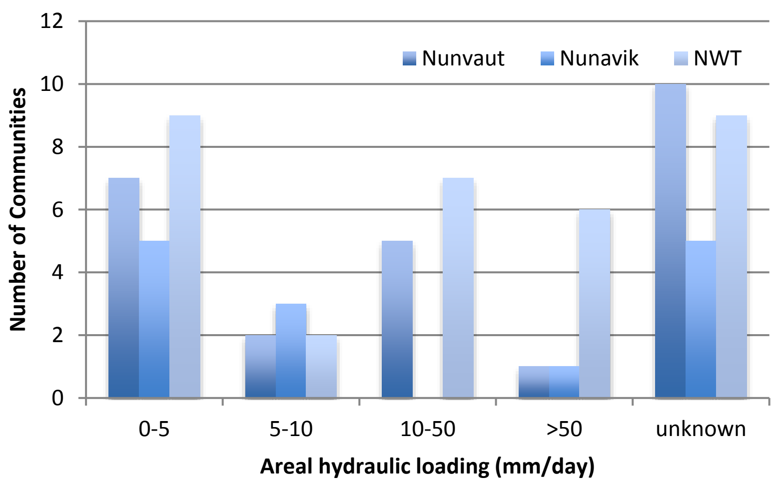

Figure 3-4: Areal hydraulic loading rates for wastewater systems in Nunavut, Nunavik and NWT.

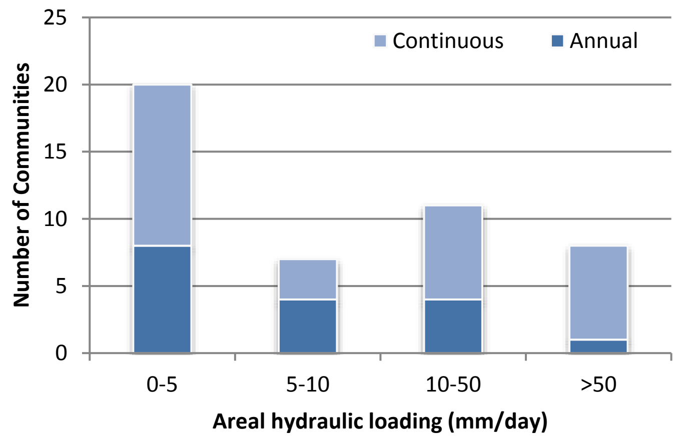

Figure 3-5: Distribution of continuous and annual discharge systems by areal hydraulic loading rate.

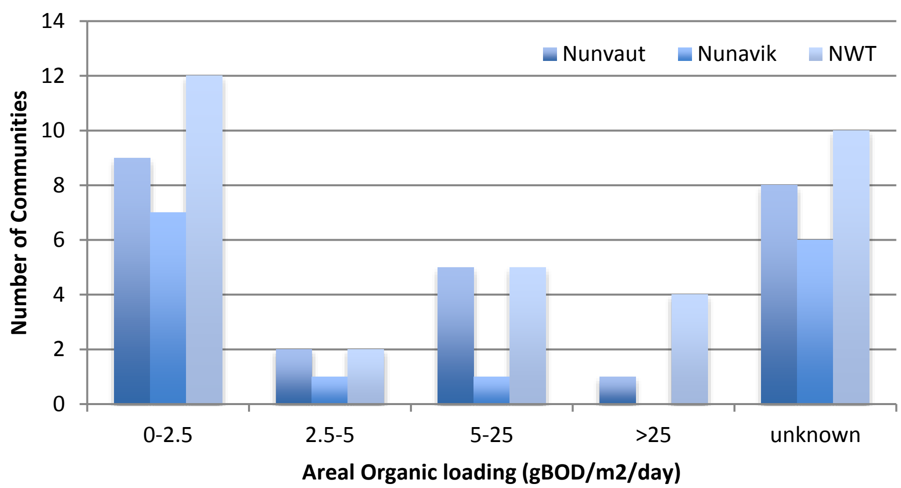

Figure 3-6: Organic loading rates for wastewater systems in Nunavut, Nunavik and NWT.

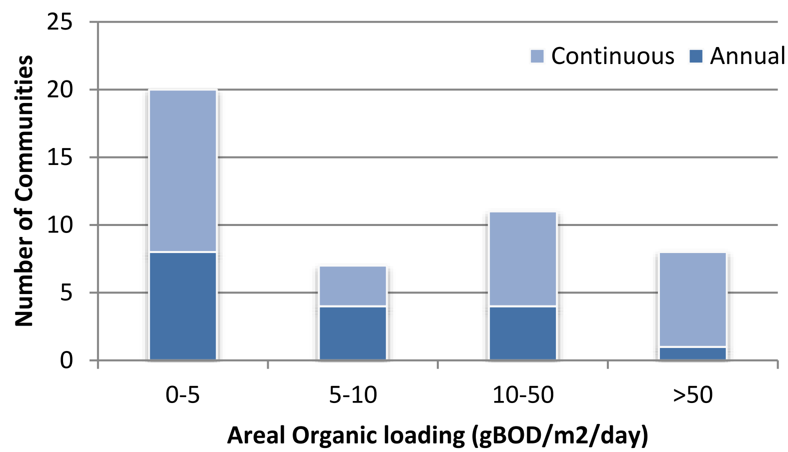

Figure 3-7: Distribution of continuous and annual discharge systems by areal hydraulic loading rate.

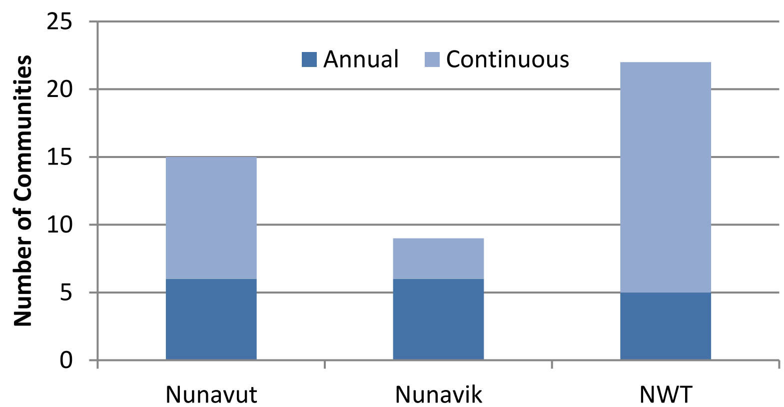

Figure 3-8: Distribution of discharge type (continuous versus annual) for the three regions.

4.0 Performance of WSPs and Wetlands Used for Wastewater Treatment in Cold Northern Climates

Domestic wastewater treatment for remote regions presents many challenges including sparse population densities, young populations, low tax base communities, lack of qualified personnel, high staff turnover, and expensive materials, construction, operation, and maintenance costs (Miyamoto & Heinke, 1979; Dillon, 2006; Gartner Lee, 2006; Nunami JW, 2007; Wooten et al. 2008). Canada's Northern Hamlets and other cold climate communities are typically located in remote regions and combined with extremely cold temperatures and long winters this makes domestic wastewater treatment even more challenging. Centralized, or piped wastewater systems are not practical in extreme cold climate regions because of the associated construction costs, human resource challenges, energy and maintenance requirements, and physical constraints such as adjacent water bodies and confining mountainous landscapes (Miyamoto & Heinke, 1979; INAC, 2003; Dillon, 2006; Nunami JW, 2007; Wooten et al. 2008). Passive wastewater management systems, such as WSPs and wetlands can be an economical option for wastewater treatment in remote northern regions where conventional centralized forms of treatment may not be feasible (Heinke et al. 1988; INAC, 2003; Trow, 2008; Wooten et al. 2008).

