Guidelines for the Design and Assessment of Tundra Wetland Treatment Areas in Nunavut

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List of Abbreviations

%	Percent
τ_n	Nominal Retention Time
°C	Degrees Celsius
APHA	American Public Health Association
BOD_5	Five-Day Biochemical Oxygen Demand
C^*	Background Concentration
$CBOD_5$	Five-Day Carbonaceous Biochemical Oxygen Demand
CGS	Community and Government Services
cm	Centimetre
CCME	Canadian Council of Ministers of the Environment
CFU/100 mL	Colony Forming Units per 100 mL
CWRS	Centre for Water Resources Studies
d	Day
d_w	Depth of Water
DEM	Digital Elevation Model
DO	Dissolved Oxygen
E. coli	*Escherichia coli*
e.g.	*Exempli gratia*
EC	Environment Canada
et al.	*Et alii*
ET	Evapotranspiration
g	Gram
GN	Government of Nunavut
GPS	Global Positioning System
ha	Hectare
HLR	Hydraulic Loading Rate
Hr	Hour
HRT	Hydraulic Retention Time
I	Infiltration

i.e.	*Id est*
ICP-MS	Inductively Coupled Plasma Mass Spectrometry
ISE	Ion Selective Electrode
K	Hydraulic Conductivity
k	Areal First Order Rate Constant
k_{20}	Areal First Order Rate Constant Normalized to 20°C
k_{fs}	Field Saturated Hydraulic Conductivity
kg	Kilogram
km	Kilometer
kPa	Kilopascal
L	Litre
m	Metre
m^2	Square Metre
m^3	Cubic Metre
mg	Milligram
mL	Millilitre
MPN/100mL	Most Probable Number of Colony Forming Units per 100mL
N	Number of Tanks
n	Sample Number
n_e	Effective Porosity
NH_3-N	Un-ionized Ammonia Nitrogen
NPS	National Performance Standards
NU	Nunavut
NWB	Nunavut Water Board
NWT	Northwest Territories
O&M	Operation and Maintenance
ORP	Oxidation Reduction Potential
P	Precipitation
P	Apparent Number of Tanks
PET	Potential Evapotranspiration

PVC	Polyvinyl Chloride
Q	Discharge
RTD	Residence Time Distribution
RWT	Rhodamine WT
SSF	Subsurface flow
TAN	Total Ammonia Nitrogen
TIS	Tanks-In-Series
TN	Total Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solids
U.S. EPA	United States Environmental Protection Agency
UV	Ultraviolet
VSS	Volatile Suspended Solids
WS	Wetland Segment
WSER	Wastewater Systems Effluent Regulations
WSP	Wastewater Stabilization Pond
WTA	Wetland Treatment Area
WTAC	Wastewater Treatment Advisory Committee
WWTP	Wastewater Treatment Plant
μg	Microgram

Executive Summary

This document provides *Guidelines for the design and assessment of tundra wetland treatment areas in Nunavut.* The guidelines were prepared by the Centre for Water Resources Studies (CWRS) at Dalhousie University for the Community and Government Services (CGS) department of the Government of Nunavut (GN). The guidelines are a deliverable of a research contract on municipal wastewater infrastructure in Nunavut funded by the GN and granted to CWRS. The guidelines provide regulators with a standardized framework for the assessment of tundra wetland treatment areas (WTAs). Furthermore, the guidelines are meant to provide engineers and wetland designers with tools to safely design and implement tundra WTAs.

Sixteen out of twenty-five of the hamlets in Nunavut treat municipal wastewater with a wastewater stabilization pond (WSP) in combination with a tundra WTA. The WTAs are distinctly different from natural tundra wetlands typical of Nunavut due to their hydrology, nutrient availability, vegetation and organic loading. WTAs are also different from constructed wetlands due to the minimal engineered control of the WTAs. Uniquely, each tundra WTA is defined by the effluent influx, yet controlled by the natural characteristics of each site.

Water quality improvements have been documented in many of these tundra WTAs and in cold climate conditions in peer-reviewed literature. However, there has been a lack of design criteria and modeling tools to initiate the formal design process due to the limited comprehensive datasets from the WTAs. The territorial regulators are beginning to recognize the treatment potential of tundra WTAs; however, the approach for assessment is not standardized. Additionally, until recently there has been a lack of data to support the formation of guidelines. In recognition of the need for design guidelines, and in light of new data on the functioning of existing systems, the design guidelines within this document were developed. The guidelines are based on the research findings of the CWRS research program and the current best practices in treatment wetland design.

The design guidelines are presented as a recommended series of steps for existing and new proposed WTAs in Nunavut. The initial step consists of a desktop mapping analysis of an existing or proposed WTA. A site-specific study proposal is developed based on the desktop mapping findings and reviewed by the Nunavut Water Board (NWB). Public consultation is recommended early on in the site-specific study. The site-specific study comprises of: a detailed characterization of the physical and biological environments; hydraulics of the WTA; and hydrological and hydrogeological settings; and a treatment performance assessment.

Results from the comprehensive site-specific studies are used to parameterize a modified tanks-in-series (TIS) model for the site, founded on the *P-k-C** first order model by Kadlec and Wallace (2009). There are slight variations of the modeling approach, depending on whether the site is existing or a new proposed WTA, and whether the flow is characterized predominately by surface or subsurface flow. The full range of conditions expected for the site is used to model the

expected treatment performance. The requirement for system upgrades are assessed based on whether or not the current WTA can meet the treatment objectives. After the performance modeling, a long-term monitoring plan is established. The final design documentation of a WTA is reviewed by the NWB. Ongoing annual monitoring and reviews of the WTAs are recommended.

The adoption of this standardized framework for the design and assessment of new proposed and existing WTAs will reduce the uncertainties in their performance. These guidelines allow for an engineered approach to reduce the risks to human health and the environment within these unique and functionally important tundra WTAs.

Preface

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

The design guidelines presented herein are founded on the research outcomes obtained during the grace period. It is hoped that the guidelines will provide the framework needed to enable: (i) the informed and safe use of tundra wetland treatment areas, and (ii) a standardized framework for regulatory bodies to assess the wetland treatment areas in Canada's Far North.

This guideline document has been written by the Centre for Water Resources Studies (CWRS) at Dalhousie University. The Community and Government Services (CGS) department of the Government of Nunavut (GN) awarded funding to CWRS to conduct site-specific research programs at select study sites in Nunavut. The site-specific studies took place during the summer treatment seasons from 2011 to 2013. The findings from the site-specific research programs are presented as a separate document titled *"Summary of site-specific studies on tundra wetland treatment areas in Nunavut"* (CWRS, 2015). The funding was also granted to develop design guidelines herein based on the site-specific research findings.

Treatment wetland technologies and best management practices for design have evolved significantly over recent years. The authors chose to base the design guidelines on the most recent design practices in the industry with slight modifications to account for the inherent differences between *constructed wetlands* and *tundra wetland treatment areas*. There are frequent references throughout this document to the well-known *Treatment Wetlands* textbook resource by Kadlec and Wallace (2009). This resource is internationally regarded as the most comprehensive assembly of information on treatment wetlands and was a major source of information for this guidance document. Readers looking for additional wetland design guidance are encouraged to refer to the Kadlec and Wallace (2009) textbook.

1.0 Introduction

1.1 Purpose

This document provides a proposed framework to govern the design and use of tundra wetland treatment areas for applications in municipal wastewater treatment in the Arctic. The document is specifically focused on tundra wetland treatment areas located in hamlet communities in Nunavut, Canada. Until recently, there has been a lack of information on the design and performance expectations of tundra wetland treatment areas. As a result, standardized recognition of tundra wetland treatment areas as a process step in the wastewater treatment train in the Far North has been challenging.

The proposed guidelines herein have been written specifically for the target audiences of regulators and engineers. This document aims to provide territorial and federal regulators with a standardized framework for the assessment of tundra wetland treatment areas. While, the proposed guidelines provide tools for engineers to facilitate the design and performance assessment of tundra wetland treatment areas.

1.2 Wastewater treatment in Nunavut

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

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

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

1.3 Tundra wetland treatment areas

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

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

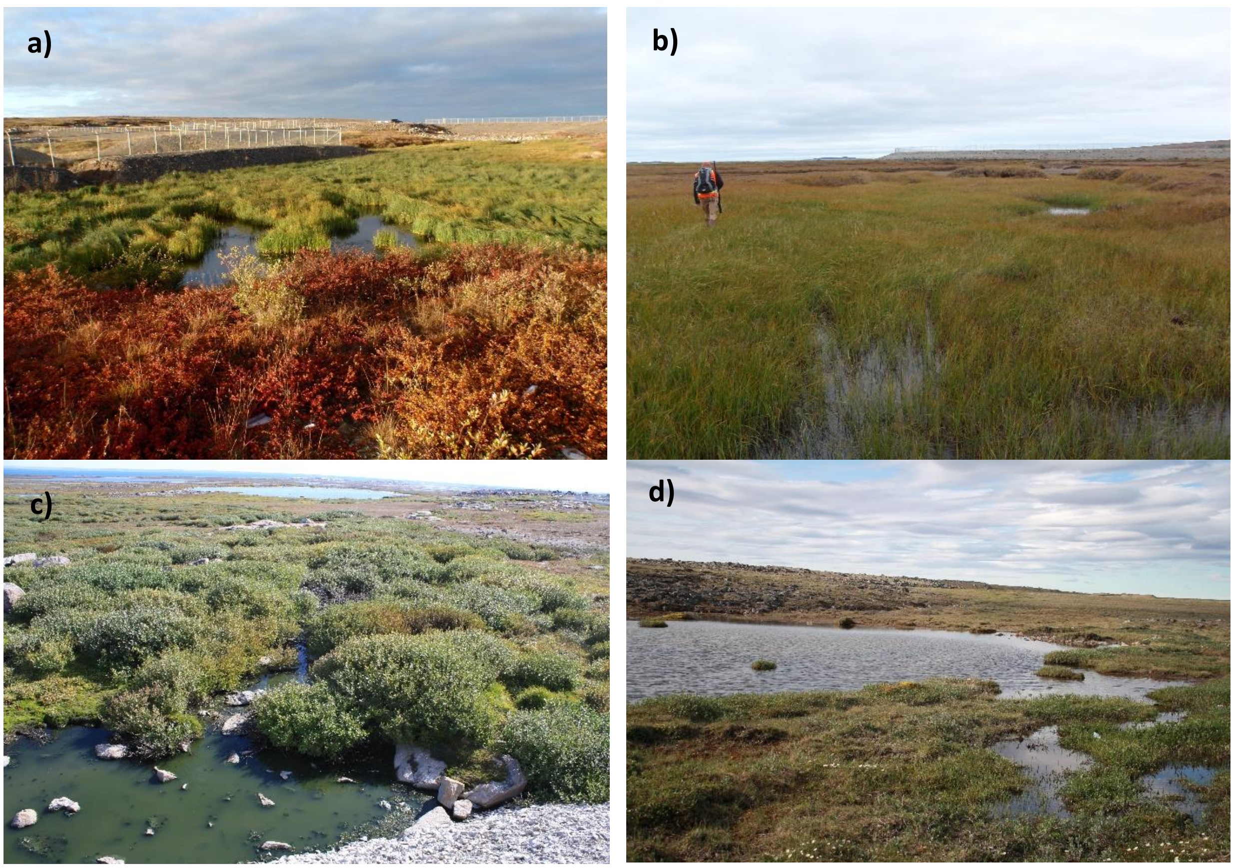

FIGURE 1. PHOTOGRAPHS OF: (A) THE WTA IN KUGLUKTUK, NU TAKEN ON AUGUST 30, 2012, (B) A NATURAL WETLAND IN KUGLUKTUK, NU TAKEN ON AUGUST 30, 2012, (C) THE WTA IN CORAL HARBOUR, NU TAKEN ON SEPTEMBER 4, 2011, AND (D) THE REFERENCE NATURAL WETLAND IN CORAL HARBOUR, NU TAKEN ON JULY 11, 2012.

