Centre for Alternative Wastewater Treatment

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May 2014

RBC Blue Water Project™

TRENT UNIVERSITY

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Tundra Wetlands: the treatment of municpal wastewaters

- RBC Blue Water Project: performance and predictive tools (manual + appendices)

funded by RBC Blue Water Project and
in partnership with the Institute
for Watershed Science, Trent
University

May 2014

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Tundra Wetlands: the treatment of municipal wastewaters

Performance Review & Operational Tools

-Full Report with appendices

Forward

Funding provided by the federal government of Canada through the International Polar Year programme and Environment Canada was awarded to the Centre for Alternative Wastewater Treatment (CAWT) to conduct site investigation at 13 tundra treatment wetland locations in Nunavut and the Northwest Territories. Funding from the Royal Bank of Canada (RBC) Blue Water Project was used to consolidate and analyze this information and to develop a guidance document for wastewater stakeholders within indigenous communities in Canada's far north. This guidance document "Tundra Wetlands: the treatment of municipal wastewaters – performance and operational tools, 374 pages", along with a smaller summary "companion" report (e.g., 34 pages) outlines the major treatment processes occurring within wetlands, provides information on the performance of 13 northern treatment wetlands and presents operational tools (e.g., SubWet 2.0) that can be used by wastewater managers and regulators. This information can be used to predictively assess how wetlands may respond to changing conditions (e.g., wastewater strength, flow rates, etc.) and how wetlands could be used in a hybridized treatment train that includes both waste stabilization ponds and wetlands as part of a wastewater strategy for northern Canada. The RBC Blue Water Project funding was awarded to the Institute for Watershed Science (IWS), Trent University who in turn subcontracted the CAWT to produce the performance and operational tools to serve as a guidance document for wastewater treatment within indigenous communities of Canada's far north. The primary focus of the RBC award to the IWS was to develop teaching materials and tools dedicated to the protection of drinking water within indigenous communities of Canada's north. To this end, the IWS has developed source water protection guidance information generated for a northern indigenous audience. The CAWT's contribution to this work was focussed on the treatment of domestic sewage in the belief that proper treatment is an important component in the overall protection of source waters used for drinking purposes.

The genesis for this wetland work began during the International Polar Year (IPY) in 2007. Once every 50 years, the attention of researchers from around the world is focussed on both the north and south poles. At this time, the Centre for Alternative Wastewater Treatment (CAWT), an applied research facility located at Fleming College, Lindsay, Ontario, Canada was awarded a grant from the federal government of Canada through the IPY programme to examine the performance of tundra wetlands that had been used for several decades in Canada's far north for the treatment of domestic sewage. During this initial IPY study, the CAWT investigated the performance of six wetlands in the Kivalliq region of Nunavut, Canada. This work was further extended to include the study of seven additional wetlands with funding provided by Environment Canada.

During the course of this work it became apparent that most of the wetlands examined do provide an effective wastewater treatment service to the northern communities utilizing them. The natural treatment wetlands provide an economical, passive system that is well suited to the needs of northern communities in that these systems are not reliant on constant supervision by highly skilled operators nor do they require support from the installation and operation of expensive infrastructure. In fact, until recent decades, natural wetlands provided the only viable wastewater treatment option available to some of these communities.

Most northern, isolated communities of Canada's far north now utilize wastewater stabilization ponds (lagoons) as their primary mode of treatment. Despite a historic reliance on tundra wetlands, these areas are typically not formally recognized as being part of the wastewater treatment strategy in the far north. The finding of the CAWT wetland studies suggests that the reasons why wetlands are not formally recognized could be due to:

- an overall lack of study documenting the treatment performance of wetlands,
- a lack of understanding in how wetlands are best managed in order to optimize treatment performance,
- a lack of a standardized sampling protocol, and
- the absence of predictive tools required by wastewater managers and regulatory agencies in order to assess operational management options and future capacities.

The RBC funding has enabled the CAWT to develop management tools (such as SubWet 2.0) and to summarize these tools and findings into one document that is being made available to northern wastewater stakeholders. This document outlines how natural tundra treatment wetlands differ from constructed or engineered wetland systems. It also provides a basic overview of the main treatment processes operative in treatment wetlands. The data and finding generated from the study of 13 natural treatment wetlands within Nunavut and the Northwest Territories are also contained in this document. To our knowledge, this work represents one of the largest and most comprehensive data sets currently existing for northern Canada. The data from these studies has been summarized into tabular form; however, the raw data table are appended along with interpolated mapping for seven of the eleven wetland sites.

During the IPY study, the CAWT joined forces with Dr. Sven Jørgensen, the originator of the SubWet wetland model, to modify this predictive tool for natural tundra wetlands. The grant provided by RCB enabled the CAWT to subsequently develop a user's manual for this model and to calibrate SubWet 2.0 to the eleven wetlands studied. This document provides an overview along with the calibrated rate constants for all eleven wetlands. The SubWet 2.0 wetland user's manual is found in the appendix.

It is believed that the material presented in this document provides valuable insight and tools for wastewater managers and regulators and addresses many of the unknowns that have hampered the formal inclusion of natural tundra wetlands into wastewater management strategies. It is hoped that the information presented will help to facilitate future discussions concerning the development of a northern wastewater management strategy that formally recognizes the critical services that tundra wetland are currently providing. It is suggested that a reclassification of the treatment wetlands from being part of the "receiving environment" to being an integral part of a hybridized treatment system could provide a treatment strategy with the capacity to meet CCME guidelines for the north. This hybridized system would include the wastewater stabilization pond as the provider for primary treatment and the wetlands as the provider to secondary treatment. It is also suggested that the SubWet 2.0 model could also provide managers and regulators the predictive capacity to determine the best management approaches and the system's capacity to accommodate future growth.

For readers wanting additional information regarding study sites and applications of the SubWet 2.0 program you are in directed to the following published manuscripts that have arisen from this work:

Chouinard, A., Balch, G.B., Wootton, B.C., Jørgensen, S.E. and Anderson, B.C., in press. Modelling the performance of treatment wetlands in a cold climate. In *Advances in the Ecological Modelling and Ecological Engineering applied on Lakes and Wetlands*. Jørgensen, S.E.; Chang, N.B.; Fuliu, X., Eds. Elsevier: Amsterdam, Netherlands

Chouinard, A., Yates, C.N., Balch, G.C., Jørgensen, S.E., Wootton, B.C., Anderson, B.C., 2014. Management of Tundra Wastewater Treatment Wetlands within a Lagoon/Wetland Hybridized Treatment System Using the SubWet 2.0 Wetland Model. *Water*, 6(3):439-454

Yates, C. N., Wootton, B. C., and Murphy, S. D., 2012. Performance assessment of Arctic tundra municipal wastewater treatment wetlands through an Arctic summer. *Ecological Engineering*, 44(0), 160-173

Yates, C.N., Wootton, B.C., Jørgensen, S.E., Murphy, S.D., 2013. Wastewater Treatment: Wetlands Use in Arctic Regions. *In* Encyclopedia of Environmental Management. Taylor and Francis: New York

Yates, C., Balch, G.B., Wootton, B.C., Jørgensen, S.E., in press. Practical Aspects, Logistical Challenges, and Regulatory Considerations for Modeling and Managing

Treatment Wetlands in the Canadian Arctic. In: *Advances in the Ecological Modeling and Ecological Engineering applied on Lakes and Wetlands.* Eds., Jørgensen, S.E., Chang, N. B. and Fuliu, X. Elsevier, Amsterdam, The Netherlands, 560 pages

Yates, C.N., Balch, G.C., Wootton, B.C., Jørgensen, S.E., in press. Exploratory Performance Testing of a Pilot Scale HSSF wetland in the Canadian Arctic. In *Advances in the Ecological Modelling and Ecological Engineering applied on Lakes and Wetlands*. Jørgensen, S.E.; Chang, N.B.; Fuliu, X., Eds. Elsevier: Amsterdam, Netherlands

Yates, C.N., Balch, G.C., Wootton, B.C., Jørgensen, S.E., in press. Framing the Need for Application of Ecological Engineering in Arctic Environments. In *Advances in the Ecological Modelling and Ecological Engineering applied on Lakes and Wetlands*. Jørgensen, S.E.; Chang, N.B.; Fuliu, X., Eds. Elsevier: Amsterdam, Netherlands

Yates, C.N., in press. A Review of Wastewater Treatment in the Canadian Arctic: Comments and Recommendations for New Municipal Effluent Performance Standards. *Arctic*

In summary, it is hoped that this work will prove to be a valued resource for wastewater stakeholders of Canada's far north.

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1.0 Treatment Wetlands

1.1 Introduction

Treatment wetlands are either natural or constructed systems managed in a specific manner for the treatment of wastewaters. Although traditionally applied for the treatment of domestic and municipal sewage from both separate and combined sewage, treatment wetlands have been applied globally since the late 1980s to treat various types of wastewaters, including agricultural wastewaters (cattle, swine, poultry, dairy), mine drainage, food processing wastewaters (winery, abattoir, fish, potato, vegetable, meat, cheese, milk, sugar production), heavy industry wastewaters (polymers, fertilizers, chemicals, oil refineries, pulp and paper mills), landfill leachate and runoff waters (urban, highway, field, airport, nursery, greenhouse) (Babatunde *et al.*, 2010; Kadlec and Wallace, 2009; Mander and Jenssen, 2003; Vymazal, 1998; Hammer, 1989). Treatment is achieved by a variety of physical, chemical and biological processes, including sedimentation, filtration, precipitation, sorption, plant uptake, microbial decomposition and nitrogen transformations (Kadlec and Wallace, 2009; Scholtz, 2005). An overview of basic treatment processes within wetlands is presented in Appendix A.

The literature related to mechanisms of action published in recent years mainly contains references to the efficient and effective use of constructed wetlands (CWs) or engineered wetlands (EWs) for the treatment of municipal effluents and specific wastewaters from a variety of sources (e.g., mining, industry, etc.). Less information has been published regarding the use of natural wetlands. The term CWs is associated with manmade structures designed to control many of the treatment processes within defined operational conditions, spatial dimensions and process parameters. Similarly, EWs generally refer to wetlands designed to optimize specific treatment processes necessary for the effective treatment of a specific waste stream such as the removal of particular trace elements or organic constituents. By contrast, natural wetlands have developed through natural or spontaneous processes; therefore, many of the characteristics regarding the biochemical,

chemical, physical processes and spatial conditions are unknown and/or unregulated. Because of this, natural wetland tends to have highly variable functional components which make them site specific. Many of the characteristics of the treatment process remain undocumented (Hayward et al., 2012).