WSPs are the most common method of domestic wastewater management in Canada's North because they are more economical, and can operate under severe cold climate conditions with minimal operation and maintenance (Heinke et al. 1988; INAC, 2003; Gartner Lee, 2006; Trow, 2008; Wooten et al. 2008; Dillon, 2007 & 2009). WSPs in Canada's North include both engineered WSP and natural "lake-lagoon" systems (INAC, 2003; Dillon, 2007). Typically within northern communities in Canada domestic wastewater is stored in a septic tank (i.e. holding tank) at each residence. Wastewater is then pumped from the tanks on a frequent schedule and trucked to the local WSP, "lake-lagoon", or treatment wetland where the wastewater is discharged (Heinke et al. 1988; Gartner Lee, 2006; Dillon, 2007; Wooten et al. 2008). The majority of WSPs in cold climate regions operate as a storage pond during the winter months with decants once or twice a year in the spring, during break-up, or in the fall, just before freeze-up. Other WSPs that do not have an impervious berm or liner are classified as continuous discharge WSPs where effluent constantly exfiltrates from the WSP during the warmer spring and summer months (Heinke et al. 1988; Gartner Lee, 2006; Dillon, 2007; Wooten et al. 2008). Studies have shown that WSP effluent concentrations often exceed water license discharge criteria within many communities in the North (Dillon, 2008). Inadequate treatment may be influenced by growing populations, operational challenges, and/or undersized WSP systems (Wooten et al. 2008). Several northern communities have adapted the use of existing natural wetland areas as a polishing step for WSP effluents. The term wetland is used generally in the north and may include tundra, open streams and ponds, bogs, emergent grasses, and fens. Typically these wetland systems are non-engineered systems, and have developed over time as a result of continued wastewater discharge (Dillon, 2009). Kugaaruk, NU is one example where the Hamlet was successful in obtaining a water license including use of a natural wetland area for the secondary treatment of WSP effluents (Dillon, 2008). Natural wetlands have been shown to provide adequate treatment of WSP effluents in many northern communities (Nunami JW, 2007; Dillon, 2008).

Although WSPs and natural wetland areas have been used for domestic wastewater management for many years in Northern Canada, adequate performance data is lacking. The nature of these northern wastewater systems makes data collection and performance evaluation extremely difficult because these systems only flow for a relatively short period of time during the spring and summer months. Challenges surrounding travel and timely sample analysis mean that most of the available data represents only small snap shots in time and may not accurately represent long-term treatment performance (Wooten et al. 2008). The main objective of this section of the literature review was to gain an understanding, and develop an inventory of the different types of wastewater management systems operating in Northern Canada and other cold climate regions. This review will summarize the treatment performance associated with existing WSP and treatment wetland systems and identify factors affecting treatment performance in cold climates and the Canadian Arctic.

4.1 Treatment Mechanisms & Cold Climate Challenges

WSPs provide wastewater treatment through both physical and biological processes including sedimentation, biological oxidation and fermentation, and disinfection by solar radiation. WSPs contain a variety of microorganisms that contribute to wastewater treatment. Bacteria consume soluble organic material, while algae and other aquatic plants contribute to nutrient removal and return oxygen to the system (Heinke et al. 1988). WSPs may operate under aerobic (in the presence of dissolved oxygen (DO)), anaerobic (no DO), or facultative (both aerobic and anaerobic) conditions (Heinke et al. 1988; INAC, 2003). The amount of dissolved oxygen within a WSP system will determine the type of microorganisms, and the rate of biological degradation. Typically, aerobic bacteria provide more efficient removal of organics. Most WSPs in Canada's North function under facultative conditions due to their intermittent flow regime (INAC, 2003). Settled solids accumulate at the bottom of the WSP creating an anaerobic sludge layer where a consortium of bacteria degrade organic compounds and produce methane, and carbon dioxide (Heinke et al. 1988). Biological activity has been shown to decrease within this anaerobic sludge zone at temperatures below 10°C (Heinke et al. 1988). Biological respiration also typically slows at lower temperatures, thus reducing the rate of organic matter degradation and treatment performance during the cold winter months. Severe cold climate temperatures cause receiving waters and WSPs to freeze-up during the winter months, which prevent wastewater discharge. Ice cover will also significantly reduce the "active" WSP volume that is available for treatment, block solar radiation from penetrating the water column, and create unique hydraulic characteristics and anaerobic conditions (Heinke et al. 1988).

Wetlands also provide wastewater treatment through both physical and biological processes including sedimentation, absorption and filtration of contaminants provided by plants and soil surfaces, biological oxidation, disinfection via solar radiation, and nutrient removal by a variety of vegetation (INAC, 2003). The use of natural wetland areas for wastewater treatment in remote northern locations is extremely attractive because these systems are pre-existing, and have the ability to provide wastewater treatment with minimal cost and maintenance (Nunami JW, 2007; Wooten et al. 2008; Dillon, 2009). Treatment wetlands would experience similar operational challenges due to extreme cold climate conditions such as freezing, and reduced biological activity during the winter months (INAC, 2003; Nunami JW, 2007). Intermittent wastewater flows and increased hydraulic loads during the spring thaw will have a significant effect on wetland hydraulics and treatment performance (Nunami JW, 2007). The type of wetland area (tundra or overland flow, channel flow, or ponds in series) and slope will influence wetland hydraulics and travel time, which may be the primary factor affecting wetland treatment performance. Hydraulic and wastewater loading to wetlands in the North for continuous discharge WSPs would be highest during the spring freshet when water temperatures are still very cold (close to 0°C), and biological activity and plant growth would be minimal (Nunami JW, 2007). Reduced wetland retention times, biological degradation, and plant growth during the spring thaw may cause significantly reduced treatment efficiency during this time. Treatment wetland systems typically function more effectively during the summer and fall when water temperatures are warmer and microorganism and plant populations have had time to establish (Nunami JW, 2007).

4.2 Performance Review

A review of existing domestic wastewater WSP and wetland treatment performance was completed for Northern Canada and other cold climate regions. A number of engineering consultant reports were referenced for data on existing systems in Northern Canada including Nunavut (NU), the Yukon (YT) and North West Territories (NWT). Data obtained from the engineering consultant reports are summarized in Table 4.1. Published literature was reviewed to gain an understanding of the treatment performance associated with wastewater WSPs and wetland systems in other cold climate regions. Data obtained from the peer-reviewed literature are summarized in Table 4.2. In some cases data for fecal coliforms (FC) was not available, and total nitrogen (TN) percent removals or concentrations may be presented instead if they were available. Typical trucked raw wastewater (WSP influent) characteristics are relatively consistent and average contaminant concentrations found within raw domestic sewage were presented by Dillon (2009); this data can be found in Table 4.3. Table 4.4 presents another summary of Tables 4.1 and 4.2 to illustrate the variability in WSP and wetland effluent concentrations and treatment variability. All dates listed in Table 41. And 4.2 correspond to the dates that the reports were produced and all effluent discharge criteria relate to the time at which the report was prepared and may have since changed.