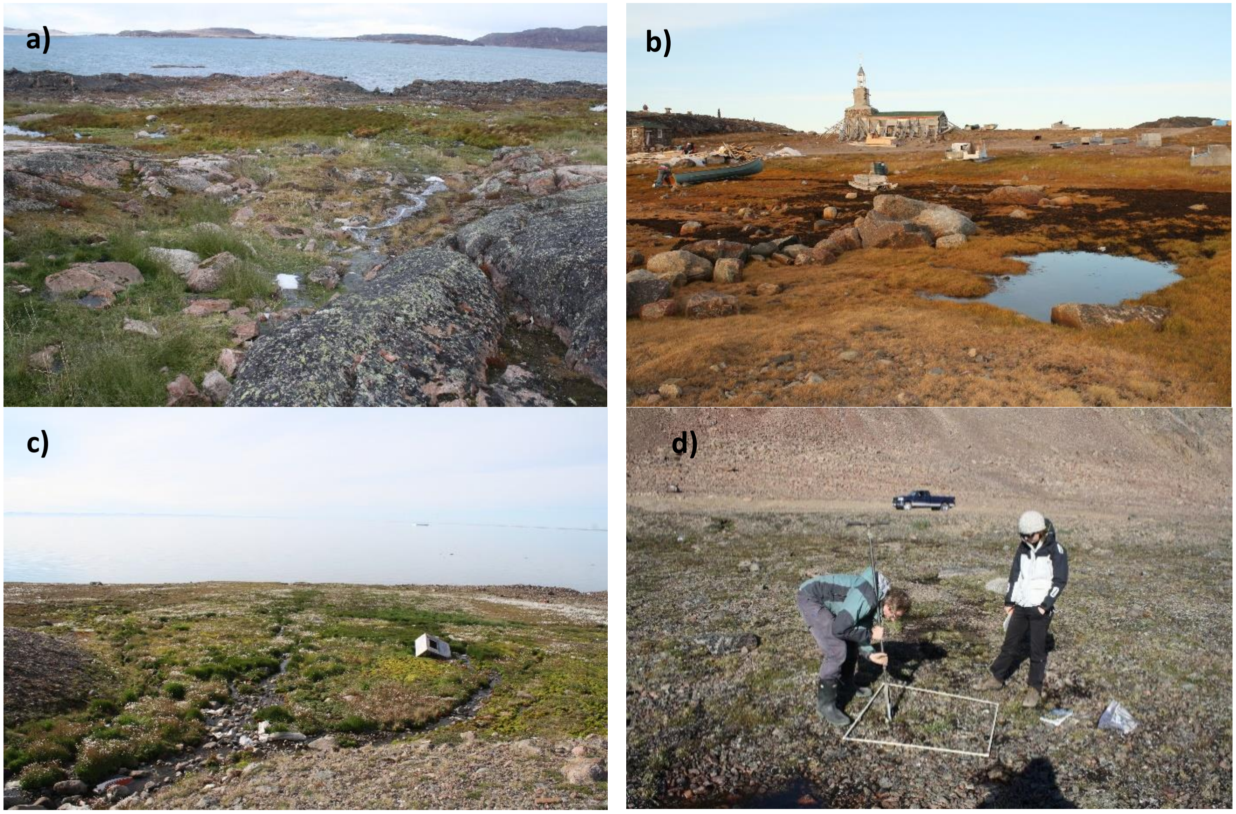

FIGURE 2. (A) THE WTA IN KUGAARUK, NU TAKEN ON SEPTEMBER 5, 2012, (B) A NATURAL WETLAND IN KUGAARUK, NU TAKEN ON SEPTEMBER 11, 2012, (C) THE WTA IN GRISE FIORD, NU TAKEN ON JULY 27, 2011, AND (D) THE REFERENCE NATURAL WETLAND GRISE FIORD, NU TAKEN ON AUGUST 3, 2011.

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

To date there have been studies that have repeatedly demonstrated that the tundra WTAs in Canada's Far North can contribute to water quality improvements of municipal wastewater effluent streams (Doku and Heinke, 1993, 1995, Wright 1974, Dubuc 1986) . In more recent studies, tundra WTAs have been shown to be capable of frequently meeting southern Wastewater Systems Effluent Regulations (WSER) set by Environment Canada (EC) (Government of Canada, 2012, Yates et al., 2012, Hayward et al., 2014, Hayward, 2013, Hayward et al., 2012, Chouinard et al., 2014a, Yates et al., 2014). Tundra WTAs are starting to become recognized for their treatment potential by the Nunavut Water Board (NWB), which are the territorial regulators. There are still uncertainties in performance expectations and a lack of published best practices for conducting WTA assessments. This means that the recognition and management of tundra WTAs is not consistent across the territory.

Tundra WTAs present a low cost and low maintenance option for secondary and tertiary levels of treatment in Nunavut. The uncertainties with their use will likely be reduced with comprehensive site-specific datasets to verify whether adequate treatment is provided. The comprehensive site-specific studies and ongoing monitoring programs will be costly; however, these studies will, in many cases, still be significantly more economical than conventional wastewater infrastructure with large associated capital and O&M costs. The WTAs will also be less prone to the operational failure observed with existing WWTP technology in northern communities.

1.4 Design procedures

There has been a succession of sizing procedures developed over the evolution of treatment wetland technology. The approach taken in these guidelines is to adopt the current best practices used by wetland designers. There are different design approaches that may be used to predict performance for treatment wetlands which generally include:

i) Empirical models,
ii) Ideal chemical reactor models,
iii) Process based models, and
iv) Non-ideal chemical reactor models.

To date it has been up to the wetland designer to select the methodology for performance modeling for treatment wetlands in Northern Canada. Most significantly, there has been a lack of data on treatment rate constants appropriate for an arctic setting. Therefore, wetland designers have extrapolated rate constants derived for southern systems (Hayward and Jamieson, 2015). The following section introduces each of the modeling methodologies and discusses their respective applicability for design of tundra WTAs.

Empirical methods have been used to predict the treatment performance of wetlands. These methods are based on site-specific data where relationships are developed between influent and effluent data, and other parameters, such as hydraulic loading rate. These methods have been described as black-box models because of their inability to represent internal wetland hydraulics (Kumar and Zhao, 2011, Rousseau et al., 2004). Similarly, loading charts, which are plots of contaminant effluent concentrations versus mass loading, have been used to model subsurface flow (SSF) wetlands. Loading charts are not ideal for northern applications because the data used to form them are all located in warmer climates. Initial work on treatment wetlands in Northwest Territories by Doku and Heinke (1993, 1995) recommended prescriptive areal hydraulic loading rates ranging from 100 to 200 m^3/ha-d, and a maximum organic loading rate of

8 kg BOD_5/ha-d. This type of rule of thumb methodology should only be used as a check on other calculations. This is because they are not based on site-specific data and it cannot be verified whether or not the effluent concentrations will meet performance standards.

The *k*-*C** ideal chemical reactor model by Kadlec and Knight (1996) has been used extensively by wetland designers. Within this model, *k* is the first order rate constant, and *C** is the background concentration of contaminant. Plug flow hydraulic behavior within the wetland is assumed. Notably, the Alberta wetland model (Alberta Environment, 2000) recommended the use of the *k*-*C** model for design of constructed and natural treatment wetlands in Alberta. More recently, the model has been demonstrated to produce non-conservative effluent concentrations (Kadlec, 2000). Furthermore, the rate constants have been shown to be dependent on variables including influent concentrations, hydraulic loading rates, and hydraulic retention times (Kadlec and Wallace, 2009, Carleton and Montas, 2010, Hayward and Jamieson, 2015). The use of the *k*-*C** model has been superseded in recent years by new methods that more accurately represent the internal hydraulics of treatment wetlands.

Process-based models are another option for modeling treatment performance of wetlands. This type of model uses a series of differential equations within a computer model to simulate individual treatment processes occurring within treatment wetlands. One challenge with using these types of models is that they require complex parameterization that render simpler approaches such as the *k*-*C** or tanks-in-series (TIS) models more favorable for practical design purposes (Rousseau et al., 2004).

Chouinard et al. (2014a, 2014b) used the horizontal SSF SubWet 2.0 software model by UNEP (2014) to model the treatment performance of a total of twelve tundra WTAs. The SubWet 2.0 model uses 25 differential process equations and 16 rate coefficients to solve for expected effluent concentrations (Jørgensen and Fath, 2011). Chouinard et al. (2014a, 2014b) recommended the use of SubWet 2.0 as a design tool for modeling tundra wetland treatment areas. The model was calibrated by adjusting the rate coefficients to produce effluent concentrations close to those measured in the field. It is not known how the calibrated rate constants from the Chouinard et al. (2014a, 2014b) modeling compared to literature values from wetlands in warmer climates. It is not possible to compare the rate constants that were calibrated for cold climates in the SubWet 2.0 model to the rate constants from more widely used first order models because of fundamental differences in the model assumptions including representation of the internal hydraulics, and the formulation of treatment rate expressions (Hayward and Jamieson, 2015). Chouinard et al. (2014a) indicated that site-specific data is the best option for parameterizing the model due to intersystem variability.

Subwet 2.0 was developed for wetlands characterized predominantly by SSF. However, many of the tundra WTAs have a large component of surface flow, especially early in the treatment season, when the active layer depth is minimized. The surface flow component is not represented with the SubWet 2.0 model. A surface water modeling technique is required to represent the treatment performance in many of the tundra WTAs in Nunavut.

Most recently, the non-ideal chemical reactor model approach has been the preferred approach by most designers to predict the treatment performance of wetlands. The advantage of this type of model is that it can represent the internal hydraulic behavior of treatment wetlands (Kadlec and Wallace, 2009, Carleton and Montas, 2010). A common version is the *P-k-C** model for performance based wetland design, which is a TIS model developed by and described in detail by Kadlec and Wallace (2009). Within the *P-k-C** model, the hydraulics of the treatment wetland are represented conceptually by a set of batch chemical reactors in series (i.e., *P* is the apparent number of tanks). The authors of this report believe that this model is the most appropriate for northern applications due to the (1) ability to model non-ideal hydraulics and incorporate external hydrologic influences; (2) reasonable input data requirements; and (3) relatively straightforward model set-up (Hayward and Jamieson, 2015).

Since the tundra WTAs are different than constructed wetlands, some modifications to the conventional sizing procedures are required. For instance, the area of the constructed wetland is typically the unknown variable that is optimized in the design process, whereas, tundra WTAs have pre-defined areas governed by the natural terrain and substrate of the site. For this reason, the expected treatment performance for a given wetland area should be calculated. If the wetland does meet target concentrations, then options for system upgrades should be considered. The proposed modifications to the traditional design sizing procedures are detailed in Section 3 of this document.

2.0 Summary of findings from Dalhousie University studies

The CWRS at Dalhousie conducted site-specific studies of three tundra wetland treatment areas in Nunavut from 2011 to 2013. Detailed information on the studies are provided in the report *"Summary of site-specific studies on tundra wetland treatment areas"* prepared for the CGS department of the GN (CWRS, 2015). The findings from these studies informed the formation of this design guideline document. In summary, the main findings of the site-specific studies are listed as follows:

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

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

ii) Temporal changes in treatment performance require special consideration.

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

iii) A modified tanks-in-series mass balance modeling approach can be used as a tool to predict performance expectations in tundra WTAs.

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

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

In the Coral Harbour, NU study, the minimum areal rate constant normalized to 20°C (k_{20}) for five-day carbonaceous biochemical oxygen demand ($CBOD_5$) fell below the 5^{th} percentile, the k_{20} for *Escherichia coli* (*E. coli*) and total ammonia nitrogen (TAN) was within the 40^{th} percentile, and the k_{20} for TN fell below the 10^{th} percentile.

3.0 Framework for site-specific studies

3.1 Overview of the framework

This section of the report describes a proposed framework for conducting site-specific performance assessments of existing or proposed tundra WTAs. It is anticipated that the outcomes of the application of the framework will:

i) reduce uncertainty in performance expectations;
ii) provide a standardized methodology to facilitate engineering of complex and unique ecological systems; and
iii) enable regulatory oversight to ensure protection of human health and the environment.

Figure 3 illustrates the process steps and the regulatory oversight for the proposed framework. The framework would be applied to existing WTAs that have been receiving municipal wastewater effluent, and for use in planning new proposed WTAs. For the purposes of this document, ***existing wetlands are defined as areas of the tundra that are currently receiving wastewater. Proposed new wetlands are defined as areas of the tundra that are under consideration but not currently receiving wastewater***.

The initial step is the desktop mapping to inform the site-specific study proposal. The proposal undergoes regulatory review by the NWB. After approval, a public consultation program is initiated in conjunction with a site-specific data collection program. The site-specific data collection program characterizes the physical and biological environments, hydraulics, hydrology, hydrogeology, and assesses the treatment performance and biogeochemistry of the site. The data collected from the site-specific study is used to inform the performance model for the site. The performance model is developed and used to estimate performance of the WTA. If the modeling results do not meet the regulatory requirements, prior to discharge into the receiving environment, then options for upgrades should be assessed and re-modeled, as an iterative process. If the modeling results meet the regulatory requirements, then a long-term monitoring plan is established and implemented. The findings from the site-specific study are submitted to and assessed by the NWB. Ongoing annual monitoring and data annual reviews are recommended to verify that adequate treatment is provided after approval of the design and operation of the system.