Harnessing natural processes or systems for wastewater quality improvement has several advantages over conventional technologies. Cost-reduction is one of them, and a prime reason for the increased interest in CWs and EWs since the high costs associated with the implementation of advanced wastewater technologies is cost prohibitive in many regions of the world. Rural areas with low population densities do not have the financial capital or tax base, and are not able to raise the public funds necessary for such an investment. Another advantage of these passive systems is their low maintenance since it is often difficult for small communities to attract qualified individuals with the technical expertise necessary to oversee large conventional treatment facilities. Some additional ecosystem services include biomass production, carbon sequestration, seasonal agriculture, reusable water supply, regional climate regulation, habitat conservation, and educational and recreational usage (Liu *et al.*, 2008).

Based on hydrological flow patterns, constructed wetlands can be divided into surface flow (SF) and sub-surface flow (SSF) systems (Fonder and Headley, 2011; Kadlec and Wallace, 2009; Kadlec *et al.*, 2000; Suthersan, 1999; Cooper et al., 1998; Cooper, et al., 1996). Sub-surface flow can, in turn, be further divided into horizontal flow (HF) and vertical flow (VF) types, and vertical flow can be either vertical downflow or vertical upflow. Table G-1 in Appendix G elaborates on the classification derived from functional definitions coupled with brief descriptions as well as relevant references. In order to achieve higher treatment efficiencies, especially for nitrogen, various types of systems may be combined. Hybrid systems most frequently combine VF and HF systems arranged in a staged manner, where the advantages of the HF and VF systems can be maximized in a complimentary manner and thus overcome some limitations inherent in each type. With HF and VF hybridized systems it is possible to produce an effluent low in BOD, which is fully nitrified and partly denitrified with an overall reduction in total-nitrogen concentrations (Cooper, 2001).

Natural wetlands can be characterized with similar terminology as the effluent flow in natural wetlands can vary from SF to SSF, or a combination of both.

1.2 CW or EW systems vs natural tundra wetlands

Natural tundra wetlands used for the treatment of municipal wastewaters are fundamentally different from CW or EW systems that are used for the same purposes. Constructed wetlands or engineered wetlands, as their name implies, refers to wetlands that are man-made and designed to specific dimensions, porosity, flow paths, hydraulic retention times, and related design features for the intended purpose of achieving predetermined levels of treatment (Akratos and Tsihrintzis, 2007; Kadlec and Wallace, 2009; Vymazal, 2005). The science regarding treatment processes, reaction rate constants, soil porosity, hydraulics, design options and management practices has been thoroughly investigated in the last two decades and is well documented (Buchberger and Shaw, 1995; Campbell and Ogden, 1999; Cooper, 2009; Hammer, 1989; Babatunde *et al.*, 2010; Kadlec and Wallace, 2009; Mander and Jenssen, 2003; Vymazal, 2011).

In contrast, tundra wetlands are significantly different in several aspects. First, tundra wetlands have developed through natural processes and have not been specifically designed to meet a desired performance characteristic. Therefore there is no control on design, and little options for alteration to enhanced treatment. Each tundra wetland is unique and very little is known about site specific hydrology, porosity, soil types and depth, flow paths and other key parameters influencing wastewater treatment. Treatment potential varies widely from site to site, and is thus site specific. Vegetative boundaries are relatively easy to identify, however it is difficult to know the subsurface flow paths that the wastewater travels and how these may change seasonally or annually and thus it is difficult to determine what portions of the wetland are actually involved in the treatment process. Likewise, soil types and depths are not homogeneous and unlike CW or EW systems it is difficult to gather information on many of the physical parameters required to make predictions regarding treatment performance.

Lastly, there are several aspects inherent within tundra wetlands used for the treatment of wastewaters that can make them logistically challenging to work with. Some of these aspects include the difficulty in identifying single or representative "point of release" where the effluent leaves the wetland. Wetlands can have more than one point of release and it is possible that the location and relative volumes delivered can change seasonally and from year to year. This makes it difficult for regulatory agencies when trying to identify the best location to obtain an effluent sample representative of treatment efficiencies. In addition, unlike engineered lagoons, it is often not possible to control the flow leaving the wetland and thus if treatment is lower than desired, then there is no way of controlling the flow from the wetland until better treatment is achieved. The remoteness of tundra treatment wetlands presents challenges for not only sample collection but also sample analysis. In most cases the nearest laboratories capable of providing the analytical services needed are located further south in Ottawa, Winnipeg or further west in Yellowknife. Some wastewater parameters such as BOD_5 and *E. coli* have relatively short (e.g. 48h) holding times to ensure sample integrity.

Further challenges include the fact that most of the research on processes and reaction rates has been generated from CW or EW systems established in warmer temperate or subtropical climates which are quite different from the harsh conditions of northern Canada were tundra wetlands freeze solid for a significant portion of the year. Because of the logistical challenges in gathering the type of information described above, most regulatory agencies have tended to view the tundra wetlands as unknowable and unpredictable and therefore of little use as part of a formally recognized wastewater treatment strategy.

1.3 Natural tundra wetlands for wastewater treatment in the Canadian Arctic

Communities in the Canadian Arctic and sub-Arctic have small populations of 100 to 2,000 people and many can only be accessed by air, or by sea during the brief summer season, making them dependent upon self-supported infrastructure to deliver community services, such as wastewater treatment, solid waste disposal and provision of potable water

(Jamieson and Krkosek, 2013; Yates *et al.*, in press). The extreme climate, the logistical challenges of bedrock and/or permafrost together with the lack of financial and human resources represent significant impediments to the development and operation of mechanized wastewater treatment infrastructure commonly used in more southern locations of Canada. Therefore, people living in the Arctic often have to rely on a trucked system for water delivery and wastewater collection. Historically, domestic sewage within these communities was trucked outside of the community and deposited into natural depressions which were typically better classified as natural tundra wetlands. Current practices have evolved somewhat with domestic sewage being initially contained within heated storage tanks of individual dwellings only to be pumped and trucked to a holding lagoon or lake with eventual release of the effluent often to a natural tundra wetland.

The Canadian Council of Ministers of the Environment (CCME) recently developed a Canada-wide strategy for the management of municipal wastewater effluent. This strategy was endorsed by the Council of Ministers on February 17, 2009. It is a strategy that sets out a harmonized framework to manage discharges from more than 3,500 wastewater facilities in Canada, many of which currently need repair and upgrading. The intent is to develop performance standards which will increase the protection for human health and the environment on a national basis. The CCME is comprised of the 14 environment ministers from federal, provincial and territorial governments. The CCME recognizes that the Canada-wide performance standards may not be appropriate for some regions of Canada because of regional differences, such those within portions of Canada's Far North (Nunavut, Northwest Territories, and regions located north of the 54th parallel in Quebec and Newfoundland and Labrador). As such, the CCME has provided a 5 year window during which time a strategy will be developed to prepare regional specific performance standards. Regardless of the outcomes, communities north of 60° N latitude will have to ensure that the domestic wastewater effluent meets the performance standards for the far north.

Tundra wetlands located downstream of waste stabilization ponds or those connected with facultative lakes are generally considered as part of the receiving environment and not part of the treatment process. The exploratory research by Yates *et al.* (2012) and Yates *et al.* (2013) has demonstrated that although tundra wetlands are not formally recognized as part of the treatment process they do in fact provide significant additional treatment benefit. Yates *et al.* (2012) and Yates *et al.* (2013) assessed the wastewater treatment potential of several tundra wetlands located downstream of primary treatment facilities. Apart from these investigations there are relatively few studies that match the scope of their tundra specific work. Most of the existing literature provides little guidance regarding treatment process reaction rates, management strategies or predictive tools for assessing the capacity of existing tundra wetlands to meet the needs of expanding populations (Doku and Heinke, 1995). Natural tundra wetlands are by nature open and diffuse systems, often with poorly defined boundaries, flow patterns and permeable boarders (Kadlec, 2009). These conditions present challenges for wastewater regulators who require well defined points of control. This manual is therefore an attempt to address some aspects of the knowledge gap and provide help to those tasked with the management and regulation of wastewaters in Northern Canada by providing background information related to how tundra wetlands process wastewaters and to provide a summary of the most recent data that assesses the efficacy of using tundra wetlands to treat municipal wastewaters along with some operational tools.

In 2008 a team of researchers, environmental educators, and national aboriginal organizations collaboratively presented a proposal to the Royal Bank of Canada under the bank's Blue Water Trust Fund that outlined a path forward to address water issues in aboriginal communities of Canada's north. The proposal addressed both source water protection and the treatment of domestic sewage. This manual has developed out of the work focussed on the development of resource tools for the management and operation of tundra wetlands for the treatment of municipal wastewaters. The manual in its current form is limited to the discussion of wetlands and does not address the operation and maintenance of sewage lagoons, facultative lakes or ponds other than to recognize that they are an important component in the effective treatment of sewage and are required as a pre-treatment step for the sewage prior to it being released to the treatment wetland. In many ways the sewage lagoons perform much of the primary treatment while the wetlands perform functions more characteristic of secondary treatment.

2.0 Tundra wetland as part of the treatment chain

2.1 Natural tundra wetland for wastewater treatment

Focusing on waste disposal as a management technique, rather than wastewater treatment was the original intent of many Arctic systems (Yates *et al.*, in press). As described by Gunnarsdottir et al. (2013) and Ritter (2007) the focus on waste disposal has also been common in many other Polar Regions. Because of the remote nature of these communities, small population sizes, harsh climates and the technical and logistical barriers that hinder the application of mechanical treatment systems more typical of developed regions in southern Canada, the use of waste stabilization ponds (sewage lagoons) and facultative lakes arose. When compared to lagoons/lakes, tundra wetlands have been generally viewed as providing little to no treatment benefit. There has also been concern about the potential release of untreated or partially-treated wastewaters into a natural environment may pose a human health risk if tundra wetlands were the sole treatment option (Doku and Heinke, 1995). In many cases, the genesis of wetlands located downstream of the waste stabilization ponds has been in response to the release of nutrients and organic matter exiting the lagoons. This in turn provided the conditions conducive to the growth and establishment of natural vegetation (Yates et al., in press; Doku and Heinke, 1995). Consequently, many tundra wetlands did not arise because of any intentional design on the part of waste managers and thus cannot be considered akin to constructed wetlands in terms of design features.