Table 4.1: Consultant Report Performance Summary for Existing Domestic Wastewater Treatment Lagoons & Wetlands in Northern Canada

		Average Effluent Concentrations			Effluent Discharge Criteria		
Site Location, Description and Reference	System Type or Sample Location	BOD_5 (mg/L)	TSS (mg/L)	FC (CFU $100mL^{-1}$)	BOD_5 (mg/L)	TSS (mg/L)	FC (CFU $100mL^{-1}$)
Kugaaruk, NU 2 cell WSP + natural treatment wetland area Fall WSP decant + constant leak to wetland area Dillon (2008)							
	WSP	218	1090	3.3E+6	120	180	1.0E+4
	Wetland	19.5	30	3.2E+4	45	45	1.0E+4
Edzo, NWT 2 cell WSP + natural treatment wetland area Dillon (2006)							
	WSP	23	15	2.3E+4			
	Wetland	7	20	2	30	35	
Old Crow, YT Spring exfiltration WSP + natural treatment wetland area Dillon (2006)							
	WSP	17	146		45	60	
	Wetland	ND	ND				
Clyde River, NU Single exfiltration WSP + natural treatment wetland area Dillon (2006)							
	WSP	NA	103-177		120	180	
Resolute Bay, NU *no info on system*, wastewater inventory says Res Bay has maceration and direct discharge Dillon (2006)							
	WSP	88	216				

Table 4.1: Consultant Report Performance Summary for Existing Domestic Wastewater Treatment Lagoons & Wetlands in Northern Canada

Site Location, Description and Reference	System Type or Sample Location	Average Effluent Concentrations			Effluent Discharge Criteria		
		BOD_5 (mg/L)	TSS (mg/L)	FC (CFU $100mL^{-1}$)	BOD_5 (mg/L)	TSS (mg/L)	FC (CFU $100mL^{-1}$)
Dawson City, YT 3 cell WSP pilot plant Dillon (2006)							
	WSP	7-136	7-63		45	60	
Inuvik, NWT WSP system (2 sludge cells, 2 primary cells, and 1 secondary cell) Dillon (2006)							
	WSP	30-140	10-65		100	70	1.0E+6
	<u>Summer</u>						
	Primary	(55)[1]	(46)	(56)			
	WSP	(80)	(78)	(99.9)			
	<u>Winter</u>						
	Primary	(54)	(55)	(77)			
	WSP	(81)	(86)	(86)			
Baker Lake, NU Natural wetland area (2 lakes in series) Dillon (2009)							
	1 – WSP Lake	(58)	(78)	(99.9)			
	2 – Finger Lake	(79)	-	(99.9)			
Repulse Bay, NU Natural wetland area (3 ponds in series) Dillon (2009)							
	Pond 1	(55)	(46)	(99)			

[1] *(55)* ***Percent (%) removal***

Table 4.1: Consultant Report Performance Summary for Existing Domestic Wastewater Treatment Lagoons & Wetlands in Northern Canada

		Average Effluent Concentrations			Effluent Discharge Criteria		
Site Location, Description and Reference	System Type or Sample Location	BOD_5 (mg/L)	TSS (mg/L)	FC (CFU $100mL^{-1}$)	BOD_5 (mg/L)	TSS (mg/L)	FC (CFU $100mL^{-1}$)
	Pond 2	(88)	(87)	(100)			
Chesterfield Inlet, NU Natural wetland area (3 ponds & wetland containing numerous braided flow channels; pond 1 flows into ponds 2 & 3) Dillon (2009)							
	Pond 1	(72)	(26)	(98.5)			
	Pond 2	(79)	(38)	(99.1)			
	Pond 3	(79)	(69)	(99.9)			
	Wetland	(81)	(81)	(99.9)			
Hay River, NWT Natural wetland treating primary effluents Dillon (2009)							
	Wetland	(97.7)	(96.8)	(98.7[2])			
Fontanges, NWT Natural wetland treating primary effluents Dillon (2009)							
	Wetland	(99)	-	(99.9[2])			
Yellowknife, NWT 4 facultative WSP-lakes in series + 13 km natural wetland area, annual spring/summer discharge Gartner Lee Ltd. (2006)							
	Final eff.						
	Annual avg.	3	10	<2	20	20	1000
	Summer	(90)		(99.9)			
	Winter	(40-60)		(55-96.7)			

[2] Total Coliforms

Table 4.1: Consultant Report Performance Summary for Existing Domestic Wastewater Treatment Lagoons & Wetlands in Northern Canada

		Average Effluent Concentrations			Effluent Discharge Criteria		
Site Location, Description and Reference	System Type or Sample Location	BOD_5 (mg/L)	TSS (mg/L)	FC (CFU $100mL^{-1}$)	BOD_5 (mg/L)	TSS (mg/L)	FC (CFU $100mL^{-1}$)
Fort Liard, NWT 3 cell facultative WSP system, annual discharge in Aug/Sept Gartner Lee Ltd. (2006)							
	Final eff. Annual avg.	6.3	12	53			
Fort Smith, NWT 2 anaerobic cells + 1 facultative cell, lined with continuous discharge Gartner Lee Ltd. (2006)							
	Final Eff. Annual avg.	96	53	1.1E+5	300	200	1.0E+6
Hay River, NWT 2 primary cells + continuous discharge to wetland treatment Gartner Lee Ltd. (2006)							
	Final Eff. Annual avg.	13	8	216	20	20	1000
Tuktoyuktuk, NWT Modified natural pond, annual Aug/Sept discharge Gartner Lee Ltd. (2006)							
	Final Eff. Annual avg.	22	69	1.7E+3	120	180	-
Inuvik, NWT 2 cell facultative WSP, continuous discharge Gartner Lee Ltd. (2006)							
	Final Eff. Annual Avg.	58	16	1.4E+5	100	70	1.0E+6

Table 4.1: Consultant Report Performance Summary for Existing Domestic Wastewater Treatment Lagoons & Wetlands in Northern Canada

		Average Effluent Concentrations			Effluent Discharge Criteria		
Site Location, Description and Reference	System Type or Sample Location	BOD_5 (mg/L)	TSS (mg/L)	FC (CFU $100mL^{-1}$)	BOD_5 (mg/L)	TSS (mg/L)	FC (CFU $100mL^{-1}$)
Norman Wells, NWT 2 facultative WSPs + wetland treatment, no discharge before 2006 Gartner Lee Ltd. (2006)							
	Final Eff. Annual avg.	12	7	24	120	180	1.0E+6
Tsiigehtchic, NWT Natural WSP + wetland treatment, continuous discharge Gartner Lee Ltd. (2006)							
	Final Eff. Annual avg.	9.5	11	150	-	-	-
Decline, NWT 2 cell WSP, spring and fall discharge Gartner Lee Ltd. (2006)							
	Final Eff. Annual avg.	87	109	5.9E+3	80	100	1.0E+4
Whitehorse, YT No system details Heinke (1988)							
	Summer	(42)	(56)	(78)			
	Winter	(34)	-	(-16)			
Fort McPherson, NWT Anaerobic WSP (abandoned gravel quarry) + natural wetland area, summer &/or fall discharge Johnson (2009)							
	WSP	17-70	51-150		120	180	1.0E+6

Table 4.1: Consultant Report Performance Summary for Existing Domestic Wastewater Treatment Lagoons & Wetlands in Northern Canada