3.2 Implementation of the framework

It is strongly recommended that in no instance is data from one WTA extrapolated to another WTA. Due to the natural attributes of the WTAs, the intersystem variability will be even greater than with constructed wetlands. Each WTA should undergo an individual site-specific study. In addition, the components of the framework should be adopted in entirety, and not in a piece-meal form. All of the elements of the framework should be included in the site-specific studies except when there is scientific basis to eliminate a step (i.e., forgo hydraulic conductivity measurement if the site is characterized by surface flow).

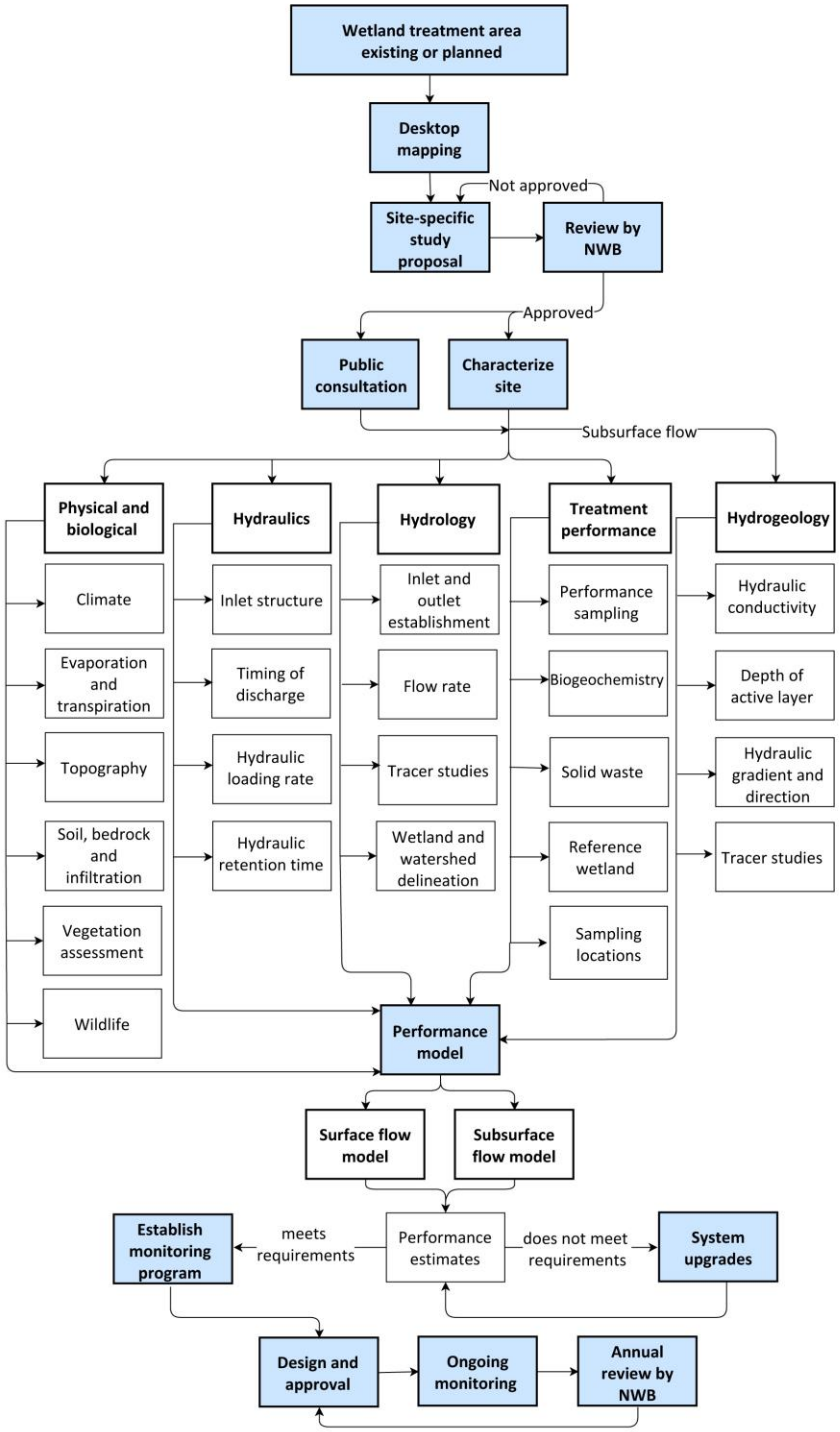

FIGURE 3. OVERVIEW OF PROPOSED SITE-SPECIFIC PERFORMANCE ASSESSMENT AND REGULATORY FRAMEWORK FOR TUNDRA WTAS.

3.3 Timing and frequency of data collection

The seasonal variations in hydraulic, hydrological, hydrogeological, and biogeochemical characteristics affect the treatment performance of tundra WTAs. For this reason, it is necessary to conduct site-specific studies at key times during the treatment season depending on the type of WTA.

- For existing WTAs, decanted at scheduled times during the treatment season, the timing of the data collection should be centered around anticipated decant schedules.
- For existing WTAs, which discharge continually over the treatment season, the timing of the data collection should capture both the spring freshet and post-freshet discharge conditions. Furthermore, the post-freshet conditions should be characterized during the middle and at the end of the treatment season.
- For proposed WTAs, the site-specific data should be collected during the anticipated time period for decanting or discharging of the WTA.

The WTA should be sampled at a frequency capable of capturing changes in hydraulic loading rates and changes in seasonal conditions. If discharge into a WTA occurs during the spring freshet, then a minimum of three performance samples and flow measurements should be collected at the inlet and outlet, during the spring freshet and post-spring freshet conditions, respectively (i.e., 6 total). If the discharge into a WTA is less than 2 weeks in length, then a minimum of three samples and flow measurements should be collected at the beginning, middle, and end of the decant. If the discharge into a WTA is greater than two weeks in length, then a minimum of three samples and flow measurements should be collected at the beginning, middle, and end of the decant, and one additional sample and flow measurement per each additional 2 weeks of discharge.

3.4 Type of wetland treatment area

There are two types of WTAs: (1) surface flow, and (2) subsurface flow. Some wetlands are characterized predominately by either surface flow or subsurface flow. Whereas, some wetlands exhibit a combination of surface and subsurface flow. The data collection and performance modeling approach is based on the predominant flow type characteristic of the WTA.

3.5 Desktop mapping

Commencement of the site-specific assessment of a WTA consists of a desktop mapping analysis. The objective of the desktop mapping is to assemble readily available information on the WTA prior to the commencement of the field data collection program. The desktop mapping will inform the planning of the site-specific study and associated proposal. The information that should be assembled in the desktop study includes, but is not limited to, the following list of items.

- Design drawings and technical reports of existing wastewater infrastructure.
- Existing water licence requirements.

- Historical water quality and performance data (if available).
- Annual municipal report to water board with usage estimates for water licence renewals.
- Aerial photographs/satellite images.
- Bedrock and surficial geology.
- Site topography.
- Population growth estimates.
- Demographic information.
- Historical climate data.

3.6 Proposed regulatory review

The site-specific assessment process would benefit from regulatory review at two specific steps. A review of the site-specific performance assessment proposal would be beneficial prior to field based data collection to ensure that all relevant areas of the framework are addressed. This initial review would reduce the likelihood of improperly conducted or inadequate assessments. The final review of the design and operation application would ensure that uncertainties with performance expectations are minimized. Ongoing annual review of the monitoring data would ensure that potential long-term changes in treatment performance are identified and adverse effects mitigated.

3.7 Site-specific study proposal

The purpose of the site-specific study proposal is to verify that the data collection program will adequately address all the relevant items detailed in the guidelines. The verification of the proposal by NWB prior to the commencement of the on-site work will reduce the risk of repeat site visits due to incorrectly performed studies. The proposal should include, but not be limited to, a detailed description of the:

i) Objectives of the study.
ii) Frequency of performance sampling events.
iii) Plan for laboratory and sample analysis.
iv) Milestones of the site characterization.
v) Methodology for data collection and analysis.
vi) Schedule for fieldwork, analysis, and reporting.
vii) Plan for public consultation.
viii) Deliverables of the study.

3.8 Public consultation

The community should be consulted during the site-specific study phase. The community consultation should involve at least one open attendance community meeting in the hamlet hosted by the agency responsible for conducting the site-specific study. Additional meetings may be required on a case-by-case basis. The meeting(s) should be well advertised on the community radio station, with posters in the community, and at the hamlet office, in advance of the meeting date. The meeting(s) and all meeting materials should be provided in bilingual languages of English and Inuktitut. Municipal infrastructure managers from the hamlet should be encouraged to attend the session(s), especially the water and wastewater foreman.

The public consultation should address the following items:

- An introduction to treatment wetland science.
- Overview of the role of tundra WTAs in Northern wastewater treatment.
- Plan view maps showing the location and extent of the proposed or existing WTA.
- Provision of educational and interactive materials to ensure knowledge continuity after the meeting.
- Overview of the plan for long-term management of the proposed or existing WTA.
- Discussion of the importance of the non-disturbance of the WTA to avoid human contact with pathogens and to ensure the preservation of vegetation.
- Training session(s) on the proper handling of bird eggs, waterfowl and mammals used for food consumption that may have come into contact with pathogens from wastewater.
- Description of the public signage to be installed at the WTA.
- Discussion with foreman and operators and site visit to locations of the compliance sampling points (if feasible).
- Introduction and provision of the names and contact information of key long-term managers for the infrastructure.
- Provision of opportunities for questions and comments to be asked from the public and provide an avenue for discussion beyond the meeting timeframe.

The training session on the proper handling of bird eggs, waterfowl and mammals used for food consumption may require separate consultations in the community. It is recommended that a specialist in game handing and food safety be tasked with hosting this training session. The local Hunters and Trappers Association should be contacted and involved in these training sessions. Media materials should be distributed, such as posters and brochures, for public awareness of the importance of proper bird egg and game handling.

There may be a need to hold a separate session or series of sessions in the communities to ensure that adequate public awareness has been created on the aforementioned topics. The proceedings and outcomes of the public consultation should be summarized in the application for design and operation approval of the WTA to the NWB.

3.9 Safety considerations

Additional safety measures must be taken beyond standard field and wastewater safety practices for site-specific studies in tundra WTAs. These additional measures are recommended because many of the tundra WTAs are located a distance from the hamlet communities, and are in close proximity to solid waste disposal facilities, which attract polar bears.

Fieldwork should be completed with a minimum of two personnel. A professionally trained polar bear monitor is recommended to accompany personnel on all site work. The polar bear monitor accompanies the field personnel to protect all personnel from the threat of polar bears.

All field personnel should be trained at minimum in standard first aid, but ideally in wilderness first aid. Some of the sites may be located at a distance from the hamlets. Therefore field personnel should be knowledgeable about first aid practices, and be equipped with a well-stocked first aid kit. All field personnel should be up-to-date on relevant vaccinations for wastewater handling.

It is the responsibly of the agency conducting the work to ensure a field safety plan and job hazard analysis is in place prior to the commencement of work.

3.10 Physical and biological characterization

3.10.1 Climate

The preliminary collection of climate data is completed during the desktop mapping analysis. Many hamlet communities in Nunavut have Environment Canada weather stations that log weather data such as precipitation, atmospheric pressure, and temperature. This data is available free for download from the Government of Canada historical climate data records. For sites that do not have a nearby weather station, it is recommended that a site-specific weather station be deployed for the duration of at least one entire treatment season. The site-specific data can then be compared to the closest available Environment Canada website. This will enable the formulation of factors of safety to apply to the design in absence of historical long-term climate datasets.

3.10.2 Evapotranspiration

The amount of evapotranspiration should be estimated for the site. This estimation may be performed a variety of different hydrometeorological equations such as the Penman equation or Priestley-Taylor method. An approximation of the potential evapotranspiration (PET) may also be formulated. The PET is an estimation of the amount of water that would be evaporated or transpired if sufficient water were available. Hayward (2013) chose to estimate the PET for a site-specific wetland study on a WTA. The method used by Hayward (2013) to estimate PET was developed by Hamon (1963) and summarized in Dingman (2002). According to Dingman (2002) and Hamon (1963) the PET (mm/d) may be estimated with the following equation:

$$PET = 29.8 \cdot D \cdot \frac{e_a{}^*}{T_a + 273.2} \quad \text{[Eq. 1]}$$

where D is the day length (hr), $e_a{}^*$ is the saturated vapor pressure at mean daily air temperature (kPa), and T_a is the mean daily air temperature (°C).

The saturated vapor pressure may be calculated using an equation from Dingman (2002) as follows:

$$e_a{}^* = 0.611 \cdot exp(\frac{17.3 \cdot T}{T + 237.3}) \quad \text{[Eq. 2]}$$

Where T is the temperature (°C).