Two major tundra wetland assessment studies funded as Canada's contribution to the International Polar Year (2007) and Environment Canada have been summarized and published by Chouinard et al., in press; Chouinard *et al*, 2014; Yates *et al.*, 2012; Yates *et* *al.*, 2013; Yates et al., in press; Yates *et al.*, in press and Yates *et al.*, in press. These studies have demonstrated that even though tundra wetlands are not formally recognized as part of the treatment process they do provide a significant additional benefit to the treatment of municipal wastewater effluents. Apart from these investigations there are relatively few studies that have matched the scope of this tundra specific work. Most of the previously collected information related to the anticipated cold climate treatment performance and predictive aspects of wetland size is found in the unpublished literature and much of this work provides little guidance regarding management strategies, treatment process reaction rates or predictive tools required to assess the capacity of existing tundra wetlands to meet the needs of expanding populations (Doku and Heinke, 1995).

Wastewaters intentionally released from waste stabilization ponds (e.g., decanted), unintentionally released as leakage from the detention berms of the ponds (exfiltration) or the natural releases from facultative lakes typically exhibited levels of carbonaceous biochemical oxygen demand (cBOD), total ammonia nitrogen (TAN) and microbial indicator organism *E. coli* and fecal coliforms that were higher than desired by territorial regulatory authorities (Yates *et al.*, 2012; Yates *et al.*, in press; Yates *et al.*, in press; Chouinard *et al.*, 2014; Challen-Urbanic, 2009). Duko and Heinke (1995) have described wetlands as an energy-efficient and low-cost treatment option for municipal wastewater in the Northwest Territories, Canada. However, they did identify that that the lack of adequate design criteria and performance data presented significant challenges to their use in the Canadian Arctic. Because of these reasons, wetlands are overlooked by some as a viable treatment option, particularly until recently when there were only a few sources from non-peer-reviewed literature that provided only limited guidance regarding their use or potential use (Kadlec and Johnson, 2008).

2.2 Logistical challenges

Because of the remote nature of the communities in the Canadian Arctic, the management and treatment of wastewater are being confronted with a number of logistical challenges. Logistical challenges related to wastewater management by communities in the Arctic at the time of their formation in the early 1960's remain (Yates et al., in press). Dawson and Grainge (1969) had suggested that heated piped systems for Arctic communities was better than haulage systems, because of a reduced chance of accidental spillage, lower chance of contamination and lower maintenance cost. However, the logistical challenges with respect to designing piped systems in Arctic communities because of permafrost, topography, poor town layout and the high construction costs remain impediments to utilodor systems.

The logistical challenges of disposal and management have largely remained unchanged to this day due to the complex nature of Arctic communities. Haulage systems remain the most common form of wastewater collection, despite periods of no service because of service repairs to vehicles or inclement weather (Yates et al., 2012). It is difficult to directly quantify volumes of wastewater discharged into the treatment systems because of the way wastewater is managed. Wastewater volumes can however be indirectly estimated by knowing the volume of potable water delivered to each building. The volume of potable water is monitored more closely since municipalities are mandated under the territorial water taking license agreements to record drinking water withdrawals (Government of Nunavut, 2002).

Access to trained personnel required for the management and operation of municipal infrastructure including wastewater facilities is a major logistical issue for Arctic communities. Johnson (2010) explained that this administrative challenge can be found at multiple levels and is often expressed as a lack of resources for hiring, and even more so a lack of resources for training and retaining qualified personnel. Poor management of records and consequently an erosion of the community's knowledge-base are results of constant shuffling of staff. For the majority of Canadian Arctic communities, this has become an endemic problem (Johnson, 2010).

The fact that accredited laboratories close to Arctic communities are lacking creates a logistical hurdle for compliance testing required for wastewater facilities. Many wastewater parameters are time sensitive and require analysis within defined time lines. The shipment of samples often requires more than twenty-four hours to reach the closest laboratory for analysis: therefore, when samples are collected for regulatory purposes, the quality of the sample arriving at the laboratory is often poor (Yates et al., in press).

2.3 Natural tundra wetland sampling

Natural tundra treatment wetlands present many logistical challenges to sampling and despite the recent studies, much still remains to be known regarding seasonal influences on treatment efficiencies and year-to-year variability in performance. The main challenges to a formal recognition of wetlands as part of a treatment strategy can likely be summarized as:

- No point of control
- No standardized protocol for the establishment of representative sampling points for wetland influent and effluent
- Seasonal and year-to-year influences on treatment performance are poorly understood
- Logistical challenges in sample analysis

2.3.1 Point of control

In most installations, waste stabilization ponds (lagoons) are engineered in a manner that provides the manager control over the release of the treated effluent. In theory, the manager has the ability to retain the wastewater until a desired level of treatment is attained, or to halt the release of wastewater if desired. In the case of natural tundra treatment wetlands, managers do not have the same control over the release of wastewater leaving the wetland. Thus if a manager determined that the wetland was under performing, they would have few options for stopping the flow and retain the wastewater in the wetland until the desired level of treatment was obtained. Therefore without an ability to manage the release of effluent, the regulatory control is undermined.

One option to gain better control over the treatment and release of effluent from the wetland would be to provide good control on what enters the wetland in terms of both effluent quality and quantity. The work outlined earlier in this document demonstrated that treatment performance of the wetland decreased when effluents were decanted (released) into the wetland in late summer over a relatively short time period of a few days (e.g., Fort Providence) as opposed to a continue slow release from an exfiltrating berm of the lagoon. Therefore controlling the volume and timing of the release is one way to better control what is potentially released from the wetland.

2.3.2 Inlet / Outlet sampling points

Site conditions vary greatly amongst individual treatment wetlands. For example, the flow patterns of wastewater released from lagoon systems into the wetland can vary widely within and amongst wetlands. In some situations the flows released from exfiltrating berms travels underground while within the same wetland, some of that flow may travel on the surface in braided streams. Determining which waters (ground waters, surface waters) to sample and in what locations in order to get a representative sample of the influent into the wetland becomes challenging. Likewise it can be just as challenging to determine sample locations of waters exiting the wetland that would provide a good representation of the treatment performance. In addition Mitsch and Gosselink, (1986) concluded that in diffuse and dynamic systems like wetlands, it was unrealistic to establish static formal sampling points since flow patterns alter on an annual basis. What is clearly needed is the establishment of a formalized sampling protocol that provides a standardized methodology for determining sampling locations for the collection of both influent and effluent samples. The sampling protocol described earlier in this document by Yates et al. (2012) provides a good starting point. However, broader input is needed by regulatory agencies and other stakeholders in order to develop a standardized protocol that is acceptable by all major players.

2.3.4 Seasonal and yearly variability

More study is needed to better understand the how treatment performance may vary over seasonal changes and amongst years. One of the major areas that need to be better defined is the period of spring freshet. Wetlands can vary significantly in how they are managed during winter months. In some cases there can be a buildup of wastewater over the winter months that rapidly melt during the freshet. Most of the recent investigations have missed monitoring this time due to logistical challenges associated with travel and sampling. Better understanding the performance dynamics at this time will help in the establishment of better management practices. Likewise, monitoring wetland performance over several years and correlating climatic conditions with treatment performance will help managers better quantify uncertainties in predicted treatment efficiencies.

In an attempt to better understand treatment processes within these Arctic tundra wetlands, the timing of sample collection is important to ensure key treatment periods are captured. Yates et al., (in press) mentioned that sampling should take place at a minimum three times within the year. Accessing these communities more frequently is recognized to not be feasible given the limited availability of resources to do so. Yates *et al.*, (in press) stated that samples should be conducted during thaw (to capture any freshet event - if logistically possible), the active summer period of the wetland, and just before freeze up. The authors explained that these shoulder periods are important, as they will represent the period of poorest performance in the wetland.

2.3.5 Logistical analysis in sample analysis

Due to the fact that the geographical location of the investigated wetlands by the CAWT and Yates *et al.,* (2012) spanned a large geographic area and because of shipping logistics, the laboratory used for sample analysis varied from location to location and between years. Appendix B provides a list of contact information regarding the specific laboratories at which the samples were analyzed.

Natural tundra wetlands have been a reliable technology to manage wastewater to-date despite the lack of knowledge regarding performance, or acceptance as part of the regulated treatment chain. Even though the climatic conditions in the Arctic are harsh wetlands have still demonstrated the capacity for wastewater treatment via natural processes; albeit at slower rates. Evidence of ecosystem response to nutrients in the Arctic wet tundra provides further detail that these systems can quickly assimilate small additions of nutrients and organic matter (Mack *et al.*, 2004; Shaver and Chapin, 1980; Shaver and Chapin, 1995; Gough *et al.*, 2002). Because of the logistical challenges in gathering the type of information described above, most regulatory agencies have tended to view the tundra wetlands as unknowable and unpredictable and therefore of little use as part of a formally recognized wastewater treatment strategy. The need and or merit of formally recognizing these lands in land use planning documents should be revisited in light of the most recent evidence regarding the efficacy of tundra wetlands for the treatment of municipal wastewater effluents. Formal recognition may include the reclassification of these tundra treatment wetlands from their current designation as the receiving environment to being classified as part of the treatment train.

3.0 Current wastewater treatment strategies in Northern Canada

3.1 Current treatment practices employed in the Canadian Arctic

The logistical challenges of bedrock and/or permafrost together with the lack of financial and human resources and within the cold arctic climate represent significant impediments to the development of mechanized wastewater treatment infrastructures commonly used in more southern locations within Canada. As such wastewater disposal to lagoons, engineered lagoons, facultative lakes and/or direct discharge to land have been seen as the most feasible historical options available. The release of primarily treated municipal effluent to the land occurs through the intentional decanting of effluent from a lagoon or via exfiltration (intentional or unavoidable leakage) of the effluent through the wall of the lagoon berm on to the land. Until recently a few communities discharged their hauled wastewater directly to natural depressions or surface water bodies termed facultative lakes without prior treatment. Anecdotal information suggests that the release of municipal wastewaters or primarily treated wastewater effluents into natural depressions appears to have either enhanced vegetative growth or in some cases may have even facilitated vegetative growth in areas that were naturally devoid of vegetation.