		Average Effluent Concentrations			Effluent Discharge Criteria		
Site Location, Description and Reference	**System Type or Sample Location**	**BOD_5 (mg/L)**	**TSS (mg/L)**	**FC (CFU $100mL^{-1}$)**	**BOD_5 (mg/L)**	**TSS (mg/L)**	**FC (CFU $100mL^{-1}$)**
Coral Harbour, NU WSP + Natural wetland area, continuous discharge to wetland area in spring/summer via WSP seepage Nunami Jacques Whitford Ltd. (2007)							
	WSP	120	100	>1.1E+5	120	180	1.0E+6
	Wetland 1	42	56	4.6E+4			
	Wetland 2* (*proposed discharge point)	<6	<5	9.3E+2			
Kugluktuk, NU WSP + Treatment wetland area Nuna Burnside (2007)							
	WSP	276	95	1.3E+7			
	Wetland	8	7	4.0E+4	45	45	2.0E+4
Pond Inlet, NU Engineered WSP + natural wetland treatment area, fall decant Enviro. Can. (2010)							
	Influent	396.5	460	-			
	WSP	71	98.7	-			
	Wetland	62.0		-			

Table 4.2: Published Literature Performance Summary for Domestic Wastewater Treatment Lagoons & Wetlands in Cold Climates

		Average Effluent Concentrations			Average Percent Removal		
Site Location, Description and Reference	System Type or Sample Location	BOD_5 (mg/L)	TSS (mg/L)	FC (CFU $100mL^{-1}$)	BOD_5 (%)	TSS (%)	FC (%)
Rostock, Germany							
Various Wastewater Ponds (WP: un-aerated (7) & aerated(7); 14 total)							
Barjenbruch & Erler (2005)							
	Un-aerated	19.4					
	Aerated	19.2					
Village of Alfred, ON							
2 cell WSP with spring discharge to engineered wetland system (marsh-pond-marsh design) + vegetated filter strip							
Cameron et al. (2003)							
	WSP	3.62	82.67	8.3E+1			
	Wetland	2.38	6.18	3.9E+1	34.3	92.5	53.0
	Vegetated Filter Strip	1.85	15.9	3.1E+1	22.3	-61.2	20.5
Williamstown, Ireland							
Packaged plant (aeration chamber & clarifier) + constructed wetland (2 reed beds + pond in series)							
Healy & Cawley (2002)							
	Packaged plant	18	52	4.5E+4			
	Wetland	9	9	1.2E+2	50	83	99.7
Northern Europe							
Various natural treatment wetland systems							
Jenssen et al. (1993)							
1. Moesgard, Denmark	Subsurface flow wetland system (SFS) receiving septic effluent	14	10	TN[3] (mg/L) 26	85	86	TN (%) 45

[3] Total Nitrogen

Table 4.2: Published Literature Performance Summary for Domestic Wastewater Treatment Lagoons & Wetlands in Cold Climates

Site Location, Description and Reference	System Type or Sample Location	Average Effluent Concentrations: BOD_5 (mg/L)	TSS (mg/L)	FC (CFU $100mL^{-1}$)	Average Percent Removal: BOD_5 (%)	TSS (%)	FC (%)
2. Rugballegard, Denmark	SFS receiving septic effluent	36	53	TN (mg/L) 44	91	51	TN (%) 51
3. Snogerod, Sweden	SFS receiving secondary effluent	1.2		TN (mg/L) 5.3	79		TN (%) 50
4. Solborg, Norway	3 facultative ponds in series receiving septic effluent	66[4]	32	TN (mg/L) 37	80	60	TN (%) 29
5. Bardu, Norway	Rapid Infiltration system	3.2[1]		TN (mg/L) 3	92		TN (%) 77
Norway, various systems Vertical flow biofilter + Horizontal subsurface flow constructed wetland receiving septic effluent (5 systems total) Jenssen et al. (2005)							
		13.6		TN (mg/L) 27.5	89		TN (%) 61
NWT, various systems Johnson & Wilson (1999)							
	WSP (4)	77	52	1.2E+5			
	WSP + wetland (1)	34	19	5.3E+3			
	Mechanical treatment plant (2)	125	25	1.8E+6			

[4] COD

Table 4.2: Published Literature Performance Summary for Domestic Wastewater Treatment Lagoons & Wetlands in Cold Climates

		Average Effluent Concentrations			Average Percent Removal		
Site Location, Description and Reference	System Type or Sample Location	BOD_5 (mg/L)	TSS (mg/L)	FC (CFU $100mL^{-1}$)	BOD_5 (%)	TSS (%)	FC (%)
	Natural Lake (3)	23	67	6.5E+2			
	Natural Lake + wetland (2)	26	17	7.6E+2			
	Trench (1)	11	5	3.2E+1			
	Wetland (1)	149	81	2.5E+5			
Fort Nelson, BC Johnson & Sarson (2007)							
	Aerated WSP system	20	21	1.8E+4	81	87	99
Inuvik, NWT Miyamoto & Heinke (1979)							
	Engineered WSP Summer	40	20		80	85	
	Engineered WSP Winter	51	20	5.0E+3[5]	71	85	98[2]

[5] Fecal Streptococci

Table 4.3 - Typical Trucked Raw Sewage Characteristics (Dillon, 2009).

Parameter	Concentration (mg/L)
Biological Oxygen Demand (BOD_5)	400
Total Suspended Solids (TSS)	350
Volatile Suspended Solids (VSS)	275
Ammonia (NH_3)	50
Total Phosphorous (TP)	15
Fecal Coliform (FC); CFU/100mL	1.5E+07

Table 4.4 - Wastewater WSP and Wetland Effluent Concentration and Performance Variability (summary of Tables 4.1 &4.2)

Parameter	WSP Performance		Wetland Performance	
	% removal	Effluent concentrations	% removal	Effluent concentrations
BOD_5 (mg/L)	34 - 90	7 – 276	40 - 81	3 – 62
TSS (mg/L)	26 - 87	7-1090	26 – 87	<5 – 150
FC (CFU/100mL)	56 - 99.9	53 - 1.3E+07	55 – 99.9	<2 – 4.6E+04

It is evident from Tables 4.1, 4.2, and 4.4 that WSP and wetland treatment performance can be highly variable and may depend on a number of factors including. It is not possible to identify specific trends in factors that affect performance due to system variability and lack of data however, some general observations can be made. In general, important factors include:

- The type of system (natural or engineered, single or multiple cell, facultative, aerobic or anaerobic conditions)
- Location (latitude): timing of spring break-up and fall freeze-up, amount of ice cover during the winter months, and number of daylight hours during the summer months. Extended hours of daylight during the summer months can greatly affect algae growth within WSP systems. Algae can have both a positive and negative influence on treatment performance because they consume nutrients and produce oxygen, but will also cause elevated suspended solids concentrations, especially during the summer months.
- System operation: timing of decant, or continuous discharge/exfiltration. The length of time that wastewater is contained within the WSP or wetland system will have a direct influence on treatment performance.
- Monitoring Period: most studies were based on data collected over a relatively short period of time, which may not accurately predict treatment performance. External hydraulic loading due to snow and ice melt during the spring may dilute WSP effluent concentrations and overestimate treatment performance. The increased hydraulic load to the wetlands may cause reduced retention times, and therefore reduced treatment capacity during the spring freshet.