The day length D (hours) may be calculated using the following equation (Dingman, 2002):

$$D = T_{hr} + |T_{hs}|, \quad \text{[Eq. 3]}$$

where T_{hr} (hours), and T_{hs} (hours), are the time of sunrise and sunset in relation to solar noon given by (Dingman, 2002):

$$T_{hr} = -\frac{cos^{-1}[-tan(\delta) \cdot tan(\Lambda)]}{\omega}, \quad \text{[Eq. 4]}$$

and

$$T_{hs} = +\frac{cos^{-1}[-tan(\delta) \cdot tan(\Lambda)]}{\omega} \quad \text{[Eq. 5]}$$

where ω is the angular velocity of the earth's rotation (15°/hr = 0.2618 radian/hour), Λ is the latitude (decimal degrees), δ (decimal degrees) is the declination of the sun given as follows (Dingman, 2002):

$$\delta = \left(\frac{180}{\pi}\right) \cdot [0.006918 - 0.399912 \cdot cos(\Gamma) + 0.070257 \cdot sin(\Gamma) - 0.006758 \cdot cos(2 \cdot \Gamma) + 0.000907 \cdot sin(2 \cdot \Gamma) - 0.002697 \cdot cos(3 \cdot \Gamma) + 0.00148 \cdot sin(3 \cdot \Gamma)], \quad \text{[Eq. 6]}$$

and Γ (radians), is the day angle determined by (Dingman, 2002):

$$\Gamma = \frac{2 \cdot \pi \cdot (J - 1)}{365} \quad \text{[Eq. 7]}$$

where *J* is the day number (J = 1 on January 1 and J = 365 on December 31).

3.10.3 Topography

The topography of the site should be determined. The spatial extent of the topographic dataset required will depend on the size of the watershed of the WTA. Topographic surveying may be necessary at sites that require high spatial resolution topographic data. Low spatial resolution topographic data is available for download online from Natural Resources Canada.

3.10.4 Soil, bedrock and infiltration

The surficial soil may be identified according to the Unified Soil Classification System ASTM D2487-11 (2011). The type of bedrock geology present at the site should be identified. Surficial and bedrock geology maps should also be consulted for the study area and summarized in the design documentation. The rate of infiltration of water into the surficial soil should be estimated. There are a variety of methods available including the Green-Ampt method and Darcy's Law. Typically the chosen method requires an estimation of the hydraulic conductivity of the soil (*K*). The estimation of hydraulic conductivity is detailed in greater detail in Section 3.13.1. It may be found that there are seasonal changes in infiltration, with limited infiltration occurring during the early treatment season, due to shallow depth of the active layer. Seasonal changes in infiltration should be characterized.

3.10.5 Vegetation assessment

The vegetation in the WTA should be identified. It is recommended that this work be carried out by a qualified botanist and/or wetland delineator trained in tundra vegetation identification. There are several methods for vegetation assessment that may be used. Quadrats are a useful way to quantify vegetation in a specific sample location. A useful reference for conducting vegetation assessments in wetlands is the U.S. EPA document on "*Methods for evaluating wetland condition: using vegetation to assess environmental conditions in wetlands"* (U.S. EPA, 2002). A local resource for vegetation identification for plants specific to Nunavut is provided in Mallory and Aiken (2004).

For existing wetland treatment areas, changes to the native natural vegetation have likely already occurred. It may be useful to conduct transects across the effluent flow path(s) in the WTA. A baseline survey in a reference wetland is recommended to provide a means for identification of community shifts from the native natural wetland vegetation. The locations of the transect sample points should be positioned with a GPS.

For proposed wetland treatment areas, the anticipated changes to the native natural vegetation are unknown. Therefore, it is useful to conduct a baseline study in the WTA prior to use for wastewater treatment, to enable change monitoring over the lifespan of the wetland. It may be useful to conduct transects across the anticipated flow path(s), perpendicular to the slope of the site. The locations of the transect sample points should be positioned with a GPS.

Mitigation strategies, such as reducing loading rates, should be explored when vegetation die-off is observed. Hayward et al. (2014) suggested that research is needed to assess the optimization of nutrient and organic loading rates for various species of tundra wetland vegetation.

3.10.6 Wildlife

There is a risk for transmission of pathogens to humans by egg collection, as well as, waterfowl and game handling for food consumption. Due to this human health risk, the species of terrestrial and avian wildlife that frequent the WTA should be identified during the site-specific studies. The community members should be engaged during the public consultation process with training sessions on the proper handling of bird eggs and game for food consumption.

3.11 Hydraulic characterization

3.11.1 Inlet structure

The inlet structure controls the hydraulic loading into the WTA. There are several different techniques that are used in existing systems in Nunavut to disperse effluent onto the WTAs. Ideally, the inlet structure should provide flow control and disperse flow over a wide area. Currently, the types of inlet structures that discharge influent into the WTAs in Nunavut include:

i) A pump powered by a generator.
The manual decant may occur once or twice over a treatment season for a few days to weeks, or as required. The pump is used to lift water from the WSP into the WTA as a point source input.

ii) A decant structure with overflow.
Effluent is pumped manually into a decant structure as scheduled. The decant structure acts to distribute the influent over a wide area. The decant structure reduces the velocity of the influent entering the wetland which would decrease the likelihood of scouring and re-suspension of sediments. The decant structure may provide additional settling of solids.

iii) Exfiltration out of the berm.
Exfiltration can have the potential advantage of filtration of the effluent through berm media prior to discharge into the WTA. A disadvantage is that in many cases, the effluent loading onto the WTA is uncontrolled. Unintentional ongoing flow through a berm may compromise the integrity of the berm.

iv) Decant pipes built into the berm.
These decant pipes have been installed in many WSPs, and may or may not have heat tracing. However, they have rarely been demonstrated to function or to be used. This is usually the result of them being frozen and/or rusted solid for most of the treatment season.

v) **Direct discharge.**

In some existing systems, raw effluent is discharged directly onto WTAs. This practice should be discouraged and replaced with a minimum of primary treatment prior to discharge into a WTA.

vi) **Seepage to groundwater**

In unlined WSPs, seepage from the bottom and sides of the WSP can add influent non-directly to the WTA. This contribution to the wetland loading is difficult to measure and may bypass the inlet structure. This contribution may change seasonally as the depth of the active layer changes with soil thawing.

There is opportunity for new types of inlet structures to be used for design of new WTAs. Flow control is important to be able to optimize the hydraulic loading onto the wetland. Inlet structures which disperse the influent over a wide area improve the hydraulic efficiency of the WTAs. Low flow inlet structures with deep zones for settling would encourage settling of solids and enhance vegetation growth downgradient of the structure, and discourage re-suspension.

3.11.2 Timing of discharge

Currently, there are existing systems that decant in an uncontrolled manner during the spring freshet. Ideal discharge or decant of effluent into WTAs should occur during the middle of the summer and/or the end of the treatment season. This will allow for time for the vegetation to become productive, for water temperatures to rise, and to avoid high flows from melting water. Discharge of wastewater into WTAs when melt flows are high during the spring freshet should be avoided. If possible, it is beneficial to extend the discharge period out over a long time frame at a low hydraulic loading rate.

3.11.3 Hydraulic loading rate

The hydraulic loading rate (HLR) is the rate at which influent is applied to the wetland treatment area. The HLR (cm/d) onto the WTA is calculated with the following:

$$HLR = \left(\frac{Q_{in}}{A_w}\right) \cdot 100 \quad \text{[Eq. 8]}$$

where Q_{in} is the influent discharge into the WTA from the WSP (m^3/d), and A_w is the wetted area of the WTA observed in active flow (m^2).

Doku and Heinke (1993) recommended an HLR for WTAs of between 1 – 2 cm/d (100 and 200 m^3/ha-d). Based on recommendations in Kadlec and Knight (1996), Alberta Environment (2000) recommended HLRs ranging from 0.2 cm/d (20 m^3/ha-d) for secondary treated effluent, to 0.5 cm/d (50 m^3/ha-d) for nitrified secondary effluent, for natural treatment wetlands. In cases where five-day biochemical oxygen demand (BOD_5), total suspended solids (TSS), and total phosphorus (TP) are reduced in the pretreatment step, an HLR of 2.5 cm/d (250 m^3/ha-d) was recommended (Alberta Environment, 2000).

HLRs at other northern Canadian WTAs were estimated at 0.43 cm/d (43 m^3/ha-d) for a 7 ha wetland in Teslin, Yukon; 0.63 cm/d (63 m^3/ ha-d) for a 32 ha wetland in Hay River, NWT; and 1.25cm/d (125 m^3/ ha-d) for 6 ha wetland in Haines Junction, Yukon (Doku and Heinke, 1993 and 1995).

The hydraulic loading rate may change over the treatment season and this variation should be quantified. A maximum HLR of 2.5 cm/d is recommended for WTAs in Nunavut. There may be WTAs that work better at lower HLRs that may be optimized based on the long-term monitoring program data.

3.11.4 Hydraulic retention time

The hydraulic retention time (HRT) is representative of the average amount of time required for water to move through the wetland. An HRT of 14 to 20 days is recommended for a natural treatment wetland (Alberta Environment, 2000; Kadlec and Knight, 1996). For an existing WTA, the HRT can be determined by conducting a tracer test. Seasonal variation in hydraulic loading rates may present the requisite for multiple tracer tests to characterize the range of HRTs. Methodologies for conducting tracer studies are detailed in Section 3.12.3.

For design cases where the WTA is proposed, the nominal HRT, τ_n (days), should be calculated. The nominal HRT of a WTA is represented by Kadlec and Wallace (2009) as follows:

$$\tau_n = \frac{V_n}{Q} \qquad \text{[Eq. 9]}$$

where V_n is the nominal wetland volume (m^3), determined as the product of the wetted area and the average depth of the wetland. The flow (Q) is typically taken as the influent flow (m^3/d). Exceptions to the assumption of influent flow arise in WTAs that have external hydrologic contributions.

For cases where external hydrologic contributions are significant, the nominal HRT should be adjusted. The nominal HRT can be adjusted, τ_{an} (days), according to the following equation (Charazenc, 2003; Kadlec and Wallace, 2009):

$$\tau_{an} = \tau_i \left(\frac{ln(R)}{R-1}\right) \qquad \text{[Eq. 10]}$$

where τ_i is the inlet flow-based nominal residence time (d), $R = \frac{Q_o}{Q_i}$, is the water recovery fraction (dimensionless), Q_i is the inlet flow rate (m^3/d), and Q_o is the outlet flow rate (m^3/d).

It is recommended that the WTAs in Nunavut should have a minimum nominal hydraulic retention time of 14 days. This will provide a factor of safety in the design, because even at 50% efficiency, the WTA will still have an actual HRT of 7 days. This will increase the likelihood that the effluent resides in the WTA for a sufficient amount of time to provide adequate treatment.

3.12 Hydrological characterization

3.12.1 Inlet and outlet establishment

The establishment of the inlet and outlet locations for a WTA is recommended to ensure consistent and representative sampling. The inlet and outlet locations should be specified in the design. The geographic coordinates of the inlet and outlet locations should be stated. If there are multiple inlet and/or outlet locations, then all the coordinates of the points should be listed. Tracer tests may be used in cases where the locations of the inlet and/or outlet are not clear. The tracer tests can provide a visual or quantitative indication of the inlet and outlet locations.

3.12.2 Flow rate

The influent and effluent flow rates and variability should be characterized. The most common method for flow measurement is stream gauging. Stream gauging is ideal for locations where there is a defined channel with surface flow. For systems that are decanted, an ultrasonic flow meter could be used to measure flow in the decant hose. When flows are sufficiently low from decant hoses, a bucket and timer method may be used to measure flow. For sites characterized by variable flow over a long time period, continuous automated flow measurement can be achieved with *in situ* monitoring of water depth, combined with discharge measurement at various flow rates, to develop a depth-discharge relationship.

External hydrologic contributions should also be characterized. Stream gauging points should be established at locations along the effluent flow path where water from external hydrologic contributions are suspected to enter the wetland. The tracer study may be helpful to discern where external hydrologic contributions may be entering the wetland.

For proposed WTAs, the influent flow can be estimated based on water use data from the NWB water licence. The effluent flow can be estimated by completing a water balance on the WTA and accounting for external hydrologic contributions from the watershed.

3.12.3 Tracer studies

Tracer studies involves the injection of the conservative tracer upstream in the wetland and measurement of the tracer concentration over a time profile at a point downstream. For existing WTAs, tracer studies are a tool to allow for determination of the: (1) HRTs; (2) wetted area; (3) inlet and outlet locations; and (4) intermediate sampling locations. Multiple tracer studies may be required for a site if there is considerable variability in the hydraulic loading rates and site hydrology. Ideally, the flow rate should remain relatively constant over the duration of the tracer study.