In most locations within Canada's Far North, municipal wastewater is first held within sewage lagoons where the wastewater undergoes primary treatment for the reduction of suspended solids and biochemical oxygen demand. In most locations, the retention of the wastewaters is not sufficient to produce municipal effluents that would meet the proposed NPS of 25 mg L^{-1} for the parameters of cBOD and TSS. Tundra wetlands that have either serendipitously or by design developed downstream of sewage lagoons may have the potential to become part of a hybridized treatment system that includes not only the lagoon but also the associated wetland

3.2 Wastewater handling

Yates *et al.*, (2012) stated that wastewater streams in Arctic communities are often quite homogenous and that in most communities it only contains blackwater and greywater. Greywater is discharged directly on to the land from the residence in some communities. Wastewater from commercial sources is typically limited to a few service providers in the community, generally consisting of a hotel, grocery and hardware stores (Yates *et al.*, 2012). In the majority of Arctic communities, industrial wastewater is not a component of the waste stream. Communities will occasionally have process/packaging plants for fish or other locally harvested foodstuff. The only other source of industrial wastewaters is provided by airports and fueling depots, but most of the waste generated in these systems is not incorporated into the municipal waste stream, as they are often diffused across the landscape (Yates *et al.*, 2012).

As stated earlier, wastewater is managed at the source by binging temporary held in insulated holding tanks located just outside or under raised buildings. Tanks are pumped out and sewage hauled via pumper trucks to the disposal area. Drinking water is also distributed via tanker trucks. Consequently, water use in these communities is significantly less than the Canadian average (Yates *et al.*, 2012). Wootton and Yates (2010) reported that the average for many communities in Nunavut is approximately 90 Liters/day/per, but some communities have usage averages below 70 Liters/day/per. Low usage in these communities is often the result of logistical issues described previously.

3.3 Long and short-term holding lagoons

Long and short-term holding (discontinuous and continuous discharge) lagoons are the most common treatment system in Canadian Arctic communities (Heinke *et al.*, 1991). Long and short-term lagoon systems are often engineered using aspects of the natural landscape. The use of small lakes, with additional berms to prevent spring overflow and engineered berms in a natural depression, are common methods of creating lagoons to treat wastewater in the Arctic. Wastewater that is directly discharged into a lake is referred to as facultative lakes or ponds. Facultative lakes may be contained (retention) or experience percolation (continuous discharge or detention) of wastewater through the berm sides. The engineered and facultative lake lagoon systems rely on algae-bacterial populations to breakdown organic matter in aerobic and anaerobic zones of the lake. Discontinuous or intermittent discharge lagoons are also common. In the past these systems have been designed in the same manner as lagoons in more temperate regions, but are often much larger to accommodate for deeper winter ice depths, lower bacterial-algae biomass and longer residency time (Dawson and Grainge, 1969). Because lower bacteria-algae populations limit the metabolism of organic particles, mechanical aeration has been recommended for northern regions (Dawson and Grainge, 1969). Although mechanical aeration is a common solution in temperate regions, in remote northern communities the availability of infrastructure to power those systems is not feasible due to operational limitations. Despite extensive use of lagoons in the Arctic there remains little peer-reviewed literature on their performance (Wootton *et al.*, 2008c; Yates *et al.*, 2012).

3.4 Mechanical and connected central serviced systems

The use of mechanical and connected centrally serviced wastewater treatment facilities in the Canadian Arctic is minimal. Some large communities utilize the Hudson Bay or Arctic Ocean as a receiving environment, with primary treatment connected on line prior to discharge into the receiving environment. These communities have municipal services (piping) that serve many of the residents, commercial buildings and any industry present. The wastewater passes through a pumping or lift station to the receiving environment. The pumping station may contain primary treatment systems, such as screening and/or communitors to remove or break down grit and large organic debris (Johnson, 2008). This form of wastewater treatment is uncommon in communities of the Canadian Arctic. The only community that is recorded to have anything more advanced than primary treatment is Pangnirtung, Nunavut on Baffin Island. Pangnirtung is reported to have a secondary treatment facility using a rotating biological contactor and activated sludge system (Wootton *et al.*, 2008a). Most Arctic communities remain without mechanical systems since earlier attempts have shown that these systems under Arctic conditions regularly fail to produce effluent that meet regulatory standards, or because of operation costs, or the lack of a skilled labor pool to maintain them (Johnson and Wilson, 1999). Initial attempts to use mechanical treatment could be considered an oversight by planners to appropriately address community needs, as many communities have returned to using simpler technologies such as lagoons (Johnson, 2008). This evidence demonstrates the need for alternative low cost, simple, yet efficient techniques for wastewater treatment in the Arctic.

3.5 Land treatment and wetlands

Land disposal or land treatment is another common method of wastewater treatment or disposal in the Arctic (Wootton *et al.*, 2008a). In Arctic Canada, wastewater disposed onto the land is done so at some distance away from the community and drinking water sources, although there are examples where the receiving environment is indirectly connected to the community water supply, as in Baker Lake (Wootton *et al.*, 2008a; Yates *et al.*, 2012). Although overland flow is present, such as in Coral Harbour, many of the land treatment locations are actually in natural wet-sedge tundra wetlands. However it is not known whether these systems existed as wetlands before receiving increased water and nutrient loads, or whether they are a result of the anthropogenic influence. Evidence from fertilization studies show that nitrophilous and hydrophilic plants have been found to colonize these environments following long periods of increased water and nutrient loading. Kadlec and Johnson (2008) suggested that the wetlands may not have been present prior to sewage being disposed at these sites.

Whether or not these landscapes have been altered, the use of wetlands is extensive secondary and, in some locations, primary treatment in Arctic Canada. They have shown excellent ability to treat wastewater in the past in more temperate locations (Kadlec and Wallace, 2009; Mander and Jenssen, 2002). However, similarly to lagoon systems in the Canadian Arctic, there is very little data from peer-reviewed literature on wetland performance.

3.6 Current and future wastewater regulations in the Canadian Arctic

Performance standards for wastewater effluents are currently in transition within Canada as the federal government is developing national performance standards (NPS) for municipal wastewater effluent. In 2009, the Canadian Council of Ministers of the Environment (CCME) released the final draft of the *Canada-wide Strategy for the Management of Municipal Wastewater Effluent* which details regulatory changes to be implemented through the Canadian *Fisheries Act.* The intent of the strategy is to ensure there are no deleterious effects to the water bodies receiving the treated effluent, particularly with regard to fish health and or fish habitat. This strategy has identified specific national performance standards for effluent of Canadian wastewater treatment facilities at 25 mg L^{-1} for the parameters of cBOD and TSS, 1.25 mg L^{-1} for un-ionized ammonia expressed as NH_3-N at 15°C±1°C and a standard of 0.02 mg L^{-1} of total residual chlorine (TRC) (CCME, 2009). The Federal Government recognizes that conditions in portions of Canada's Far North (Nunavut, Northwest Territories, and regions located north of the 54th parallel in Quebec and Newfoundland and Labrador) are unique and as such NPS have not yet been determined for these areas. A five-year research period was initiated in 2009 to determine what NPS (treated effluent concentration levels) would be appropriate in the Canadian north (CCME, 2009).

4.0 Cold Climate Treatment Wetland Studies: Overview from the 1970s to present day

This section includes a synthesis of the studies that have been conducted on the treatment performance, and potential impacts, of natural wetlands used for municipal wastewater treatment operating specifically in cold climates. This information is intended to summarize the current performance of tundra treatment wetlands in Canada's far north and to identify knowledge gaps that need to be addressed to improve the application.

Our knowledge of wastewater treatment in remote Canadian Arctic communities has grown very little since the 1970s, despite a half-century of operation. Current knowledge of treatment performance of natural treatment wetland systems in the Canadian Arctic is largely restricted to site-specific governmental and consultant reports (Dillon Consulting Ltd., 2004; Environment Canada, 1985), and other sources of unpublished literature. Only a few peer-reviewed documents, as well as conference proceedings (Miyamoto and Heinke, 1979; Johnson and Wilson, 1999) exist to contribute to our current understanding of performance with most investigations confined to the performance of lagoons. In the Canadian Arctic, wastewater treatment facilities such as lagoons and wetlands are generally designed and managed using southern engineering standards, adopting design models to reflect Arctic temperature (Kadlec and Johnson, 2008; Prince *et al.*, 1995; Heinke *et al.*, 1991).

Most of the intentional use of natural wetlands for the treatment of municipal wastewater has been primarily for the provision of tertiary treatment (Breaux *et al.*, 1995; Cooke, 1994; Kadlec *et al.*, 1979). In the 1990s, it was estimated that approximately half of the 200 surface flow wetlands used for wastewater treatment in North America were natural wetland systems (Brix, 1994). There has been a general reluctance to use natural wetlands for treatment purposes since the long term impacts upon the natural ecology of these areas is generally uncertain (Kadlec and Wallace, 2009). Despite these uncertainties, it has been demonstrated on numerous occasions that natural wetlands are effective in the treatment of municipal wastewater. Previous studies and reviews on this topic have demonstrated that wastewater treatment can be effective even in cold climate regions (Mander and Jenssen, 2002; Kennedy and Mayer, 2002; Wittgren and Mæhlum, 1997; Jenssen *et al.*, 1993). The following paragraphs in this section summarize the research conducted to date on cold climate treatment wetlands in Canada, particularly the arctic and sub-arctic.

Wright (1974) conducted one of the first natural treatment wetland studies in northern Canada. This site was a 32 ha natural swamp in Hay River, NWT that received primary treated municipal wastewater from three wastewater stabilization ponds WSPs. The author reported that the effluent discharge area was estimated at 110 m^2 per capita per year. In this study, hydrological context for the swamp was not quantified; therefore, dilutive effects could not be estimated. The swamp was sampled monthly from August 1972 to September 1973 (Wright, 1974). Favorable percent reductions in concentrations of treatment performance parameters were observed in Wright's study, including: 97.7% for BOD; 96.8% for TSS; 98.0% for VSS; 96.2% for Un-ionized Ammonia Nitrogen (NH_3-N); 97.6% for TP; and 98.7% for Total Coliform (TC). The author observed an ecological alteration to the swamp in terms of decreased benthic organism diversity, zooplankton, nekton, and alterations in the overall composition of the ecological community. Flows were observed to be transient in the swamp over the treatment season with a high spring freshet flow. Increased bacterial concentrations were observed at the swamp's outlet during the spring freshet. Wright (1974) recommended guidelines for the use of similar natural swamps as part of the wastewater treatment process. These recommendations stipulated that the: 1) wetland treatment areas be sited away from groundwater recharge zones; 2) alteration of the natural wetlands should be deemed acceptable; and 3) wetland morphology should be such that the HRT is relatively long. Doku and Heinke (1993) reported that the Hay River, NWT swamp was studied for over twenty years and during that time it consistently met the regulatory compliance requirements for the treatment system.