- Sampling: For wetland samples, the consideration of the natural background including natural levels of TSS in the environment as well as wildlife inputs. Sample storage (i.e. refrigerated, frozen) and transportation time can also produce variability.

5.0 Review of WSP and Wetland Design Approaches

5.1 WSP Design

WSPs, have been widely used in North America for the management of domestic wastewater. Although these types of systems are viewed as a simple technology, and they have been used and studied for decades, we still have a limited ability to predict and quantify the many biological, chemical and physical processes which occur within these open environmental systems (Shilton, 2005). WSPs are typically classified according to: (i) primary biological reactions which occur within the WSP (aerobic vs anaerobic), and (ii) duration and frequency of discharge.

As presented in previous sections of this review the predominant type of WSP system utilized in Nunavut would be classified as a facultative WSP with seasonal discharge. These systems are relatively shallow (1.5 – 2.5 m maximum water depths) and rely on natural aeration and algal photosynthesis for oxygen introduction. In a northern application they operate as storage WSPs during the 9-10 month period of ice cover, with no discharge. During the short summer season, effluent from the WSP is released in either a controlled (pumped) or uncontrolled (continuous exfiltration) manner. These operational characteristics will have a large influence on the selection of appropriate performance modeling approaches.

During the treatment season, wastewater constituents are transformed and broken down by various biological processes in the WSP environment. Shilton et al. (2005) and USEPA (1983) are excellent sources of information on the specific microbial and chemical processes that take place in WSP systems. Key environmental parameters that influence these processes are temperature and solar radiation. In this section the equations and methodologies that have been used to size facultative WSPs in North America and their applicability to the design of WSPs operating in arctic environments are reviewed.

5.1.1 WSP Design Approaches

Equations and models that have been developed to size facultative WSPs range from very simple rule-of-thumb approaches to complex computer simulation models. In general, the simple methods have been used and recommended by most regulatory agencies for WSP design. Design models can be divided into four types (i) Empirical models, (ii) Rational models, (iii) Process-Based models, (iv) Computational Fluid Dynamics models. It should be noted that all models for predicting facultative WSP performance have been developed for continuously discharging systems. Although these design approaches have been applied to seasonal discharge systems, very little research has taken place to support this application. Primary reference documents and guidelines for WSP design in North America have been produced by the USEPA (1983), Alberta Environment (2006), Ontario Ministry of Environment (2008), and Heinke et al. (1991).

5.1.2 *Empirical Models*

Empirical approaches are commonly applied for WSP design in North America (Heinke et al. 1991; Heaven et al. 2003). WSPs are sized using either a specified Areal Loading Rate (ALRs) of BOD_5 or a specified Hydraulic Retention Time (HRT), or a combination of the two. Design ALRs have been developed based on maintenance of aerobic conditions in the WSP (i.e. the loading of organic matter is not greater than the amount of oxygen that can be naturally produced to decompose it). Recommended ALRs for North America range from 11 – 67 kg BOD5/ha-d (USEPA, 1983). The USEPA recommend that WSPs in regions experiencing average winter temperatures less than 0^oC be sized using ALRs between 11 – 22 kg BOD5/ha-d, while the Province of Ontario recommends an ALR of 22 kg BOD5/ha-d be used. It should be noted that no ALRs for use in arctic climates have specifically been produced.

Several empirical equations have also been developed to determine appropriate ALRs for facultative WSP systems (Gloyna, 1976; McGarry and Pescod, 1970; Mara, 1987). For all three approaches, the ALR is directly related to temperature. These empirical equations were developed using performance data from primarily warm climate systems. In addition, these empirical equations do not allow for a precise prediction of effluent quality. Ellis and Rodrigues (1999) developed a more sophisticated multiple regression model to predict WSP performance (BOD and FC removal) in the Cayman Islands. They related removal of these pollutants to a variety of environment parameters. For FC, treatment in facultative WSPs was correlated with hydraulic loading rate, retention time, pond depth and conductivity. For BOD, treatment was related to solar radiation and hours of sunshine, rainfall, and pond depth.

Recommended WSP HRTs for cold climates in North America vary between 180 and 365 days, but there appears to be a growing consensus that 365 days is required for seasonal discharge WSPs (Heaven et al. 2003). Ontario recommends that minimum HRTs should be equal to the time period during which wastewater cannot be discharged, or the time period of seasonal ice cover. Alberta Environment provides detailed criteria for WSP treatment system components and associated HRTs. They recommend that a WSP system consist of: (i) 2-4 anaerobic pretreatment cells each possessing 2 day HRTs, (ii) a shallow (1.5 m) facultative cell with a 60 day HRT, and (iii) a final deeper (2.5 m) storage cell with a 365 day HRT. Several researchers have noted that for WSPs designed for annual discharge, the key design parameter is the time the wastewater is held in the WSP after spring break-up. Heinke et al. (1991) recommend that wastewater be held for at least 60 days after break-up. Autumn discharges are generally preferred, as several studies have demonstrated that ammonia levels in cold climate WSPs are acutely toxic for several weeks following break-up (Novatec Consultants, 1996). Rockne and Brezonik (2006) studied treatment processes in seasonal discharge WSPs in Minnesota. They showed that the predominant process contributing to ammonia removal in facultative WSPs was volatilization. Relatively high pH is required for this process to occur. Significant algal growth is necessary to achieve elevated values of pH, and associated ammonia removal, thereby necessitating autumn discharges.

5.1.3 Rational Design Models (Reactor Theory)

WSP design models have also been developed through the application of conventional chemical reactor design principles. Completely Mixed Flow Reactor (CMFR; Marais and Shaw, 1974), Plug Flow Reactor (PFR; USEPA, 1983) and Non-Ideal Flow (Thirumurthi, 1969) models have all been applied to performance assessment of WSP systems. With all three model types the processes controlling the removal of wastewater constituents are represented by a lumped first order rate constant (k). The rate constant can vary as a function of temperature as in the CMFR model of Marais and Shaw (1974) and the non-ideal flow model of Thirumurthi (1969), or as a function of temperature and BOD5 loading rate, as in the PFR model proposed by the USEPA (1983). An additional parameter required for the Thirumurthi model is the dispersion number. The USEPA compared the various design models in their guidance document, and noted that the commonly used empirical models (Gloyna Equation), PFR, and Thirumuthi models tended to produce similar results over a range of environmental conditions, but that the Marais and Shaw CMFR model produced unrealistic results for low temperature (< 5^{o}C) situations. These models have all been developed for the assessment of continuously discharging WSPs. Although The USEPA states that these design equations, in particular the PFR model, could be applied to intermittent discharge WSPs, there is little to no research to support this recommendation.

The selection of k is crucial to the use of rational design models, and various researchers have noted the sensitivity of WSP design to this parameter (Heaven et al. 2003; Kehl et al. 2009). Dillon Consulting (2006) used a simple PFR with a first order kinetics modeling approach to examine the influence of temperature and detention time on BOD removal within WSPs. They assumed a k_{20} value of 0.1 d^{-1}, a temperature correction coefficient of 1.06, and predicted the effluent BOD_5 concentration from WSPs operating at 3 – 7 ^{o}C, for detention times of 30, 60, and 120 days. They found that 90 days of treatment during the ice-free season would be required to achieve effluent BOD_5 concentrations less than 25 mg/L, assuming an influent concentration of 625 mg/L. Again, these types of models have not been parameterized and validated, with data from WSPs operating in an intermittent discharge mode in an arctic climate, and receiving variables quality and quantities of trucked sewage.