3.12.3.1 Tracer selection

There are many types of tracers for surface water tests. The most common are fluorescent dyes, such as Rhodamine WT (RWT), and salt tracers, such as lithium and bromide salts. A major advantage of dye tracers over the salt tracers is the visual indication of water movement within the wetland. Dye tracers tend to adsorb onto particulate and organic matter in the water column and become degraded with long term UV exposure. Generally, RWT is a suitable tracer for wetlands with a HRT of less than a week (Headley and Kadlec, 2007). Therefore, salt tracers are better candidates for wetlands with long HRTs or SSF wetlands. The tracer should be non-reactive in water and non-toxic.

3.12.3.2 Background concentration

The background concentration of the selected tracer should be measured for a period prior to the tracer test. This is especially important if a tracer test with the selected tracer has previously been used in the test area of the wetland.

3.12.3.3 Hydraulic residence time determination

The determination of the HRT based on the tracer data can be completed by using a moment analysis of the residence time distribution (RTD) curves generated from the tracer tests. The output of a tracer test is a concentration versus time curve, which is termed a tracer response curve, represented by the notation C(t) (µg/L or mg/L). The measured concentrations from the tracer response curve require correction. The correction is performed by subtracting the averaged background from the measured concentrations obtained from the tracer tests.

The RTD curve is a fractional representation of the amount of tracer that still exists in a wetland (or chemical reactor) at a particular time after tracer injection into the flow path. The common notation for the RTD is denoted by E(t) (dimensionless). The RTD is defined by Fogler (2006):

$$E(t) = \frac{C(t)}{\int_0^\infty C(t)dt} \qquad \text{[Eq. 11]}$$

The mean residence time, τ (minutes), of the WTA is determined by taking the first moment of the RTD as defined by Fogler (2006):

$$\tau = \int_0^\infty tE(t)dt \qquad \text{[Eq. 12]}$$

The tracer response and RTD curves can be numerically integrated using Simpson's rule quadrature formula which is demonstrated in Fogler (2006).

3.12.3.4 Tracer injection

The mass of tracer should be selected to produce a downstream concentration of tracer that is within the detection range of the instrumentation to be used to analyze the samples. Kadlec and Wallace (2009) suggest using a peak tracer response concentration of at least 50 times the minimum detection limit of the tracer. An estimation of the mass of tracer, M_{in}(g), required to obtain the target concentration at the termination point of the tracer may be calculated according to the re-arranged equation from Kadlec and Wallace (2009) as follows:

$$M_{in} = C_t V_n \qquad \text{[Eq. 13]}$$

where C_t is the target concentration at the tracer termination point (g/m^3), and V_n is the nominal wetland water volume (m^3). The tracer should be injected over a prolonged time interval such that the ambient discharge at the injection location is minimally increased to avoid the formation of density gradients (Dierberg and Debusk, 2005). The tracer should be diluted with water collected from the injection area to sufficiently avoid the formation of density gradients.

3.12.3.5 Monitoring techniques

Depending on the tracer type, the tracer concentrations may be measured *in situ* with instrumentation, or sampled and transported to an analytical laboratory. *In situ* monitoring will produce the results on site in real time. Therefore, sampling strategies and subsequent tracer tests may be optimized during a site visit. However, the monitoring instrumentation may not be readily available. Therefore samples may need to be collected in bottles and transported to a laboratory for analysis within the respective holding time of the tracer.

Fluorescent dye tracers can be measured *in situ* with optical fluorometers, or in the laboratory with spectrophotometers or fluorometers. Salt tracers can be measured *in situ* with Ion Selective Electrode (ISE) probes or in the laboratory with ISE probes, ion chromatography, or Inductively Coupled Plasma Mass Spectrometry (ICP-MS).

The flow rate should be monitored at the injection point and the downstream outlet over the course of the tracer study to verify for quasi-steady-state flow conditions and facilitate the mass recovery calculation.

3.12.3.6 Sampling frequencies

Headley and Kadlec (2007) suggest that 30 to 40 samples are sufficient to define the tracer response curve. The peak and rising and falling limbs of the tracer response curve should be well defined. The sampling frequency can be decreased for the tail end of the tracer response curve.

In situ monitoring devices, such as optical or ISE probes, can enable fine-scale sampling frequencies and may be preferred for systems that have short HRTs. If the HRTs are expected to be long (e.g., greater than a week), then *in situ* monitoring devices can collect data in absence of field personnel on site.

Automatic samplers powered by a battery may be used to collect samples in absence of field personnel on site. They can be programmed to collect samples at defined intervals during the tracer test. The number of samples collected from automatic samplers are limited by the number of sample bottles, which is commonly 24.

Grab samples can be collected to obtain discrete samples during the tracer test. The limitation of this method is the requisite for personnel. Therefore, grab sampling is not well suited for wetlands with long HRTs.

3.12.3.7 Mass recovery

The mass recovery of the tracer should be verified for each tracer test. This ensures that the tracer accurately represents the hydraulics of the wetland system. The mass recovered may be calculated with the following equation from Kadlec and Wallace (2009):

$$M_o = \int_0^\infty Q_o\, C(t)dt = ? = M_i \qquad \text{[Eq. 14]}$$

where C(t) (g/m^3) is the exit tracer concentration, M_i (g) is the mass of tracer introduced with inflow, M_o (g) is the mass of tracer exiting with outflow, and Q_o is the average outflow rate (m^3/d).

3.12.4 Wetland delineation

A delineation of existing WTAs on site is recommended. The wetland delineation will enable the determination of the wetted area available for treatment. The wetland areas should be recorded with GPS instrumentation (+/- 10 m accuracy). Wetland delineation should be performed in accordance with the guidelines in the US Army Corps of Engineer Wetlands Delineation Manual (Environmental Laboratory, 1987).

The delineation of existing wetland areas is recommended for proposed WTAs. It is possible that there may be no wetland areas present for sites where a new system is to be implemented. The total required wetland area, A_w (m^2), anticipated for new systems is determined from the performance modeling procedure. The area required to meet treatment performance targets is optimized iteratively. The total estimated wetland area is obtained by adding the existing natural wetland area to the wetland area guess as follows:

$$A_w = A_g + A_e \qquad \text{[Eq. 15]}$$

Where, A_e is the existing natural wetland area (m^2), and A_g is the wetland area guess that is optimized to obtained target concentrations for treatment performance (m^2).

Hydraulic structures may need to be incorporated into the design to ensure the wetland area required is obtained.

3.12.5 Watershed delineation

The watershed of existing and proposed WTAs should be determined. The watershed delineation can be done manually with a topographic map or automated with software (e.g., ArcHydro tool in ArcGIS). The outlet of the WTA determined from the site visit is used to set the outlet of the watershed. The area of the watershed should be calculated from the topographic map or within a software program after delineation.

Digital Elevation Models (DEMs) are required for automated delineation of watershed areas. Low spatial resolution DEMs (approximately 20 m) are typically available free for download from Natural Resources Canada. Depending on the complexity of the hydrology of the site, a detailed topographic survey may be necessary to generate a DEM of sufficient spatial resolution to compute the watershed delineation.

3.13 Hydrogeological characterization

The hydrogeological setting requires consideration only for WTAs that are significantly characterized by subsurface flow.

3.13.1 Hydraulic conductivity

The hydraulic conductivity of the soil (K) should be characterized. A falling head permeameter, or a slug or bail test, may be used to determine the field saturated hydraulic conductivity (K_{fs}). The methodology will depend on the method chosen to assess the field saturated hydraulic conductivity. Alternatively, hydraulic conductivity can be determined by collection of soil samples and analysis in a soil materials laboratory. A method for laboratory analysis is the constant head standard test method ASTM D2434-68 (2006). The laboratory method is less desirable, and should only be used to verify *in situ* methods, because disturbance of the soil will increase the hydraulic conductivity.

3.13.2 Depth of active layer

The depth of the active layer should be determined if possible. A handheld earth auger may be used to reach a depth of refusal. If possible, seasonal changes in the depth of the active layer should be measured.

3.13.3 Hydraulic gradient and direction of groundwater flow

The hydraulic gradient and direction of groundwater flow should be characterized when sites are characterized predominately by SSF. Observation wells can be used to assess the hydraulic gradient and direction of groundwater flow. Typically, a minimum of three observation wells positioned in triangular formation are required. Additional wells may be useful depending on the site conditions.

The borehole for the observation wells can be extended using a handheld earth auger. The depth of the well should extend to refusal if possible. The observation wells may be constructed with PVC casing and screened pipes with diameters of approximately 2.5 to 5 cm. The casing and screens can be either screwed together with the pre-made pipe threading or connected using pipe couplers. The bottom of the well should be fitted with a well point plug and the top should be sealed with a locking compression plug cap. The length of screened sections for each observation well should be chosen to ensure that the water level measured within the well falls within the screened section of the well. The casing section of the pipe should extend from the high water level to a minimum height of 10 cm above the ground to avoid well contamination from surface flow. The well bore should be backfilled with clean silica sand and the top 15 cm of the well bore should be sealed with bentonite clay.

After construction, the observation wells require development by pumping the equivalent of three well volumes from the well. The elevation of the top of the casing of each observation well should be determined with a survey technique, such as differential leveling. Relative difference in elevations between wells is sufficient to determine the hydraulic gradient. The position of each observation well should be determined with GPS. The depth to water in each observation well should be measured with a water level meter.

The hydraulic gradient and direction of groundwater flow can be determined by plotting the survey, and water table elevation to scale, and determining the potentiometric surface. Alternatively, a gradient method may be used such as the Microsoft Excel spreadsheet developed by Devlin (2003). The average linear velocity, v (m/s), of the groundwater can be estimated with the following equation from Fetter (2001):

$$v = \frac{K_{fs} i}{n_e} \qquad \text{[Eq. 16]}$$

Where i is the hydraulic gradient (m/m), and n_e is the effective porosity (dimensionless). The effective porosity should be estimated based on the soil characteristics present on site. The hydraulic gradient is given by:

$$i = \frac{h_i - h_o}{L} \qquad \text{[Eq. 17]}$$

Where h_i (m) is the head of water at the inlet of the WTA, h_o (m) is the head of water at the outlet of the WTA, and L (m) is the longitudinal horizontal distance between the two head measurements.

The advective time of travel, t (days), through the groundwater flow area is estimated with:

$$t = \frac{d}{v} \cdot 60\ seconds \cdot 60\ minutes \cdot 24\ hours \quad \text{[Eq. 18]}$$

where d is the horizontal distance of travel (m).

3.13.4 Groundwater tracer studies

Tracer studies in groundwater require special considerations beyond the items described in Section 3.12.3. Fluorescent dye tracers are not ideal for subsurface applications due to sorption of the dye to soil media. They may be used as a supplementary tracer for visual indication of groundwater flow. However, measurements for quantification of HRT should be based on transport of a conservative tracer. Movement of a tracer in groundwater may occur over a long time period therefore automated monitoring with *in situ* probes may be advisable. Monitoring of groundwater tracer movement is facilitated by sampling observation wells down gradient of the injection area. A hand-operated vacuum or peristaltic pump or other suitable low-flow pump may be used to obtain water samples from the observation wells.

3.14 Treatment performance assessment framework

3.14.1 Pre-treatment recommendation

Treatment wetlands are not designed as a front end treatment process and should be used exclusively for provision of secondary or tertiary levels of treatment. Doku and Heinke (1995) and Yates et al. (2012) recommended that a minimum of primary treatment should occur prior to effluent discharge into WTAs. Their recommendation should be adopted to ensure that the solids and organic matter loading into the WTAs do not overwhelm the vegetation. A minimum of primary pre-treatment is recommended for proposed and existing WTAs.

3.14.2 Performance parameters and biogeochemistry

The treatment performance assessment may include analyzing for the following suite of common wastewater parameters including: $CBOD_5$, *E. coli*, TSS, volatile suspended solids (VSS), TN, TAN, un-ionized ammonia nitrogen (NH_3-N), and TP. The biogeochemistry of the WTA should be characterized with the measurement of water quality parameters of temperature, specific conductivity, pH, dissolved oxygen (DO), and Oxidation Reduction Potential (ORP). The treatment performance parameters should be analyzed according to the *Standard methods for the examination of water and wastewater* (APHA, 2012).

3.14.3 Solid waste considerations

In many of the hamlets in Nunavut, the wastewater treatment facilities are located in close proximity to the solid waste facilities. This poses challenges for assessment of the tundra WTAs because it may be difficult to ascertain whether contaminants originating in the solid waste facility migrate into the WTA. It may be possible for additional contaminants to be added into the wetland from the solid waste treatment facility leachate either by surface flow or subsurface flow. Landfill leachate can contain heavy metals, acidic pHs, organics, and other more complex contaminants.