The work of Dubuc *et al.* (1986) is one of very few papers to investigate long-term performance of treatment wetlands in Northern Canada. The authors demonstrated that a natural peat wetland in Northern Quebec was highly effective at treating domestic wastewater. The study site was located at the James Bay Energy Company's Fontanges construction camp for the James Bay Energy Company in Northern Québec and was a mid- to high boreal wetland area near the 55th parallel. The camp wastewater was discharged into a peatland that was approximately 1.5 km in length. For most treatment performance parameters, average percent reductions were greater than 90%, indicating that the natural peatland system was highly effective at treating the wastewater. Dubuc *et al.* (1986) noted that the study failed to quantify the hydraulic parameters of this area and thus the proportion of treatment related to dilution could not be assessed.

Doku and Heinke (1993) reported that Canada's northern communities are small and remote, experience extreme climates, have limited infrastructure funds for construction, design and maintenance of facilities, and have a chronic shortage of skilled labour. Natural tundra wetland areas in northern territories are generally nutrient deficient, and abundant. Doku and Heinke (1993) suggested that the addition of municipal wastewater to tundra wetlands could improve the ecological functioning of the area through the addition of nutrients, while minimizing deleterious water quality impacts to other receiving environments. According to Doku and Heinke (1993), the primarily domestic origin of the wastewater generated and the relatively small size of northern communities render the use of natural tundra treatment wetlands an appropriate option for use in the North, particularly for communities that have sufficient land available for the application. Increased long-term monitoring data collection and interpretation as a precursor to the identification of the most appropriate design criteria for use in the arctic and sub-arctic regions were recommended by the authors.

The use of natural wetlands in the Yukon was also discussed by Doku and Heinke (1995). The Yukon Water Board had at that time issued five licenses to communities in the territory to permit the use of natural wetlands for secondary municipal wastewater treatment. The Yukon Water Board required that treatment performance and site-specific hydraulic assessments be conducted before use of the systems as part of the wastewater treatment train. Primary treatment of wastewater, at a minimum, prior to discharge into the wetlands was a regulatory requirement. The demonstration of long-term treatment of effluent discharge in the absence of ecological impacts was a stipulation of acceptance by the regulatory body. Doku and Heinke (1993) suggested, as part of their study, recommendations to guide the use of natural treatment wetlands as a viable and effective secondary or tertiary treatment technique. Their recommendations included: 1) requiring that all natural treatment wetland systems be capable of meeting treatment guidelines established by the NWT government during the time of their study; 2) that site-specific ecological studies be conducted to determine local vegetation pollutant removal capabilities; 3) that a minimum of primary treatment occur in advance of wastewater discharge to the natural wetland; and 4) that an areal BOD loading rate not exceed 8 kg BOD_5/ha·d, and that a HLR of between 100 and 200 m^3/ha·d be maintained. In a subsequent publication (Doku and Heinke, 1995), the authors provided additional recommendations: 5) conduct further research on the use of natural treatment wetlands in order to assist in the establishment of design criteria; 6) that the NWT government encourage the informed and responsible use of natural wetlands for wastewater treatment; and 7) that communities be informed and become engaged on the responsible use of natural wetlands for treatment.

A study by Kadlec and Johnson (2008) addresses some mechanistic function in a Canadian Arctic treatment wetland but did not provide significant background data. Much of the current knowledge on plant and microbial influence on wastewater treatment in the Arctic has been derived from smaller-scale fertilizations and carbon cycling studies in different

Arctic environments (Shaver and Chapin, 1995; Arens *et al*., 2008; Edwards and Jefferies, 2010). Edwards and Jeffries (2010), in a study on the winter treatment abilities of arctic wetlands, disproved the common assumption that arctic wetland treatment mechanisms cease in the winter. Their study located in a low arctic meadow in Churchill, Manitoba, focused on nitrogen uptake by *Carex aquatilis*. The authors determined that plant uptake still occurs at temperatures below 0°C. They suggested that decomposition processes occur year-round in tundra ecosystems, and mentioned that vegetation nitrogen uptake was elevated during spring melt. These studies demonstrate the effective use of natural arctic and sub-arctic wetlands for use in municipal wastewater treatment.

Recently, researchers and graduate students from Dalhousie University's Centre for Water Resources Studies have established environmental monitoring programs in six Nunavut communities: Grise Fiord, Pond Inlet, Clyde River, Coral Harbour, Pangnirtung, and Kugaaruk. Hayward *et al*., (2012) conducted hydrological characterization and assessed treatment performance of a natural tundra wetland receiving effluent from a single-cell wastewater treatment exfiltration lagoon in Coral Harbour, NU. The authors reported that the hydraulic loading rate of effluent on the wetland was highly dynamic, depending on seasonal factors with greater loading occurring during the spring melt period. The HRT of the natural treatment wetland was also highly variable depending on the period of observation; generally, the HRT was much shorter during the spring melt when flows into the wetland were high. Treatment performance (in terms of concentration reductions) of the natural treatment wetland was observed to be reduced in June compared to September, attributable to decreased retention time and higher amounts of dilution. Hayward *et al*., (2012) concluded that the incorporation of natural tundra wetland areas in wastewater treatment may be a viable option in Canada's North; however, appropriate rate constants must be applied when determining appropriate hydraulic loading rates, and sizing the required wetland treatment area.

The Centre for Alternative Wastewater Treatment (CAWT), Fleming College, Lindsay, Ontario has also been investigating the treatment performance of Arctic wetlands since 2008. The majority of this work was funded by the Federal government through the

International Polar Year (IPY) program and from Environment Canada (EC). Much of this work has been published in Yates *et al*., (2012, 2013 and in press) and Chouinard *et al*., (2014 and in press). The IPY study assessed the treatment performance of six natural tundra wetlands that received municipal wastewater from the hamlet communities of Arviat, Baker Lake, Chesterfield Inlet, Coral Harbour, Repulse Bay, and Whale Cove in the Nunavut region of Kivalliq. During the EC study the treatment performance of seven additional northern treatment wetlands located in both Nunavut and Northwest Territories were investigated. The focus of the EC study was to monitor treatment as the wastewater traversed the wetland in order to provide Environment Canada background information needed to help in the determination of appropriate NPS specific to arctic conditions within Canada. The overall goal of both studies was to evaluate the efficacy of using northern tundra wetlands to treat municipal wastewaters. The results are presented in section 6.1.2 and 6.2.2 of Chapter 6. The treatment performance assessments conducted on the natural tundra wetlands demonstrated that the passive wastewater treatment technology has promising potential to be an effective technology for use in communities in the Canadian Arctic.

5.0 Natural tundra wetlands for wastewater treatment

The following represents the culminating summary for two separately funded studies investigating the performance of northern treatment wetlands undertaken by the Centre for Alternative Wastewater Treatment (CAWT), Fleming College, Lindsay, Ontario. Data from these two studies likely represent the most extensive data base currently existing. This data base assesses the capacity of 13 tundra treatment wetlands situated in Nunavut and the Northwest Territories of Canada. The first study was funded by the Federal government through the IPY program. During the IPY study (2008-2011) the treatment wetlands associated with six Nunavut communities (Kilvalliq region) were investigated by monitoring key water quality parameters within the influent and effluent (e.g., two sample locations) over the course of an Arctic summer (e.g., several weeks of sampling per wetland). A summary of the IPY investigation has been published in Yates *et al*., (2012, 2013 and in press) and Chouinard et al., (2014 and in press). Subsequent funding was provided by Environment Canada (EC) through the EC Aquatic Ecosystem Management Research Division to investigate the treatment performance of seven additional northern treatment wetlands located in both Nunavut and Northwest Territories (2009-2011). The focus of the Environment Canada study was to monitor treatment as the wastewater traversed the wetland. This meant that each of the EC wetlands was studied more intensely than the IPY wetlands (e.g., multiple sites between inlet and outlet of wetland). The duration of time spent at each of the EC wetlands was generally only a few days per year (unlike the IPY study); however, several of the EC wetlands were revisited in subsequent years. The overall scope of both studies was to evaluate the efficacy of using northern tundra wetlands to treat municipal wastewaters. This involved monitoring the change in chemical, biochemical and physical characteristics of municipal wastewater effluent as it traveled through wetland areas and to assess major influencers within the wetland that affect wetland performance. The EC study was undertaken to provide Environment Canada background information needed to help in the determination of appropriate NPS specific to arctic conditions within Canada.

5.1 International Polar Year Wetland Study

The CAWT was awarded a research grant from the Federal government through IPY to investigate the efficacy of northern treatment wetlands and to document efficiencies in the treatment of municipal sewage received from six adjacent hamlets in the Kivalliq region of Nunavut. Systems in the Hamlets of Arviat, Baker Lake, Chesterfield Inlet, Coral Harbour, Repulse Bay and Whale Cove were studied (Figure 5.1). Three of the six treatment wetlands, located in the communities of Arviat, Coral Harbour, and Whale Cove received effluent after pre-treatment in waste stabilization ponds or lakes. The other wetlands in

Figure 5.1 Map of Canada showing location of communities studied (Map Credit: Noreen Goodliff).

Baker Lake, Chesterfield Inlet, and Repulse Bay received either wastewater that had received minimal pre-treatment or raw wastewater from trucks directly. This section provides a summary the study results. Those wishing more detail regarding this work are referred to the published work of Yates *et al.* (2012 and in press). All IPY wetlands sites studied in these six communities were all physiographically distinct, with varying cover and composition of vegetation communities, presence of surface water and treatment area (Yates *et al.*, 2012).

5.1.1 Methodology

Samples were collected from six treatment wetlands between June 21st and September 24th, 2008 which approximates the historical ice-free period of the year (9-12 weeks); June 10-15 to September 5-20 (Mack, 2004; Yates *et al.*, 2012). Samples were transported in coolers to a laboratory in Rankin Inlet and analyzed within 24 h of collection for time sensitive analysis of parameter (e.g. $cBOD_5$, and pathogens) following Standard Methods for Wastewater (Yates *et al.*, 2012). At each of the six wetlands, samples of 500 mL each from the point of influence and effluence were obtained. The samples gathered weekly were used to evaluate the temporal variation associated with treatment efficacy of the tundra wetlands (Yates *et al.*, 2012). Biological, chemical and physical water quality parameters were assessed; particularly $cBOD_5$, TSS, and NH_3-N which are regulatory parameters of the Fishery Act regulations (Government of Canada, 2010).