5.1.4 Process-Based Models

In recent years, a number of dynamic process-based models have been developed to simulate biological processes within wastewater treatment systems (Kayombo et al. 2000; Liwarska-Bizukojc and Biernacki, 2010). The most widely used modeling algorithms are those contained within the Activated Sludge Models (ASM) produced by the International Water Association (IWA). Although the algorithms were specifically developed for designing activated sludge treatment systems, they theoretically could be applied to any suspended growth biological wastewater treatment process. The ASM algorithms form the basis of the commercial software product, BIOWIN, which was developed and distributed by ECOSIM Software Ltd. The BIOWIN modeling system is becoming more widely used for the design and assessment of mechanical wastewater treatment systems, although there is little peer-reviewed literature on the parameterization and performance of the model. Liwarska-Bizukojc and Biernacki (2010) performed a sensitivity analysis with the most recent version of BIOWIN. They documented dozens of sensitive parameters that could be adjusted and calibrated, and concluded that the model would have to be calibrated with site-specific data. To date, no studies have been published in which BIOWIN, or the IWA ASMs, have been applied to WSP design.

5.1.5 Computational Fluid Dynamics

As computer technology has advanced, Computational Fluid Dynamics (CFD) has been more widely applied to the field of wastewater system process design. CFD-based simulation models numerically solve fundamental equations of mass, momentum and energy transfer within fluid systems. CFD models have been applied to wastewater WSPs and have proven to be very useful in evaluating mixing regimes and factors contributing to short-circuiting (Shilton and Harrison, 2002). This type of modeling approach would be useful for the analysis of continuously discharging systems, but would have limited use for the analysis of the stagnant, storage WSP systems commonly used in arctic climates.

5.1.6 Limitations and Gaps

The models and approaches currently used for designing facultative WSPs focus solely on the removal of BOD. There has been comparatively little research and development with respect to design equations for predicting the removal of TSS, microorganisms, or nutrients. It is typically assumed that the majority of suspended solids originating from the sewage will settle in the initial stages of the treatment process (USEPA, 2003). TSS measured at the outlet of WSPs with extended HRTs is usually comprised of algal and microbial biomass generated internally within the WSP. This internal generation of TSS during periods of algal growth and decay is a key issue to consider for the operation and assessment of WSP systems. The Ontario MOE recommends that intermittent sand filters be used for removal of suspended solids after WSP treatment, in order to meet TSS discharge criteria. Another key parameter that has received little attention is ammonia. For northern WSP systems, ammonia will be the wastewater constituent of most concern with respect to acute toxicity (Novatec, 1996). Mechanistic equations have been developed to predict ammonia removal rates as a function of temperature and pH (USEPA, 1983), but these models have not been validated for arctic conditions. In their survey of WSPs operating in cold climates, Novatec (1996) found that very few were capable or producing a non-acutely lethal effluent on a year-round basis. The Ontario MOE also recommends that intermittent sand filters be used for ammonia removal prior to discharge to the receiving environment.

The models presented in the previous sections were developed, parameterized and validated for continuous discharge WSPs. There is very little evidence supporting the ability to transfer these modeling approaches and design parameters to intermittent discharge systems. In particular, it is questionable as to whether first order rate constants that have been fit using performance data from a continuously discharging system can be applied to model stagnant storage WSPs.

All of these models were initially developed for southern climates. The majority of design approaches include either one or two climate related parameters as factors influencing performance and sizing. The environmental parameters that control the performance of a WSP operating in an arctic climate may be different, and/or the functional relationships between the environmental parameters and treatment performance may be different. For example, photoperiod is not included as a variable in any of the established models, yet this parameter will undoubtedly be an important parameter to consider for WSPs in the high arctic.

5.2 Wetland Design

Wetlands, both natural and constructed, have been used to treat a variety of wastewaters for several decades. The most widely used application of wetland technology is for secondary or tertiary treatment of domestic wastewater. Like WSPs, wetlands are viewed as simple technologies, however the processes governing the treatment performance are extremely complex and difficult to mechanistically model. Performance modeling approaches have evolved along the same path as for WSP systems.

Both natural and constructed wetlands have been used for wastewater treatment in the North. The use of natural wetlands can be advantageous as the hydrology, biological communities and geochemical environment have already been established, which decreases construction costs and start-up times. Disadvantages with the use of natural wetlands include the fact that most natural wetlands are not structured to provide hydraulic efficiency, and the possible alteration of valuable natural ecosystems due to the inputs of wastewater constituents. From an engineering perspective, issues associated with poor hydraulic efficiency, and the influence of external hydrologic fluxes on treatment processes, can be difficult to predict and manage.

Constructed wetlands are engineered systems that are designed to mimic the physical, chemical, and biological environment of natural wetlands. Constructed wetlands used for wastewater treatment can be configured and controlled to maximize hydraulic efficiency and treatment performance. Wetland treatment processes have been intensively studied during the past two decades. Kadlec and Wallace (2009) have provided a comprehensive summary and analysis of this literature. They also describe current approaches used to model wetland treatment performance. In this section, we will provide an overview of commonly used performance modeling techniques. The applicability, and challenges, associated with current state-of-the-art modeling techniques to the assessment of arctic wetland systems will be discussed.

5.2.1 Wetland Design Approaches

Methodologies for designing and modeling treatment wetlands are very similar to those used to design WSP systems. Categories of design equations/models include: (i) empirical methods, (ii) rational methods based on ideal chemical reactor design principles, (iii) rational methods based on non-ideal flow models, and (iv) process-based computer simulation models. Commonly used models have been thoroughly evaluated using data collected from treatment wetlands operating in southern climates. These same models have been applied to the design of wetland systems operating in arctic climates, but no studies have been published to date on the validation and applicability of these models in arctic environments.

5.2.2 Empirical Models

A number of researchers and agencies have proposed simple rule-of-thumb design criteria for wetlands treating domestic wastewater. These criteria have been summarized by both Kadlec and Wallace (2009) and Rousseau et al. (2004), and include recommended hydraulic retention times, areal BOD loading rates, hydraulic loading rates, and per-capita area requirements. Recommended ALRs for BOD_5 have ranged from 40 kg/ha-d to 100 kg/ha-d (Reed et al. 1988; USEPA, 2000). Recommended HRTs ranging from 2 - 14 days and hydraulic loading rates between 0.2 – 30 cm/d have been proposed (Rousseau et al. 2004; Alberta Environment, 2000). Doku and Heinke (1993) reviewed empirical design criteria for treatment wetlands, and suggested that hydraulic loading rates for wetlands operating in arctic regions should range from 100 – 200 m^3/ha-d, and that organic loading rates be limited to less than 8 kg BOD_5/ha-d.

In addition to the use of simple rule-of-thumb approaches, numerous researchers have attempted to develop empirical equations to predict treatment wetland performance using regression analysis. Primary parameters that have been related to treatment performance have included hydraulic loading rate, inlet concentrations, retention time, temperature, and solar radiation (Kadlec and Wallace, 2009). Rousseau (2004) provides a useful summary of the expressions that have been produced. However, regression-based equations have not been widely used for wetland design, as each equation would only be applicable to predicting treatment performance within a relatively narrow range of parameter values. Intersystem variability in wetland functioning and performance is a well-recognized issue that severely limits the use of these equations.