There are few steps that should be taken to determine whether there is interaction between the municipal wastewater effluent and the landfill leachate. These steps include:

i) A watershed delineation of the WTA which will give an indication whether surface leachate from the landfill may be entering the wetland.
ii) Visual inspection of the down gradient area of the landfill to verify for potential seepage into the WTA.
iii) Installation of observation wells down gradient of the landfill to facilitate subsurface leachate sample collection and analysis.

If leachate is suspected to enter the WTA, treatment performance samples should be collected upstream and immediately downstream of the leachate plume. If possible, an estimation of the flow rate of leachate entering the WTA should be obtained. This additional loading to the WTA must be considered as part of the performance modeling assessment. The WTA may require upgrades if landfill leachate contributes excessive additional contaminants such that target effluent quality objectives at the wetland outlet cannot be met.

3.14.4 Reference wetland

A reference wetland is a natural wetland that is similar to the WTA. The hydrology, geology and physical characteristics of the reference wetland should be as similar as possible to the WTA. The reference wetland should be located upstream or hydraulically disconnected from the WTA or proposed WTA. A minimum of three performance samples is recommended to be collected from the reference wetland at different times during the study. The data from the reference wetland is necessary to obtain the background contaminant concentrations (C^*) to parameterize the treatment performance model. Additionally, the reference wetland provides a benchmark for comparison of vegetation community deviations from native natural tundra wetland conditions.

3.14.5 Sampling location and frequency

The influent and effluent, from the inlet and outlet locations respectively, should be sampled. A minimum of three samples of both influent and effluent is recommended. If discharge into a WTA occurs during the spring freshet, then three samples should be collected at the inlet and outlet, during the spring freshet, and post-spring freshet conditions respectively. Ideally these would be collected at the beginning, middle, and end of the discharge into a WTA. If discharge into a WTA occurs over a period of greater than 2 weeks, then one additional set of influent and effluent samples per 2 weeks of decant is recommended. Composite samples for influent and effluent may be collected instead of discrete samples except for microbiological parameters. Composite samples should not exceed a 12 hour collection time frame.

Intermediate performance samples may be recommended for wetlands that are large in surface area or characterized by complex flow patterns. Specifically, if multiple tracer studies are required to characterize a particular hydraulic condition within a WTA, then intermediate performance samples should be collected at the injection point of each tracer test. When intermediate sampling is undertaken, a minimum of three samples per sample location should be collected. If discharge into the WTA occurs over a period of greater than 2 weeks, then one additional set of samples is recommended per each 2 weeks of decant.

3.14.6 Positioning of sample locations

The locations of all sample points taken in a WTA and reference wetland should be positioned with GPS. Each sample point should be physically identified with the installation of a secure sign post with the identification label of the point. This will ensure consistent sampling throughout the lifespan of the WTA.

3.14.7 Conditions for suspended solids exemptions

Algae growth in a WTA has been shown to sometimes increase suspended solids concentrations within the wetland above influent concentrations (Hayward et al., 2014). It is recommended that performance sampling for suspended solids be exempt during periods when significant algae is present. It is recommended that the exemption be applied for suspended solids when the water is visibly green in color, when pH is above 8.5, and when the DO concentration is above 10 mg/L. To verify the presence of algae, chlorophyll a analysis may be coupled with suspended solids analysis. When chlorophyll a concentrations are greater than 50 μg/L, the suspended solids exemption should be applied.

3.14.8 Conditions for pathogen exemptions

Waterfowl have been suspected to add a source of fecal indicator bacteria to wetland treatment areas (Hayward et al., 2014, Yates et al., 2012). During periods when migratory waterfowl are present within a WTA it is recommended that fecal indicator bacteria (e.g., *E. coli*) be exempt from analysis.

3.14.9 Proximity to accredited laboratories

Consideration must be given to geographic distance to an accredited laboratory capable of completing the analysis on the treatment performance samples. Select parameters have holding times within which the analysis must be completed. Some parameters such as $CBOD_5$ and *E. coli,* have sample holding times of only 24 hours after sample collection, and cannot be preserved. There may be a need to consider establishment of an accredited laboratory in a strategically located community in Nunavut. This would be needed when the flight time from surrounding communities renders 24 hour sample turnaround infeasible. Currently, samples from Nunavut must be shipped to accredited laboratories in Yellowknife, Winnipeg or Ottawa. For many communities in Nunavut, this geographic distance renders sample analysis within holding times impossible.

3.15 Performance model method

3.15.1 Objectives

The objective of the performance modeling is to:

i) Generate estimations of the treatment performance of a WTA under the expected range of operational conditions;
ii) Assess and optimize the effects of operational changes on treatment performance; and
iii) Compare options for system upgrades when the modeled effluent quality does not meet requirements.

The choice of modeling approach depends on whether the WTA is characterized by surface or subsurface flow. The approach for surface flow wetlands also differs slightly between new proposed WTAs and existing WTAs. All of the modeling approaches are modified versions of the *P-k-C** model by Kadlec and Wallace (2009).

3.15.2 Surface water modified tanks-in-series model

A modified TIS model is recommended to facilitate treatment performance modeling of predominately surface flow wetlands (Hayward and Jamieson, 2015). The modified TIS model is based on a conventional TIS chemical reactor model. The TIS model was modified to account for the external hydrologic contributions from the watershed that are cumulatively added along the length of the wetland. The model represents the wetland hydraulically by a series of completely mixed tanks with equivalent HRTs. Hayward and Jamieson (2015) specify the general mass balance for each tank in the modified TIS model with the following equation:

$$Q_{out}C_{out} = Q_{in}C_{in} + \left(\frac{Q_{ws}}{N}\right)C^* - \frac{k\tau Q_{out}}{Nd_w}(C_{out} - C^*) \qquad \text{[Eq. 19]}$$

where $Q_{in}$is the flow into tank *N* (m^3/d), C_{in} is the concentration into tank *N* (kg/m^3), Q_{out} is the flow out of tank *N* (m^3/d), C_{out} is the concentration out of tank *N* (kg/m^3), Q_{ws} is the external hydrologic contribution into the wetland segment (m^3/d), C^* is the background concentration (kg/m^3), *N* is the number of tanks (dimensionless), *k* is the areal rate constant (m/d), τ is the actual HRT determined from the tracer tests (d), and d_w is the average wetland depth (m).

The water balance components of evapotranspiration, precipitation, and infiltration are assumed to be negligible within Equation 19. The assumption of negligible water balance components may be justifiable when WTAs have particularly short HRTs (i.e., less than 2 days). Furthermore, it may be appropriate to assume negligible infiltration, if the depth of permafrost is particularly shallow (i.e., less than 20 cm).

Hayward and Jamieson (2015) re-arranged the mass balance in Equation 19 to solve for the outflowing contaminant concentration, C_{out} (kg/m^3), as follows:

$$C_{out} = \frac{\left(\frac{Q_{in}}{Q_{out}}\right) C_{in} + \left(\frac{\frac{Q_{ws}}{N}}{Q_{out}}\right) C^* + \frac{k\tau C^*}{N d_w}}{1 + \frac{k\tau}{N d_w}} \qquad \text{[Eq. 20]}$$

3.15.2.1 Compartmentalization

The model compartmentalization involves determination of the appropriate number of tanks required to represent the hydraulics of the wetland system (Hayward and Jamieson, 2015). The data from each tracer test conducted in the wetland can be analyzed to assess how the wetland should be compartmentalized. The compartmentalization of the data from a tracer test is performed by fitting the RTD data to a gamma distribution of residence times according to Kadlec and Wallace (2009). Kadlec and Wallace (2009) present the gamma distribution of residence times as:

$$g(t) = \frac{N}{\tau \Gamma(N)} \left(\frac{Nt}{\tau}\right)^{N-1} exp\left(-\frac{Nt}{\tau}\right) \qquad \text{[Eq. 21]}$$

where $\Gamma(N)$ is the gamma function of *N, = (N-1)!,* factorial, if *N* is an integer (min^{-1}), and t is the time elapsed (min).

A detailed description of fitting an RTD to a gamma distribution is available in Kadlec and Wallace (2009). In short, each tracer test requires the development of a gamma distribution function which can be completed in Microsoft Excel with the GAMMADIST function. The gamma distribution function can be fit to the tracer test RTD by using SOLVER tool in Microsoft Excel. The fitting is performed by selecting *N* and τ to minimize the sum of squared errors (SSQE) between the gamma distribution function and the RTD from the tracer data (Kadlec and Wallace, 2009). The *N* value from the gamma fit to the RTD should be rounded up to the nearest integer (Hayward and Jamieson, 2015). The *N* value for new proposed systems would have to be assumed from literature values. The most common reported literature values for *N* are 4 and 11, for surface flow and subsurface flow treatment wetlands, respectively (Kadlec and Wallace, 2009).

3.15.2.2 Water balance considerations

The water balance components of the WTA should be assessed as this information is used to determine the outflow in a proposed WTA and the nominal retention time. The steady-state water balance is represented as follows:

$$Q_{out} = Q_{in} + Q_{ws} + A \cdot (P - ET - I) \qquad \text{[Eq. 22]}$$

where *A* is the area of the wetland, *P* is the precipitation (m/d), *ET* is the evapotranspiration (m/d), and I is the infiltration (m/d).

If the water balance components are significant for the WTA, then they must be incorporated into the TIS model. Precipitation can be assumed to be negligible, because it is already incorporated into the external hydrologic contribution term Q_{ws}, and there is typically insignificant contaminants in precipitation. The general mass balance for each tank in the modified TIS model with evapotranspiration and infiltration components is given with the following equation:

$$Q_{out}C_{out} = Q_{in}C_{in} + \left(\frac{Q_{ws}}{N}\right)C^* - \frac{I\tau Q_{out}C_{out}}{Nd_w} - \frac{\alpha ET\tau Q_{out}C_{out}}{Nd_w} - \frac{k\tau Q_{out}}{Nd_w}(C_{out} - C^*) \quad \text{[Eq. 23]}$$

where I is the infiltration (m/d), α is the transpiration fraction of ET (dimensionless), and ET is the evapotranspiration (m/d). The mass balance in Equation 23 is re-arranged to solve for the outflowing contaminant concentration, C_{out} (kg/m^3) as follows:

$$C_{out} = \frac{\left(\frac{Q_{in}}{Q_{out}}\right)C_{in} + \left(\frac{\frac{Q_{ws}}{N}}{Q_{out}}\right)C^* + \frac{k\tau C^*}{Nd_w}}{1 + \frac{\tau}{Nd_w}(I + \alpha ET + k)} \quad \text{[Eq. 24]}$$

Infiltration may be seasonally variable as the depth of active changes with seasonal freeze and thaw processes. Therefore the range of characteristic infiltration rates for the site should be assessed during the modeling process.

3.15.2.3 Areal first order rate constants

The selection of areal first order rate constants (k) is required to parameterize the modified TIS model. There is limited published data on the range of areal first order rate constants characteristically observed in tundra WTAs (Hayward and Jamieson, 2015). Hayward and Jamieson (2015) observed seasonal variability in k values. For the Hayward and Jamieson (2015) study, the k values were compared to literature values of over a hundred treatment wetlands in more southern latitudes assembled by Kadlec and Wallace (2009). The minimum k_{20} values fell below the 5th percentile for $CBOD_5$, and 10th percentile for TN, and was within the 40th percentile for *E. coli* and TAN. Hayward and Jamieson (2015) suggested that the adoption of k values from the low percentiles (i.e., less than 10 – 40 %) compared to literature values would likely be conservative for tundra WTAs.

3.15.2.4 Temperature correction

The rate constants of some of the performance parameters require temperature correction. In particular, nitrogen removal rates are sensitive to temperature, in contrast to BOD and phosphorus removal rates, which are not particularly temperature sensitive (Kadlec and Reddy, 2001). The rate constants can be adjusted for temperature effects using the Arrhenius equation given by Kadlec and Wallace (2009):

$$k_T = k_{20}\theta^{(T-20)} \quad \text{[Eq. 25]}$$

where k_T is the rate constant at the field temperature (m/d), k_{20} is the rate constant normalized to 20°C (m/d), T is the field temperature in °C, and θ is the temperature correction coefficient (dimensionless). The temperature correction coefficients must be adopted from literature values due to the lack of data on values specific for an arctic environment. Hayward and Jamieson (2015) suggested values from literature that may be used for temperature correction.