Other sampled parameters include DO, TC, *E. Coli.*, TP and COD. Temperature was recorded continuously over the ice-free period, with Onset Temperature logging tidbits situated in the surface water of the influent and effluent streams, obtaining readings at 0.5 h intervals (Yates *et al.*, 2012). The focus of this study was to assess treatment efficiencies over the duration of one Arctic summer (June – September). This was accomplished by monitoring selected wastewater quality parameters in both the influent entering the wetland and the in the effluent exiting the wetland. No attempts were made to monitor the progression of treatment at sample locations between the influent and effluent sites. Sampling at the influent and effluent is considered the minimum required sampling for wastewater treatment facilities (Kadlec and Wallace, 2009). Yates *et al.*, (2012) reported that sampling more than once per week was not logistically possible, given restrictions of flight schedules in the Arctic to transport samples within a 24-h period. A second season of data was collected in 2009 only for Baker Lake.

5.1.2 Results

Within these communities, the collected wastewater was place into either wastewater stabilization lagoons (sewage lagoons), into facultative lakes or discharged directly into the wetland without pre-treatment. Yates *et al.*, (2012) found that the concentration of the $cBOD_5$ entering these systems ranged between 550-1000 mg/L, and noted that influent wastewater entering wetlands following pre-treatment in either facultative lakes or lagoons was significantly less than that of direct discharge into the wetland. Influent values observed in Whale Cove (facultative lake pre-treatment) as compared to Chesterfield Inlet (direct discharge) (Table 5.1) shows this difference. For each community, the performance of wetland measured varied for different wastewater parameters; some wetlands were much more efficient in the treatment of TP or NH_3-N than other wetlands, while TSS was particularly variable (Yates *et al.*, 2012). TSS reductions were generally high in systems where wastewater was diluted in stream and small water bodies; believing that sedimentation was a primary treatment process. This was especially noticeable in Repulse Bay and Baker Lake.

$cBOD_5$ and COD removal was observed to vary between 47-94% and 57-96%, respectively amongst the wetlands. The percent removal of COD and $cBOD_5$ and TSS were generally lower in the wetlands that received wastewater that was first pre-treated in either a facultative lake (e.g., Whale Cove) or an engineered lagoon (e.g., Coral Harbour). The reason for the lower treatment rates in these wetlands likely relates to the fact that much of the oxidative treatment and settling of TSS was occurring within the pre-treatment phase (Yates *et al.*, 2012). In all wetlands the effluent was below 25 mg/L for $cBOD_5$ and TSS, which are the effluent standards for municipal wastewater for $cBOD_5$ and TSS in southern Canada. Yates *et al.*, (2012) found that at the time of study, treatment facilities with minimal holding capacity during the winter months observed increases in $cBOD_5$ effluent concentrations during the spring freshet, such as in Chesterfield Inlet. Amongst the wetlands removal was observed to vary between 80-99% and 85-100% for TP and NH_3-N, respectively. Systems with more surface water flow obtained high levels of DO, although all achieved concentrations of greater than 8 mg/L on average in the effluent. Pathogen concentrations were generally reduced significantly, although results were variable and likely influenced by natural sources such as snow geese (*Chen caerulescens L.*) which were commonly present throughout some of the wetlands (Yates *et al.*, 2012).

Air temperature and soil temperature can significantly influence the treatment of wastewater in the Arctic and during winter time temperatures (e.g. -17° C to -32° C between November and May) no significant biological treatment occurs (Yates *et al*., 2012). The authors also mentioned that wastewater treatment would be expected to be minimal during the spring freshet during the release of thawing wastewater that had accumulated over the winter in communities that did not have the capacity of long term storage and thus discharged to the wetland during these frozen periods. The sampling conducted in this study captured a portion of the spring freshet, which likely accounted for variation in effluent concentration of many of the parameters tested. These variations are the most prominent at the end of June during final snow melt and at the end of September following senescence and short periods of freezing temperatures.

Yates *et al.,* (2012) reported that some treatment wetlands such as Arviat and Cambridge Bay, were modified through the construction of berms to help both direct and detain the flow of wastewater through the wetland in an attempt to increase the hydraulic residence time (HRT) and thus allow more time for the microbial uptake/transformation of nutrients in the wastewater (Yates *et al*., 2012).

Table 5.1 Mean influent and effluent data, with percent concentration change, and wetland characteristics from six tundra treatment wetlands studied in Nunavut.

Performance measured & Wetland characteristics / Wetland Site	Coral Harbour	Arviat	Repulse Bay	Whale Cove	Baker Lake	Chesterfield
Wetland – Conc. In ($cBOD_{5\ mg\ L^{-1}}$)	181	103	385	40.3	466	221
Wetland – Conc. Out ($cBOD_{5\ mg\ L^{-1}}$)	14	16	25	21	6	14
% Reduction between in & out	92	85	93	47	99	94
Wetland – Conc. In ($COD_{mg\ L^{-1}}$)	308	236	450	133	798	300
Wetland – Conc. Out ($COD_{mg\ L^{-1}}$)	66.3	100	64.4	39.5	24	64.3
% Reduction between in & out	79	58	86	70	97	79
Wetland – Conc. In ($TSS_{mg\ L^{-1}}$)	93.2	55.7	197	29.4	314	74.9
Wetland – Conc. Out ($TSS_{mg\ L^{-1}}$)	10.5	19.1	34.8	18.0	3.2	10.3
% Reduction between in & out	88	66	82	39	99	86
Wetland – Conc. In ($TP_{mg\ L^{-1}}$)	5.5	11.3	9.2	4.1	13.9	5.6
Wetland – Conc. Out ($TP_{mg\ L^{-1}}$)	0.8	2.3	1.4	0.1	0.2	0.4
% Reduction between in & out	86	80	85	97	99	92
Wetland – Conc. In ($NH_3\text{-}N_{mg\ L^{-1}}$)	21.8	73.2	70.0	9.0	82.5	39.6
Wetland – Conc. Out ($NH_3\text{-}N_{mg\ L^{-1}}$)	2.8	11.0	2.8	0.0	0.1	0.1
% Reduction between in & out	87	85	96	100	>99	99>
Wetland – Conc. In (*E Coli* $_{mg\ L^{-1}}$)	3.7E4	2.9E4	14.6E6	7.5E3	16.4E6	1.3E6
Wetland – Conc. Out (*E Coli* $_{mg\ L^{-1}}$)	1.7E2	9.0E2	1.6E2	3.6E1	1.4E1	8.7E1
% Reduction between in & out	100	97	100	100	>99	>99
Wetland – Conc. In ($TC_{mg\ L^{-1}}$)	4.9E6	6.3E5	2.1E9	1.2E5	30.6E6	57.1E6
Wetland – Conc. Out ($TC_{mg\ L^{-1}}$)	6.9E3	4.7E3	1.9E3	2.0E2	1.1E3	7.7E2
% Reduction between in & out	100	99	100	100	>99	99>

Wetland – Conc. In (DO $_{mg\,L^{-1}}$)	3.3	1.9	1.3	10.0	0.7	1.7
Wetland – Conc. Out (DO $_{mg\,L^{-1}}$)	10.6	9.1	10.1	10.9	8.9	11.0
% Reduction between in & out	68	79	87	8	92	84
Temperature In (°C)	11.7	9.2	6.1	8.2	14.2	6.6
Temperature Out (°C)	9.7	6.3	6.2	10.7	3.2	6.2
Volume discharged (m^3/day)	96	235	66	82	167	36
Size of wetland (ha)	10	7.8	9.5	3.7	1.1	55
Approximate length (m)	650	500	1,400	900	70	700
Approximate width (m)	130	140	70	35	150	200
Water holding capacity (m^3)						

5.1.3 Discussion

The study results obtained in the harsh climatic conditions and low biomass producing ecosystems of the Canadian Arctic exemplifies the ability of natural wetlands to act as sinks and transformers of nutrients, organic material and pathogens. Yates *et al*., (2012) noted that the exact mechanisms and processes of transformation and removal have not been identified in this study and should be examined further. The wetlands surpassed expectations for the removal of organic matter in the form of $cBOD_5$/COD, pathogens, NH_3-N, TP and had reasonable TSS removal, despite the lack of knowledge in processes. In all cases, removals for $cBOD_5$ were below regulatory standards for effluent in southern Canada (CCME, 2009). TSS was also below regulatory standards in southern Canada; only the Coral Harbour wetland was the exception. Pathogen concentrations were variable, which may be attributed to local wildlife populations, a common variable in natural wetlands (Yates *et al*., 2012).

Treatment efficiencies are negatively impacted during the spring freshet in areas where large volumes of frozen wastewater have accumulated during the winter months. An appropriate management strategy to improve treatment during the spring freshet would be to store wastewater generated over the winter period in lagoons or facultative lakes (Yates *et al*., 2012). These lagoons should be designed as continuous flow exfiltrating systems, which slowly decant into throughout the summer months. This way, the wetlands would be able to sustain performance with lower and longer sustained loading rates, than with an annual rapid release of frozen wastewater during spring freshet or the annual end of summer decant when most plants have already begun to senesce (Yates *et a*l., 2012). Chesterfield Inlet and Baker Lake have both received larger lagoons as part of their treatment systems since the time of study by Yates *et a*l., (2012).

5.2 Environment Canada Wetland Study (2009-2011)

During the 2009 field season the CAWT investigated the treatment wetlands associated with Paulatuk (NT) and Pond Inlet (NU). The additional sites of Edzo (NT), Fort Providence (NT), Gjoa Haven (NU), and Ulukhaktok (NT) were studied in the 2010 field season. During the summer of 2011 Edzo (NT) was revisited and Taloyoak (NU) was studied for the first time. Figure 5.2 illustrates the generalized locations of these wetlands and Table 5.2 provides specific information concerning the dates of the on-site visits.

This study was undertaken to:

- Better understand the range of treatment efficiencies currently achieved at existing tundra wetlands to inform the development of a NPS for the Far North in the regulations of the Fisheries Act;
- To present these data in an interpolated format to provide a visual overview of treatment performance within the wetland, and
- Better understand correlations between effluent strength and influential factors that modulate treatment efficiencies in order to determine if there are some common insights / principles that could be used to develop better operational (design) standards for the use of tundra wetlands.