5.2.3 Rational Methods Based on Ideal Chemical Reactor Design Principles

The most widely used approach for modeling treatment performance within constructed wetlands is the use of a first order plug flow reactor equation. Kadlec and Knight (1996) proposed the use of this type of modeling approach, but also included background concentrations in the model to account for internal generation of pollutants within wetland environments. The model has been referred to as the k-C* model and has been promoted by numerous researchers (Rousseau et al. 2004), and included in design guidelines (Alberta Environment, 2000). The governing equation can be formulated using either a volume-based or area-based first order rate constant. The area-based rate constant formulation is recommend by Kadlec and Wallace (2009) as research has shown that rate constants can vary with water depth (Carleton and Montas, 2010). The k-C* model, however, has been repeatedly criticized within the literature. The primary criticism is related to the fact that numerous tracer studies have shown that both natural and constructed wetlands do not possess ideal plug flow hydraulics. Virtually all wetlands will possess a hydraulic regime that would be characterized as non-ideal, with a skewed distribution of residence times. Secondly, the simple k-C* model is often used in a deterministic manner, with designers computing treatment performance, or required retention time, based on a single estimate of the rate constant, inlet concentration, and hydraulic loading rate. It is now recognized that there is significant intrasystem and intersystem variability in all of these parameters. Thirdly, within first order models, all of the factors and processes that influence pollutant removal and transformation are represented by a static rate constant.

Several researchers have demonstrated that first order rate constants appear to be dependant on hydraulic loading rate, or retention time (Shepard et al. 2001; Jamieson et al. 2007). This phenomena is believed to be largely due to a “weathering” effect associated with many pollutants such as BOD, TP, etc, where easily biodegradable or settleable components of the pollutant category are removed quickly, leaving behind materials that are difficult to remove from solution (Carleton and Montas, 2010). However, despite these proven deficiencies, the use of the k-C* model is still promoted as the best available method (Rousseau, 2004; Crites et al. 2006). This is due to the fact that a large amount of information has been produced on the selection of first order rate constants. Rousseau et al. (2004) compared predictions, and levels of uncertainty, associated with empirical wetland models, first-order plug flow models, and complex process-based models, and concluded that the first-order plug flow model still remained the most reliable for wetland design. The empirical models were generally much too conservative, while complex, process-based models are not yet useful due to the inability to adequately parameterize these models.

The k-C* model is currently used within Alberta Environment’s guidance document for designing wetlands for wastewater treatment. The following model parameters are specified (Table 5.1), which were selected based on available information presented in Kadlec and Knight (1996):

Table 5.1 - Recommended k-C* model parameters provided in Alberta Environment's Guidelines for the Approval and Design of Natural and Constructed Treatment Wetlands for Water Quality Improvement (2000). Ci refers to initial concentration.

PARAMETER	k (m/yr)	C* (mg/L)
BOD5	34	3.5 + 0.053Ci
TSS	1000	7.8 + 0.063Ci
TP	12	0.05
TN	22	2
NH4-N	18	0
Org-N	17	1.5
FC	77	100 CFU/100 mL

The model parameter values presented in Table 5.1 were determined based on an analysis of performance data from hundreds of treatment wetlands throughout North America.

5.2.4 Rational Methods Based on Non-Ideal Chemical Reactor Design Principles

In the past 10 years advancements have been made in the use and validation of non-ideal hydraulic models for predicting treatment wetland performance. As mentioned in the previous section, it is well known that wetland hydraulic regimes rarely approximate ideal plug flow or completely mixed tank systems. Modeling approaches that have been used to simulate this non-ideal flow behavior include: (i) tanks in series (TIS) models (Kadlec, 2003), (ii) the advection-dispersion equation (Keefe et al. 2004), and (iii) stochastic-convective models (Carleton, 2002).

Both Kadlec and Wallace (2009) and Carleton and Montas (2010) are now recommending the use of the TIS modeling approach for treatment wetlands. The TIS model formulation is commonly used within the field of chemical engineering to simulate non-ideal flow behavior. The model contains two parameters: (i) a first-order rate constant, and (ii) α, which represents the number of tanks in the system. If a conservative tracer study is used to determine α, then the model has been termed the TIS wetland performance model. If however, α is treated as a fitting parameter, and is calibrated along with k using performance data, then the model is termed the "relaxed" TIS wetland performance model (Carleton and Montas, 2010). Carleton and Montas (2010) in their recent review state that the relaxed TIS model provides more flexibility in fitting, and allows the modeler to represent the "weathering" behavior associated with many contaminants. One issue associated with the use of the TIS modeling approach is that designers typically do not have the data necessary to calibrate or fit a relaxed TIS model, although Kadlec and Wallace (2009) suggest that many wetland systems can be adequately modeled using α equal to three. Another issue that needs to be addressed is that the majority of first-order rate constants reported in the literature have been computed, or fit, assuming plug-flow hydraulic behavior. These rate constants need to be re-derived using a TIS modeling approach.

A few researchers have also attempted to model wetland hydraulics and performance using the classical advection-dispersion equation (ADE). Keefe at al. (2004) modeled the transport of a reactive tracer in a surface flow wetland using a one-dimensional advection-dispersion equation that included a transient storage term, sorption, and first order decay. Several researchers have argued that the ADE may not be appropriate for wetland systems, as they typically do not possess true “Fickian” dispersion (Kadlec and Knight, 2009; Carleton and Montas, 2010). Carleton (2002) developed another alternative wetland performance model by conceptualizing a wetland as possessing a collection of separate flow tubes. Each tube would possess a different advective velocity and first order rate constant. They termed their model the “DND” model (Damkohler Number Distribution), or a “stochastic convective” model. Carleton and Montas (2010) compared DND model results to those produced from a relaxed TIS model. Although there were small differences in model performance they concluded that both models could adequately represent pollutant removal processes observed in most wetlands. They recommended that the relaxed TIS model be used in place of k-C* model for wetland design. Many researchers have commented on the inherent variability that should be expected when predicting or assessing treatment wetland performance (Werker et al. 2002; Kadlec and Wallace, 2009). Kadlec and Wallace (2009) presented a design approach that takes this expected variability into account. Wetland performance, and model parameters, should be evaluated in a stochastic, not deterministic, manner. This requires a solid understanding of intersystem and intrasystem variability in rate constants, inlet concentrations, hydrologic inputs, and environmental factors.

5.2.5 Process Based Computer Simulation Models

Process based models incorporate more sophisticated equations and algorithms for simulating treatment mechanisms. They can be formulated as either steady-state or non steady-state models, and can include compartmentalization of the treatment wetland to account for spatial variability in model parameters. The simplest of these types of models would be the use of a Monod-type expression for predicting treatment rates. This type of expression was used by Mitchell and McNevin (2001) to predict BOD_5 removal in a subsurface flow constructed wetland. This type of kinetic expression is more realistic than the simple first order model, as it accounts for the fact that treatment rates will eventually plateau as inlet concentrations increase. The disadvantage with this type of model is that it contains two parameters that must be estimated by the user.