3.15.3 Surface flow wetlands modeling

There are two procedures for modeling the treatment performance of surface flow WTAs. The type of method applied depends on whether there is: (1) an existing WTA; or (2) a proposed WTA. The two procedures are similar, yet differ in the parameterization of a few keys variables. The differences between the methodologies are summarized in Table 1. Generally, there are fewer assumptions made in the assessment of existing WTAs compared to proposed areas. Two example spreadsheet calculators for the existing and proposed WTAs respectively are included in Appendix I.

TABLE 1. COMPARISON OF PERFORMANCE MODELING METHODOLOGIES FOR EXISTING VERSUS PROPOSED WTAS.

Existing	Proposed
Tracer studies required to parameterize.	No tracer studies possible.
Wetland surface area known.	Wetland surface area optimized.
Actual hydraulic retention time known.	Actual hydraulic retention time unknown.
Water depth known.	Water depth estimated.
Number of TIS known.	Number of TIS assumed.
Design outflow known.	Design outflow estimated.

3.15.3.1 Existing wetland treatment areas

For an existing WTA, the known parameters gained from the site-specific study are used to parameterize the modified TIS model. The known input parameters consist of the: design flow (Q_{in} in m^3/d), design outflow (Q_{out} in m^3/d), external hydrologic contribution from the watershed (Q_{ws} in m^3/d), precipitation (P in cm/d), total wetland area (A in m^2), water depth (m), hydraulic retention time (HRT in days), number of TIS (N is an integer), influent contaminant concentrations (C_{in} in mg/L or MPN/100mL), background contaminant concentrations (C^* in mg/L or MPN/100mL). The estimated parameters consist of: evapotranspiration (ET in cm/d), infiltration (I in cm/d), and the areal first order rate constants (k in m/year).

These parameters are input into the modified TIS performance model to generate output contaminant concentration estimates. A range of influent concentrations and hydraulic loading rates expected for the site should be assessed with the model. The wetland should meet the target effluent contaminant concentration at least 95% of the time. It is recommended that the existing wetland should also have a nominal retention time of 14 days, and an HLR of less than 2.5 cm/d. If the existing wetland fails to meet the target effluent concentrations, and/or the nominal retention time of 14 days, and/or a maximum HLR of 2.5 cm/d is not achieved, then options for system upgrades should be considered.

3.15.3.2 Proposed wetland treatment areas

For a proposed WTA, the known parameters gained from the site-specific study, as well as, assumptions from literature are used to parameterize the modified TIS model. The known input parameters consist of the: design flow (Q_{in} in m^3/d), existing wetland area (A_e in m^2), precipitation (P in cm/d), influent contaminant concentrations (C_{in} in mg/L or MPN/100mL), and background contaminant concentrations (C^*in mg/L or MPN/100mL). The estimated input parameters consist of the: design outflow (Q_{out} in m^3/d), external hydrologic contribution from the watershed (Q_{ws} in m^3/d), water depth (m), evapotranspiration (ET in cm/d), infiltration (I in cm/d), number of TIS (N is an integer), wetland area guess ($A_g$in m^2), total estimated area (A_w in m^2), and the first order areal rate constants (k in m/year).

The wetland area is the unknown variable for the proposed wetland scenario. First an initial guess of a wetland area is made. Then the resulting effluent contaminant concentrations are compared against the target effluent concentrations. The WTA should meet the target effluent contaminant concentration at least 95% of the time. The full range of influent and hydraulic loading rates estimated should be assessed with the model. The total area required is iteratively optimized until the effluent contaminant concentrations meet the target concentrations with a minimized wetland area. The proposed wetland should also have a nominal retention time of 14 days and an HLR of less than 2.5 cm/d. The design of the proposed WTA must demonstrate that the optimized design area will be a reality in the post-construction phase.

3.15.4 Subsurface flow wetlands modeling

The performance modeling method for subsurface flow (SSF) wetlands is the same as described for surface flow WTAs with the exception of additional hydraulic calculations at the tail-end of the calculations. The identical modified TIS performance modeling technique described in Equations 19 – 25 should be applied for SSF WTAs. After the performance modeling is complete, the following hydraulic calculations should be performed to check the feasibility of the SSF WTA.

3.15.4.1 Hydraulic assessment of the porous media

The hydraulic calculations on the porous media are performed to ensure that the volume of porous media in the SSF WTA can convey the design flows. This check on the hydraulics of the SSF WTA enables an assessment whether hydraulic failure is a possibility (i.e., overland flow of effluent or ponding at the inlet), and mitigation of potential failures. Additionally, the hydraulics of the system should be such that the vegetation in the SSF WTA is not starved of water.

First, the calculation of the frictional losses through the porous media bed should be performed. Darcy's law which describes fluid flow through a porous media may be used if the flow is laminar. Flows are typically laminar in sand media and turbulent in gravel and rock media (Kadlec and Wallace, 2009). When turbulent flow conditions are expected the designers should consult Kadlec and Wallace (2009) for additional design guidance. The components of Darcy's law governing fluid flow through porous media are shown in Figure 4.

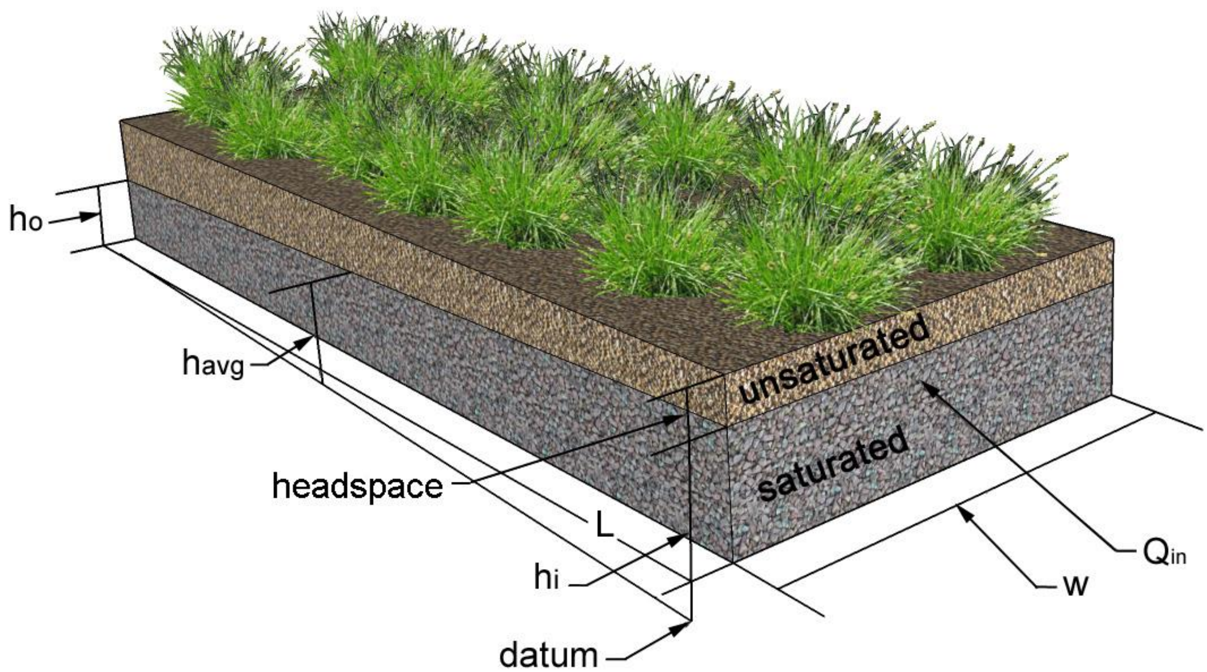

FIGURE 4. A SCHEMATIC DENOTING THE NOTATION FOR THE DARCY'S LAW FOR SUBSURFACE FLOW WTAS.

A form of Darcy's law is given by the theoretical Darcy flux, q ($m^3/m^2/s$), relationship:

$$q = Ki \quad \text{[Eq. 26]}$$

where K is the hydraulic conductivity (m/s), and i is the hydraulic gradient (m/m). The hydraulic gradient is defined by a change in head over a change in distance shown in Equation 17. In existing systems the hydraulic gradient may be known from groundwater monitoring. However, the hydraulic gradient in new proposed systems may require estimation based on assumptions of inlet loading, inlet structures, depth of active layer, and site topography.

The approximate width, depth, and effective porosity of the WTA would be used to calculate the cross sectional area available to convey fluid flow through the SSF wetland. The effective cross sectional area, A_e (m^2), available to convey fluid flow is given by:

$$A_e = w \cdot h_i \cdot n_e \quad \text{[Eq. 27]}$$

where h_i (m) is the depth of water at the inlet, w (m) is the width of the wetland, and n_e (dimensionless) is the effective porosity.

The theoretical Darcy flux calculated in Equation 26 is compared to the design Darcy flux, q_d (m^3/m^2/s). The design Darcy flux is obtained by:

$$q_d = \frac{Q_{in}}{A_e} \quad \text{[Eq. 28]}$$

where Q_{in} is the influent flow rate (m^3/s). The design Darcy flux must be less than or equal to the theoretical Darcy flux (i.e., $q_d \leq q$). If this condition is not met, the design must be adjusted to reduce the design Darcy flux to less than the theoretical Darcy flux. The designer should include factors of safety into the design, to account for the gradual clogging of the WTA media over time, which will decrease the hydraulic conductivity. The factors of safety should be at the discretion of the designer and should be sufficient to avoid hydraulic failure of the WTA.

Finally, the average depth of the water in the SSF, h_{avg} (m), should be checked to ensure that it is not too near to the surface, and adequate to provide water to the wetland vegetation. If the SSF WTA is designed to have a constant water depth, then this check can be performed with the following equation re-arranged from Kadlec and Wallace (2009):

$$h_{avg} = \frac{Q_{in} i}{K w} \quad \text{[Eq. 29]}$$

In existing SSF WTAs, there are likely longitudinal variations in hydraulic conductivity. Therefore, the depth of water along the length of the wetland should be integrated. The integration procedure is described by Kadlec and Wallace (2009).

As a general rule, the average water depth should allow for a maximum headspace of 10 cm between the average water surface and the wetland surface (Kadlec and Wallace, 2009).

3.16 Establishment of monitoring program

It is recommended that a monitoring program be established after the performance modeling demonstrates that the treatment objectives will be met. The monitoring program will set the recurrent long-term sampling frequencies and requirements. Long-term monitoring data will enable the proactive identification of system problems which will allow for mitigation. The monitoring datasets will also enable regulatory oversight with ongoing compliance sampling routines. Additionally, the long-term monitoring datasets on multiple systems will eventually form a comprehensive library of data on the functioning of the WTAs. This type of comprehensive library will be highly useful for the long-term management of these systems and to inform the design of new proposed WTAs.

The establishment of the monitoring program will first involve the physical installation of labelled signage to clearly indicate where samples and measurements are to be taken. The signage is important to ensure consistent sampling occurs over the life of the WTA. Personnel responsible for the ongoing compliance monitoring should be made aware of the physical location of the sample points ideally in person, or alternatively with GPS coordinates. The monitoring program should comprise of treatment performance and water quality samples, hydrological, hydraulic, biological, physical, and if applicable, hydrogeological measurements. Each site will have different priorities for monitoring. Each monitoring program will also be different depending on whether the WTA has a short discharge period (i.e., less than two weeks), or long discharge period (i.e., greater than two weeks).

Table 2 details the recommended annual minimum monitoring program components. The monitoring program suggested in Table 2 is intended for adaptive management of the WTAs. This means that different levels of monitoring are recommended based on case-by-case basis and they can be adjusted as changes are made to the systems.

The proposed monitoring program for a WTA should be reviewed by the NWB as part of the design review process. The regulatory review will ensure that the monitoring program is appropriate for the site and includes all of the essential datasets. The results of the monitoring program will be compared against the treatment requirements of the WTA. If there are deviances from the design estimates over time, then there may be a need for mitigation.

TABLE 2. RECOMMENDED ANNUAL MINIMUM MONITORING PROGRAM COMPONENTS.

Data collection type	**Discharge period**	
	(< 2 weeks)	**(> 2 weeks)**
Treatment performance and water quality sample sets[2]	• 1 at the inlet & outlet in middle of the discharge.	• 2 at the inlet & outlet during the spring freshet[1] & post-freshet conditions if possible.
Flow measurements	• 3 at the inlet & outlet over a period of at least 2 days • 3 at each intermediate sample locations if external hydrologic contributions are significant.	• 3 at the inlet & outlet during spring freshet & post-freshet conditions if possible. • 3 at each intermediate sample locations per site visit if external hydrologic contributions are significant.
Biological measurements[3]	• 1 vegetation assessment of WTA and reference wetland.[4] • 1 survey of terrestrial & avian wildlife.[5]	• 1 vegetation assessment of WTA and reference wetland.[4] • 1 survey of terrestrial & avian wildlife per site visit.[5]
Physical measurements	• 3 depth of active layer.	• 3 depth of active layer per site visit.
Hydrogeological measurements	• 1 hydraulic gradient measurement.	• 1 hydraulic gradient measurement per site visit.