5.2.1 Methodology

The wetland surveys conducted for Environment Canada were performed in midsummer (e.g., late July to early September) for each of the three years of investigation. Each wetland was visited over a one to six days duration depending on whether the investigation undertaken was ether: i) a full survey or a reconnaissance survey and ii) the physical size of the wetland with larger wetlands requiring more time to survey. Reconnaissance surveys were employed only for Fort Providence and Edzo, both surveyed in 2010. Full surveys were conducted on all other Environment Canada wetlands including Edzo which was revisited for a second time in 2011. Reconnaissance surveys were intended to provide a rapid assessment of wetland performance and differed from full surveys in that the number of sample collections sites was reduced, along with a reduction in the number of water quality parameters investigated. The water quality parameters eliminated from the reconnaissance survey were typically those parameters such as cBOD5 or microbial samples whose analysis was time sensitive. Both survey methods provide a one-time "snap-shot" analysis of wetland performance, with most water quality parameter samples collected on one day. Thus the data generated for Environment Canada are discrete and do not represent time series data. The following provides a detailed explanation of what constituted a full survey and a reconnaissance survey.

Figure 5.2 Generalized location of treatment wetlands investigated by the CAWT for Environment Canada during the summer months of 2009 - 2011.

Table 5.2 Summary of wetland studied, by year and intensity of study.

Location	Territory	lat / long	2009	2010	2011
Paulatuk	NT		full		
Pond Inlet	NU		full		
Edzo	NT			RC	full
Fort Providence	NT			RC	
Gjoa Haven	NU			full	
Uluhaktok	NT			full	
Taloyoak	NU				full

Legend: full means full study protocol; RC means reconnaissance study protocol

Full Survey

Each wetland was surveyed using a standardized methodology developed for this investigation. In brief, transects were established to provide full coverage of the portion of the wetland believed to be actively involved in the treatment of municipal effluents. Sample locations were established at various points along each transect in a standardized manner in order to achieve the desired intensity of sample collection. The location of each collection site, along with numerous other points was geo-spatially referenced with the use of a TopCon 3105W reflectorless total station that provided not only referenced site locations but also elevation differences and the boundary of the active portion of the wetland involved in the treatment of municipal effluents. The full survey was designed to assess key water quality parameters of the effluent as it traversed the length of the wetland in order to determine the effectiveness of the wetland treatment process. In a similar manner, soil samples were collected to monitor key parameters influenced by municipal effluents in order to better assess effluent / soil interactions such as nutrient concentrations and trace elements within the soil matrix. Physical and hydrological parameters of the wetland's soil matrix, such as, grain size, porosity, hydraulic conductivity and percent moisture were also assessed to better understand the primary factors influencing subsurface flow and preferential flow of the effluent within the wetland. Lastly, the full survey also included information regarding the vegetative community structure within the wetland. The information presented in this document will summarize the major parameters such as $cBOD_5$, TSS, TAN and TP, and the hydrological and hydraulic context of the wetlands.

The establishment of transects and sample locations and the mapping of micro-topographic changes within the wetland

A thorough ground-truthing of the wetland was first undertaken by an initial walk around the site to determine point(s) where influent entered the wetland and the effluent exited the wetland and major preferential flow pathways through the wetland complex. During this time, effort was also taken to determine the approximate boundaries within the wetland believed to embody the landscape actively involved in the effluent treatment process. This information was then used to establish a series of transects at right angles to the general flow path; beginning near the point of influence and ending near the point of effluence. The number of transects established longitudinally through the wetland was dependent on the length of the wetland assessed. The placement of transects was done in a manner that captured the primary treatment areas identified during the ground-truthing exercise. The number of sample locations along each transect was dependent upon the width of wetland that a particular transect traversed. It should be noted however, that a transect may or may not contain a surface water/ preferential flow sample point depending on the physical makeup of the wetland. Groundwater sampling locations were established approximately every 15 m.

A TopCon 3105W reflectorless total station was used in Paulatuk, Gjoa Haven, Ulukhaktok, and Taloyoak, to map wetland boundaries, elevation, and microtopographic variation within the wetland. Similar data was collected in Edzo, Pond Inlet and Fort Providence via a global positioning system (GPS, Garmin eTrex Vista HCx) since factors such as thick vegetative understory interfered with line of sight for the total station or the lack of human resources available did not permit the use of the total station. For the collection of total station data, a single base station was established to which bench marks were tied together spatially using back sighting. An individual with the prism and rod walked along transects throughout the wetland in order to accurately reference the sample locations. Surveying was conducted by running cross-sectional transects across the entire width of the wetland, making sure to capture surface and groundwater sampling locations. Transects traversed the length of the wetland and spaced approximately 30 m apart or closer in some locations. Measurements were recorded every 10-15 m across the wetland. Each point was also referenced with a global positioning latitude-longitude coordinate. At surface and groundwater sampling points used in the water quality analysis, measurements were also taken 0.25 m and 0.75 m away from the sampling point. This was conducted to help map micro-topographic changes within the wetland.

Surface Water Sampling

The surface water samples were generally collected from surface flow or preferential flow locations. Surface samples were often collected into the sample bottle by submerging the sampling container below the water surface. However, in cases where water depth was shallow, syringes were used to minimize the disturbance of sediment that could have been collected inadvertently using the other method. Surface water samples were obtained from a minimum of 40 sample points throughout active treatment zone but could be more depending on the dimensions of the wetland. The chemical and biochemical water quality parameters surveyed in surface waters are summarized in Table 5.3 Likewise physical and ionic parameters of surface water samples are summarized in Table 5.4 with the trace elemental parameters identified in Table 5.5.

In addition, surface water temperature was recorded during the site visit with the placement of a hobo tidbit data logger into the surface water of the wetland in one location. Likewise, air temperature was also logged during this time by the suspension of one hobo tidbit data logger at one location in the wetland.

Table 5.3 Chemical and biochemical water quality parameters surveyed in surface waters collected from tundra wetlands

Ammonia (NH_3-N)	Total Phosphorus (TP)
Nitrite (NO_2-N)	Phosphate (PO_4)
Nitrate (NO_3-N)	Dissolved Organic Carbon (DOC)
Total Kjeldahl Nitrogen (TKN-N)	Dissolved Oxyen (DO)
Total Coliforms (TC)	Chemical Oxygen Demand (COD
Escherichia coli (EC)	Carbonaceous Biological Oxygen Demand - 5 Day (cBOD5)

Table 5.4 Physical chemistry and ionic parameters surveyed in surface water samples collected from tundra wetlands

Temperature	Conductivity
Total Alkalinity	pH
Hardness	Total Solids (TS)
Sulfate (SO_4^-)	Total Suspendid Solids (TSS)
Chloride (Cl^-)	Volatile Solids (VS)
Flouride (F^-)	Volatile Suspended Solids (VSS)

Table 5.5 Trace elements surveyed in surface water samples collected from tundra wetlands

Aluminum (Al)	Copper (Cu)	Rubidium (Rb)
Antimony (Sb)	Iron (Fe)	Selenium (Se)
Arsenic (As)	Lead (Pb)	Silver (Ag)
Barium (Ba)	Lithium(Li)	Sodium (Na)
Beryllium (Be)	Magnesium (Mg)	Strontium (Sr)
Calcium (Ca)	Manganese (Mn)	Thallium (Ti)
Cadmium (Cd)	Mercury (Hg)	Uranium (U)
Cesium (Cs)	Molybdenum (Mo)	Vanadium (V)
Chromium (Cr)	Nickel (Ni)	Zinc (Zn)
Cobalt (Co)	Potassium (K)	

Subsurface Water Sampling

In locations where surface waters were not present, subsurface water samples were collected with the use of a lysimeter (0.05 m diameter) constructed from polyvinyl chloride (pvc) piping which was placed into a bore hole at a maximum depth of 0.25 m or less where soils were shallow. A series of 1/8 inch holes were drilled into the lower 10 cm portion of the lysimeter which were then covered with a microfilter sheath to allow the infiltration of groundwater into the tube without the intrusion of sediment or organic matter. Sample water was collected with the aid of a sterile 60 mL syringe fitted with peristaltic pump tubing that allowed the extraction of water from deep within the lysimeter. A single syringe/tube system was designated to a specific subsurface sampling point and corresponding lysimeter. Lysimeters were purged prior to sampling followed by the collection of a 500 mL water sample after recharge. Once completed syringes and tubing were discarded. If a new sampling period was required, then a new syringe and tube was prepared for that lysimeter.

Groundwater flow

Groundwater flow was surveyed only at the Ulukhaktok, Edzo and Taloyoak treatment wetlands. This work was undertaken to provide information regarding the subsurface flow of wastewater through the wetland and to provide in a generalized manner an ability to compare one treatment wetland with another in order to gain insight to the relative flow rates and hydraulic retention times. To accomplish this, piezometers were installed at each groundwater water quality sampling station. Piezometers were constructed from 0.02 m diameter polyvinyl chloride (PVC) pipe, with perforations for the inflow of water in the bottom 0.15 m of the piezometer tip. The length of the piezometer piping was 0.53 m. Two piezometers were installed at each collection site, with up to 50 sites per wetland. Tundra wastewater treatment wetlands have been found to be rarely greater than 0.30 m in depth. The piezometers were installed at the two different depth ranges of 0.10-0.20 m depth and 0.20-0.30 m depth. A subsurface well (lysimeter), for subsurface water quality samples was included in the cluster with the piezometers. A description of the subsurface well or lysimeter is provided in the water quality sampling section (above).

The characterization of the wetland's hydrology was further augmented with the use of soil moisture probes. This provided a rapid infield assessment of the relative closeness of the water table to the surface. At each topographic sample location, soil moisture content was assessed. A TDR soil moisture probe was used to take readings of percent soil moisture of the upper 12cm of soil. These data were used to conduct a spatial analysis of moisture gradients throughout the wetland, potentially indicating primary flow subsurface paths of wastewater passing through the wetland.

Vegetative Community Structure

A digital photograph of a 1 m^2 plot centered on each water quality sample location was taken. The dominant plant species were later determined for each plot with each of the dominant plants expressed as a percent cover of the entire vegetative cover in the photograph.

Quality Assurance / Quality Control

For all samples, HDPE bottles were used. Each filled sample bottle was labeled with sample location and Fleming College and packed in appropriate coolers together with a chain of custody form identifying each bottle and the analyses required. Coolers were packed with ice and Onset Hoboware temperature logging tidbits to record temperature variances during sample shipment. The shipment of samples may have been 24 to 48 hours in duration and therefore it was necessary to monitor the temperature to ensure sample integrity was known. The desired temperature was 4±3°C.