Several researchers have developed more complicated process-based models; an example would be the model developed by Wynn and Liehr (2001) to simulate treatment processes in subsurface flow wetlands. The model consists of a complex set of coupled equations describing carbon and nitrogen processing, bacterial growth and decay, and oxygen production and consumption. The model contains 42 different input parameters, and 15 initial conditions must be specified. Rousseau et al. (2004) compared this type of model to simpler first order approaches and concluded that for practical applications, a process-based model would provide little utility due to parameterization challenges. Other process-based models have been developed or used by

Langergraber et al. (2009), Toscano et al. (2009), and Ojeda et al. (2008). Kumar and Zhao (2011) reviewed many of these models, and concluded that process-based models for describing contaminant removal with treatment wetlands are still in their infancy stage of development. Considerable work must be undertaken before they can be reliably applied by practitioners working in the field of treatment wetland design.

5.2.6 Examples of Arctic Wetland Design Methodologies

Treatment wetland planning and design studies have been completed for several Nunavut communities during the past five years. Earth Tech Inc., in collaboration with Wetland Management Services, recently completed a treatment wetland planning study for the community of Kimmirut (Earth Tech 2008). The planned future system for municipal wastewater management in Kimmirut calls for a two-cell detention WSP system which would discharge partially treated effluent to a 15 ha natural wetland complex during the ice-free season. A TIS wetland performance model was used to assess the treatment that would be expected by the wetland system. As there was very little data available on the hydrologic and hydraulic functioning of the wetland, it was assumed that 20% of the wetland area would be active in wastewater treatment, and that the hydraulic regime could be approximated as a series of three completely mixed tank reactors. The hydraulic inputs to the model accounted for wastewater flows, evapotranspiration and precipitation. The study authors utilized performance data and first order rate constants from southern wetlands, and applied temperature adjustments for certain wastewater parameters. The authors used a probabilistic approach for selecting k-values, generally selecting values on the lower end of the probability distribution (15 – 25 % percentiles) (Table 5.2).

Table 5.2 - Values of model parameters used within the Kimmirut Wetland Study.

PARAMETER	k_{20} (m/yr)*	k_5 (m/yr)**	C* (mg/L)
BOD_5	35 (25th)	35	20
TSS	35	35	20
TP	2 (15th)	2	0.002
TN	15	6	1.5
NH_4-N	8 (25th)	4	0
Org-N	10 (25th)	10	1.5
FC	83 (50th)	83	50 CFU/100 mL

* k_{20} refers to the rate constant at 20 degrees Celsius
** k_5 refers to the rate constant at 5 degrees Celsium

In this study they assumed that only the nitrogen parameters (TN and NH4-N) would be affected by lower temperatures. The major uncertainty associated with their modeling approach was related to the hydraulic functioning of the wetland system. However, by assuming that only 20% of the wetland contributed to treatment, and using lower values of literature-derived rate constants, they felt that their assessment was conservative.

Wetland Management Services also conducted a performance assessment of a 3 ha natural wetland for polishing WSP effluent in the community of Cambridge Bay (Kadlec et al. 2008). Based on the wetland area, an assumed wetland depth of 30 cm, and predicted wastewater loading rates during the summer season, they estimated that the wetland would provide a two-week detention time. They applied a first order TIS model to predict the wetland treatment performance. They specified that the k values for TSS and BOD_5 removal were 50 and 30 m/yr, respectively. They did not specify the values used for nutrient and microbial parameters, but noted that they assumed lower rate constants than those used for southern wetlands.

Dillon Consulting attempted to predict the treatment performance of a small 160 x 100 m natural wetland receiving WSP effluent in Kugaaruk (Dillon Consulting, 2008). They applied the modeling procedure (k-C* model) and rate constants specified in the Alberta Environment wetland design guidelines, assuming that the entire wetland area was active in wastewater treatment. Based on these computations they concluded that the wetland was of sufficient size to meet the desired effluent quality objectives. They noted that the anticipated hydraulic and organic loadings to the wetland exceeded those proposed by Doku and Heinke (1993), but felt that those guidelines were too generic, and that the wetland should be monitored to determine appropriate hydraulic loading criteria.

Nunami Jacques Whitford completed a performance assessment of a large 20 ha natural wetland receiving effluent from a detention WSP in Coral Harbour. They simply assumed a hydraulic loading rate (HLR) of 0.2 cm/d, and computed the required wetland area based on anticipated sewage loading rates. Based on this computation they predicted that approximately 7 ha of wetland area would be required for treatment. Based on the fact that 20 ha of wetland was available for treatment, and that they used a relatively conservative HLR, they expected the wetland to meet effluent quality objectives.

These case studies have illustrated the variability in modeling approaches, rate constant selection, and level of assessment currently undertaken within wetland planning studies in Nunavut. It is clear that consultants are currently required to make significant assumptions with regards to hydraulic functioning and treatment kinetics.

5.2.7 Limitations and Gaps

A considerable body of literature has been produced on the topic of treatment wetland performance and modeling. The current generation of rational-based models (TIS) should be applicable to the simulation of treatment processes in arctic wetlands. However, there are two primary issues that currently limit the use of these modeling approaches for assessing wetlands receiving municipal wastewater effluents in Nunavut:

The models that have been discussed were developed and validated primarily for constructed wetlands operating under relatively steady-state conditions. Northern treatment wetlands are typically natural, or non-engineered systems, that operate under very dynamic conditions (i.e. they are intermittently loaded during the summer months). It can be extremely challenging to accurately define the physical boundaries, hydrologic fluxes, and flow pathways within natural wetland systems. As well, many northern wetlands currently used for wastewater treatment are comprised of both surface and subsurface flow wetland components. Adequately defining the physical and hydrologic characteristics of these systems is critical to understanding and modeling their treatment performance. Understanding and accounting for temporal dynamics in hydraulic and pollutant loading will also be a critical issue for design of northern treatment wetlands. This may involve the application of a non steady-state modeling approach, which can be implemented with the current generation of performance models, or the identification of worst-case scenarios for design purposes. This will be especially important if the wetland will be relied upon to provide treatment of pollutants that can cause acute environmental or human health effects (i.e. ammonia, enteric microorganisms).

We currently do not have adequate data from field scale arctic wetlands to generate estimates of kinetic parameters (first order rate constants). It is possible that kinetic parameters that have been derived from the non-summer seasons for wetlands operating year-round in cold climates would be representative of kinetics in arctic wetlands. It is also possible that treatment kinetics within arctic wetlands are different than those observed in temperate climates due to fundamental differences in the types and diversity of microbial populations.

These issues need to be assessed through detailed field studies of operational field scale arctic systems, which would include a thorough characterization of both wetland hydraulics and treatment performance. This would allow for the derivation of treatment rate constants for arctic systems. Other factors that should be assessed include effluent composition, hydraulic loading rates and distribution between surface and subsurface flow. Also, a number of wetlands must be studied in order to develop an understanding of the level of intersystem variability.

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7.0 List of Abbreviations

ADE Advection Dispersion Equation

ALR Areal Loading Rate

ASM Activated Sludge Model

BOD5 Five Day Biological Oxygen Demand

CCME Canadian Council of Ministers of Environment

CFD Computational Fluid Dynamics

CMFR Completely Mixed Flow Reactor

DO Dissolved Oxygen

EDO Effluent Discharge Objective

EQO Environmental Quality Objective

FC Fecal Coliform

HRT Hydraulic Retention Time

HLR Hydraulic Loading Rate

K First order rate constant

PFR Plug Flow Reactor

TIS Tanks in Series

TSS Total Suspended Solids