[1]The spring freshet should only be sampled if there is a release of effluent during this period.

[2]Water quality measurements consist of DO, specific conductivity, dissolved oxygen, temperature, and ORP.

[3]The biological measurements that are recommended are not intended to be as comprehensive as the first initial site characterization.

[4]Vegetation survey may only need to identify inter-annual changes in vegetation.

[5]Wildlife survey can be as simple as noting and reporting the species of mammals and birds visibly present on site during the site visits.

3.17 Design and approval

The design document is generated following the performance modeling stage of the site-specific study of the WTA. The design document provides a comprehensive summary of all of the findings from the site-specific study. It is recommended that the design document includes, but is not limited to, the following list of items:

i) Site description.
ii) Data collection methodologies
iii) Desktop mapping results.
iv) Public consultation findings.
v) Summary of the treatment performance.
vi) Summary of the site hydraulics.
vii) Summary of the site hydrology.
viii) Summary of the biological and physical environment.
ix) Summary of the site hydrogeology (if applicable).
x) Treatment objectives.
xi) Performance modeling results.
xii) Mitigation techniques and/or system upgrades (if deemed necessary).
xiii) Detailed maps of the existing or proposed WTA.
xiv) Proposed long-term monitoring program.

It is recommended that the proposed design document undergo review by the NWB. If changes or additional information are required they should be identified at this stage. If the existing or proposed WTA meets the treatment requirements without adverse environmental and health impacts, then the NWB would approve the design. If the WTA does not meet the treatment requirements, then revisions to the design would be necessary prior to the approval of the design by the NWB. The ongoing operation of the WTA would require a yearly review to ensure that the treatment objectives continue to be met over the duration of the life of the WTA. The yearly review will also provide opportunity for operational optimization over time.

3.18 Construction considerations

If upgrades are deemed necessary to existing or proposed wetland treatment areas, then all measures should be taken to minimize the disturbance to the natural vegetation present at the site. Tundra vegetation is difficult to establish and can take decades to centuries to grow (Johnstone and Kokelj, 2008). Therefore all efforts should be taken to preserve and maximize existing vegetation.

4.0 Conclusions

In conclusion, the tundra WTAs are a valuable resource that with the appropriate management procedure, can be important part of the treatment train in Nunavut's municipal wastewater management strategy. Published literature to date has shown time and again that the tundra WTAs demonstrate water quality improvements. The site-specific research program conducted by CWRS narrowed in to identify the specific elements required to develop an adequate understanding of the WTAs from a risk and engineering stand-point. The resulting proposed framework for site-specific studies guidelines provides a standardized tool to assess the treatment performance expected from WTAs.

This framework covers the many aspects that affect the complex functioning of WTAs and therefore requires a robust data collection component. It would be ill-advised to extrapolate from data observed at other WTAs and expect similar performance results. In addition, all components of the recommended framework for the site-specific assessments of WTAs are essential to reduce the risks associated with use of this type of treatment process. Therefore, it would be ill-advised to cherry pick elements of the framework, while ignoring other elements, without scientific basis for elimination. In other words, the framework is intended to be used in its entirety and not in piece-meal form.

The modified TIS model has shown to be an effective tool for the assessment of expected treatment performance of WTAs at a range of operational conditions. If particular WTAs do not meet the targeted treatment objectives according to the model results, then options for system upgrades may be explored at the modeling stage. This model is an important design tool which is recommended for use in the assessment of the existing and new proposed WTAs in Nunavut.

Finally, the recommendation for the long-term monitoring for each WTA will help to build a database for the performance of the systems in Nunavut. This database will eventually help to refine to rate constants that should be used for modeling the systems, as well as, optimize other operational features of the WTAs, such as loading rates.

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Appendix I
Example spreadsheets of modified TIS model

Existing tundra wetland treatment areas - Example calculation spreadsheet

Modified tanks-in-series performance modeling for existing surface flow wetland treatment areas.

Instructions:

1. Use the data gathered in the site-specific study to fill in the red bolded input parameter boxes.

2. Specify the number of tanks required to represent the hydraulics of the wetland and modify spreadsheet accordingly.

3. Calculate the values for the performance model output boxes.

4. Re-calculate the performance model output boxes for all ranges of flows and influent concentrations expected.

5. Verify that the concentrations leaving the final tank meet the target effluent concentration.

6. Verify that the HLR is less than 2.5 cm/d.

7. Verify that the nominal retention time is greater than 14 days.

8. Adjust design attributes to ensure wetland meets target concentrations at least 95% of the time.

Disclaimer:

This spreadsheet was produced by the Centre for Water Resources Studies at Dalhousie University.

The spreadsheet was meant to accompany the *Guidelines for the Design and Assessment of Tundra Wetland Treatment Areas in Nunavut* (2016).

The spreadsheet should be used by a wetland designer who is knowleagable in performance modeling using chemical reactor theory.

The authors assume no liability for the use of this spreasheet in wetland design.

It is the ultimate responsibility of the user of this spreadsheet to ensure that the calculations for the wetland design are performed correctly and conservative.

Modifications to the equations may render the spreadsheet incorrect.

Site: ___________________________

Water balance components

Design flow (m^3/d)	Q_{in}=	1000
Design outflow (m^3/d)	Q_{out}=	1250
External hydrologic contribution from watershed (m^3/d)	Q_{ws}=	250
Hydraulic retention time (d)	HRT=	24
Total area (ha)	A=	10
Total area (m^2)	A=	100000
Area per tank (ha)	A_{tank}=	3.333333
Water depth (m)	d_w=	0.3
Volume per tank (m^3)	V_{tank}=	10000
Rain (cm/d)	P=	0.05
Evapotranspiration (cm/d)	ET=	0.04
transpiration fraction (dimensionless)	$\alpha =$	0.5
Infiltration (cm/d)	I=	0.05
Number of tanks (integer)	N=	3

	Inflow	Tank 1	Tank 2	Tank 3	Total
Flow rate (m^3/d)	1000	1070	1140	1210	
Watershed flow (m^3/d)	250	83	83	83	
Rain (m^3/d)	n/a	16.7	16.7	16.7	50
ET (m^3/d)	n/a	13.3	13.3	13.3	40
Infiltration (m^3/d)	n/a	16.7	16.7	16.7	50
Nominal retention (d)	30.0	9.3	8.8	8.3	26.4
HLR (cm/d)	1.00				

Steady-state

$$Q_{out} = Q_{in} + Q_{ws} + A \cdot (P - ET - I)$$

Treatment performance components

		CBOD$_5$	*E. coli*	TN	TAN	NH_3-N	TP
Influent concentration	C_{in}=	60	1.0E+05	30	30	3	2
Target effluent concentration	C_e=	25	200	4	2	1.25	0.2
Background concentration	C*=	5	100	2	0	0	0.05
Areal rate constant at 20°C (m/year)	k_{20} =	5	70	3	12	12	1.4
Areal rate constant at 20°C (m/d)	k_{20} =	0.014	0.192	0.008	0.033	0.033	0.004
Temperature correction factor	θ =	1.012	1.07	1.03	1.053	1.053	0.986
Field water temperature (°C)	T =	10	10	10	10	10	10
Areal rate constant at field temperature (m/d)	k =	0.012	0.097	0.006	0.020	0.020	0.004

Number of tanks **N=** 3

Performance model output

Concentration leaving tank 1	C_1=	43.1	25864.1	24.0	18.1	1.8	1.6
Concentration leaving tank 2	C_2=	31.5	6772.8	19.4	11.0	1.1	1.4
Concentration leaving tank 3	C_3=	23.4	1834.5	15.8	6.7	0.7	1.1

$$C_{out} = \frac{\left(\frac{Q_{in}}{Q_{out}}\right) C_{in} + \left(\frac{\frac{Q_{ws}}{N}}{Q_{out}}\right) C^* + \frac{k\tau C^*}{N d_w}}{1 + \frac{\tau}{N d_w}(I + \alpha ET + k)}$$

Proposed tundra wetland treatment areas - Example calculation spreadsheet

Modified tanks-in-series performance modeling for proposed surface flow wetland treatment areas.

Instructions:

1. Use the data gathered in the site-specific study to fill in the red bolded input parameter boxes.

2. Estimate the number of tanks required to represent the hydraulics of the wetland and modify spreadsheet accordingly.

3. Make an initial guess of the wetland area required to reach target concentrations.

4. Calculate the performance model output values.

5. Re-calculate the model output values until the target concentrations are met with the smallest wetland area.

6. Re-calculate the performance model output boxes for all ranges of flows and influent concentrations expected.

7. Calculate the nominal HRT and re-adjust area until 14 days is obtained.

8. Calculate the HLR and re-adjust area until a maximum of 2.5 cm/d is obtained.

9. Verify that the concentrations leaving the final tank meet the target effluent concentration.

10. Adjust design attributes to ensure wetland meets target concentrations at least 95% of the time.

Disclaimer:

This spreadsheet was produced by the Centre for Water Resources Studies at Dalhousie University.

The spreadsheet was meant to accompany the *Guidelines for the Design and Assessment of Tundra Wetland Treatment Areas in Nunavut* (2016).

The spreadsheet should be used by a wetland designer who is knowleagable in performance modeling using chemical reactor theory.

The authors assume no liability for the use of this spreasheet in wetland design.

It is the ultimate responsibility of the user of this spreadsheet to ensure that the calculations for the wetland design are performed correctly and conservative.

Modifications to the equations may render the spreadsheet incorrect.

Water balance components

Design flow (m^3/d)	Q_{in}=	100
Design outflow (m^3/d)	Q_{out}=	150
External hydrologic contribution from watershed (m^3/d)	Q_{ws}=	50
Nominal retention time (d)	τ_n=	28.7
Total existing wetland area (m^2)	A_e=	1000
Wetland area guess (m^2)	A_g=	12000
Total estimated area (m^2)	A_w=	13000
Total estimated area (ha)	A=	1.3
Area per tank (m^2)	A_{tank}=	4333.333
Water depth (m)	d_w=	0.3
Volume per tank (m^3)	V_{tank}=	1300
Rain (cm/d)	P=	0.5
Evapotranspiration (cm/d)	ET=	0.4
transpiration fraction (dimensionless)	α =	0.5
Infiltration (cm/d)	I=	0.05
Number of tanks (integer)	N=	3

$$A_w = A_g + A_e$$

	Inflow	Tank 1	Tank 2	Tank 3	Total
Flow rate (m^3/d)	100	119	138	157	
Watershed flow (m^3/d)	50	17	17	17	
Rain (m^3/d)	n/a	21.7	21.7	21.7	65
ET (m^3/d)	n/a	17.3	17.3	17.3	52
Infiltration (m^3/d)	n/a	2.2	2.2	2.2	6.5
Nominal retention (d)	39.0	10.9	9.4	8.3	28.7
HLR (cm/d)	0.77				

Steady-state

$$Q_{out} = Q_{in} + Q_{ws} + A \cdot (P - ET - I)$$

Treatment performance components

		$CBOD_5$	*E. coli*	TN	TAN	NH_3-N	TP
Influent concentration	C_{in}=	100	1.0E+05	30	30	3	2
Target effluent concentration	C_e=	25	200	4	2	1.25	0.2
Background concentration	C*=	5	100	2	0	0	0.05
Areal rate constant at 20°C (m/year)	k_{20} =	5	70	3	12	12	1.4
Areal rate constant at 20°C (m/d)	k_{20} =	0.014	0.192	0.008	0.033	0.033	0.004
Temperature correction factor	θ =	1.012	1.07	1.03	1.053	1.053	0.986
Field water temperature (°C)	T =	10	10	10	10	10	10
Areal rate constant at field temperature (m/d)	k=	0.012	0.097	0.006	0.020	0.020	0.004

Number of tanks **N=** 3

Performance model output

Concentration leaving tank 1	C_1=	56.7	19871.1	19.4	14.3	1.4	1.3
Concentration leaving tank 2	C_2=	33.6	4110.7	13.0	7.0	0.7	0.9
Concentration leaving tank 3	C_3=	20.9	926.2	9.0	3.5	0.3	0.6

$$C_{out} = \frac{\left(\frac{Q_{in}}{Q_{out}}\right) C_{in} + \left(\frac{\frac{Q_{ws}}{N}}{Q_{out}}\right) C^* + \frac{k\tau C^*}{N d_w}}{1 + \frac{\tau}{N d_w}(I + \alpha ET + k)}$$