A series of measures were adopted to ensure that all water samples collected in the wetland had not been contaminated by poor handling, or pre-assessment contamination of sampling bottles. Nutrient parameters were also preserved with acid at the site of collection prior to being shipped for analysis.

5.2.2 Results

The results generated from the work on the seven Environment Canada wetlands are summarized below. In brief, the following text describes in a generalized manner the similarities and differences amongst the wetlands in terms of $cBOD_5$, TSS, Ammonia, microbial presence, and the hydrology of the sites. The first portion of the results section focuses on treatment performance differences amongst the wetland site. The later portion of the results section provides a summary of the major findings for each individual wetland. Many of the water quality parameters of the analyzed wetland effluent samples have also been expressed as an interpolated map for ease in visualizing the trends noticed at each wetland site. A collection of selected interpolated maps can be found in the Appendix.

Review of overall treatment performance amongst wetlands

This section summarizes the generalized treatment performance patterns evident in each of the wetlands at the time of study. The values expressed here are intended to provide an overview of the generalized performance with the understanding that these results provide only a "snap shot" overview that can vary seasonally and from year to year. However, this high level overview is helpful in understanding basic information regarding the level of treatment afforded by the wetlands and major differences amongst the wetlands.

Wetland Characteristics

Each wetland is unique in both its natural characteristics and how municipal effluents are discharged to the wetland. In some locations such as Paulatuk and Taloyoak the municipal sewage is pre-treated by disposal to a facultative lake while pre-treatment occurs within engineered lagoons at Pond Inlet, Edzo, Fort Providence, Ulukhaktok, Gjoa Haven. In addition, the effluent from the pre-treatment lagoons at Fort Providence and Pond Inlet sites are decanted, meaning that a large volume of effluent is discharged over a short period of time. This is different from the other sites where the effluent either exfiltrates through the berm wall of the lagoon or overflows through a natural drainage channel from the facultative lake with the result that the effluent is released at these sites in generally a continuous manner with smaller daily volumes than what is experienced at the sites where decanting takes place. Most wetland sites are relatively flat, allowing a slow progression of effluent over the length of the wetland. Pond Inlet is different in that the slope of the site is much steeper.

Apart from the descriptors above, wetlands can also be characterized by the associated hydraulic loading rate (e.g., depth of water applied per unit area), organic loading rate (e.g., mass of organic material applied per unit area), hydraulic conductivity (flow rate through the substrate) and hydraulic retention time (turn over time of the water volume retained in the substrate). Each of these parameters will affect treatment efficiencies by influencing how long the effluent is retained in the wetland which in dictates the length of treatment (often microbial and/or transformation and mechanical filtration). Treatment can also be influenced by many other parameters such as the inflow of new water from melt or precipitation events (e.g., dilution), temperature, vegetation cover (areal extent and speciation), substrate grain size, composition of the effluent and so on.

Some of the more prominent wetland characteristics and hydrological parameters have been summarized in Table 5.6. These values can be used to provide an overall indication as to the major similarities and differences amongst the wetlands. In this table, the depth of the active wetland substrate has been arbitrarily set at 0.4 m in order to provide an estimate of the relative groundwater holding capacity of the wetland. Survey results generated from this study suggests that the depth of the saturated substrate level is close to this value (e.g., 0.4 m), however, it should be understood that a standardized depth has been chosen to facilitate comparisons amongst wetlands. Although the porosity of each wetland was measured, some of the measurements appear high (particularly for Pond Inlet) and may have been influenced

Table 5.6 Wetland characteristics: daily volume applied equals the annual effluent released in a 122 day period; organic loading based on cBOD5 influent concentrations.

	wetland size m^2	arbitary depth m	average porosity	water holding capacity m^3	daily vol applied m^3/d	cBOD5 influent mgL^{-1}	Hydraulic Loading cm / d	Organic Loading kg/ha · d	Hydraulic Retention d
Paulatuk	14600	0.4	0.48	2803	102	40	0.69	2.8	27
Pond Inlet	5800	0.4	0.82	1902	312	70	5.4	38	6.1
Edzo	21300	0.4	0.50	4260	325	26	0.51	1.3	13
Fort Providence	8700	0.4	n.a.	n.a.	n.a.	60	2.6	16	n.a.
Gjoa Haven	169000	0.4	0.46	31096	356	113	0.21	2.4	87
Ulukhatok	72900	0.4	0.62	18079	121	94	0.17	1.6	149
Taloyoak	61200	0.4	0.48	11750	257	80	0.42	3.4	46

by the high organic content of the soil which absorbed water and artificially inflated the corresponding pore space volume. The water holding capacity of the wetland has been generated by multiplying the wetland size by substrate depth and associated porosity. The daily volume of effluent entering the wetland is based on the annual volume of wastewater generated by the community and dividing this value by 122 days or the number of days in June, July, August and September. It is believed that effluent enters the wetland only during periods above freezing and hence the reason for this calculation. It is not known however, how evenly this volume is distributed over the 122 day period and it is anticipated that greater flows are experienced early in the season when the thaw first begins. The hydraulic loading rate is an expression of the depth of water entering the wetland on a daily basis if this water was evenly distributed and it is one way of visualizing how flows differ amongst wetlands. The organic loading rate is based on the concentration of the $cBOD_5$ in the influent entering the wetland. The hydraulic retention time (HRT) provides a measure of how quickly the volume of water contained in the substrate of the wetland is replaced with the associated volume of influent discharged to the wetland per day. It should be noted that the HRT expressed in Table 5.6 is based on the assumption that the hydraulic conductivity of the substrate is large enough to not impede the subsurface flow rate needed to accommodate this volume. However, an evaluation of the hydraulic conductivity of the wetland substrates was found to be slow enough to like impede the total infiltration of these volumes thus resulting in overland flow. The extent and duration of overland flow is still unknown.

From the data contained in Table 5.6 it can be seen that the wetland at Gjoa Haven is the largest while the Pond Inlet site is the smallest. Pond Inlet also has the highest hydraulic loading rate with Fort Providence being having the second highest HLR. Likewise the greatest organic loading rates are occurring at the Pond Inlet and Fort Providence wetland sites. The flow of ground water through the subsurface substrate was studied more intensely at the Ulukhaktok, Taloyoak and Edzo wetland sites. Groundwater flow through these wetlands was estimated using the Darcy equation.

$$Q=K_h d_s(dh/dx)$$

Where *Kh* is the hydraulic conductivity, which was estimated by conducting pumping tests at each of the piezometers using the methods described by Luthin (1966).

The hydraulic conductivities for the Ulukhaktok site ranged from 1.20 m/d to 1.24 x 10^{-3} m/d. The term *dh/dx* is the hydraulic gradient estimated by the elevation of the water table at a transect in relation to the adjacent transects. The d_s is the cross sectional area of the saturated zone, which is the elevation difference between the permafrost layer and the water table. The depth of the permafrost layer was considered the deepest point at which the drivepoint piezometers could penetrate to.

The hydraulic conductivity of the Ulukhaktok wetland is highest in the vicinity of the lagoon berm. The average hydraulic conductivity of the soils in Transect 1, closest to the lagoon, is 7.98 x 10^{-2} m/d, considerably higher than the 3.9 x 10 $^{-2}$ m/d averages of the remaining 7 transects. As expected, the hydraulic conductivity of the wetland decreases with depth. The average hydraulic conductivity of the soils surrounding the shallow piezometers was 6.38 x 10^{-2} m/d, whereas hydraulic conductivity of the soils surrounding the deep piezometers was 2.34 x 10^{-2} m/d. The result is that flow rates are substantially higher in the upper portion of the saturated layer. The piezometer data shows that the water table is perched in at multiple locations in the south-eastern part of the wetland. The areas where this perching occurs are adjacent to locations with extremely low hydraulic conductivities, which is to be expected. At sites where there were both deep and shallow piezometers (and both contained water), it was possible to estimate if water was recharging or discharging at that particular location. All but three nests locations showed hydraulic gradients that indicated a downward movement of water. Three nests (2D, 5C and 6C) had gradients that would indicate upward discharge of water indicating that the flow of water through the wetland subsurface matrix was complex. Overall water flow through the subsurface saturated layer of the wetland is limited. The low hydraulic conductivities and low hydraulic gradients in the wetland result in estimated groundwater flows ranging from 0.00001 m^3/day per unit width to 0.0004 m^3/day per unit width.

The hydraulic conductivity values for Taloyoak were similar to Ulukhaktok in that the upper portion of the substrate (shallow) was slightly faster flowing (0.0035 m/d) in comparison to the deeper layers of the substrate (0.00082 m/d). Overall the hydraulic conductivity range within the Taloyoak substrate varied between 0.013 m/d to 9.76 X 10^{-6} m/d. The hydraulic conductivity at the Edzo wetland was found to be slightly faster flowing in the deeper portions of the substrate (0.0054 m/d) than the upper portions (0.0035 m/d). Overall the hydraulic conductivity values at the Edzo site ranged from 0.016 m/d to 3.46 X 10^{-5} m/d. Hydraulic conductivity measurements were conducted on composite soil samples taken from the Paulatuk and Pond Inlet wetland sites. These soils were first oven dried and later the soil clod were gently broken and placed into a static head permeameter. The resulting values were 1.81 m/d for Paulatuk and 1.04 m/d for Pond Inlet indicating that in general terms the hydraulic conductivity of Paulatuk was greater than that of Pond Inlet.

Carbonaceous Biochemical Oxygen Demand (5 day)

An overview of the general treatment performance has been summarized in Table 5.7. For comparative purposes, this table indicates the $cBOD_5$ target identified in the hamlet's water licence (at the time of study) and an approximate $cBOD_5$ concentration entering the wetland and exiting the wetland in order to provide an approximate indication of overall treatment expressed as a "% reduction". For example if the $cBOD_5$ concentration entering the wetland is 40 mg L^{-1} and exiting the wetland this concentration has decreased to 2 mg L^{-1}, then this is expressed as a 95% reduction, or the $cBOD_5$ concentration has been reduced by 20 times.

The concentration of the $cBOD_5$ leaving the wetland is then compared to the CCME national performance standard of 25 mg L^{-1} set for southern municipalities. It is understood that national performance standards have not yet been determined for northern communities; however, this southern standard is being used for comparative purposes in order to assess the relative ability of the wetlands in the treatment of this parameter. This comparison is expressed as a percent value. For example if the $cBOD_5$ exiting the wetland is 2 mg L^{-1} then this value is lower than the NPS of 25 mg L^{-1} and is expressed as approximately 8% of the NPS. If however, the $cBOD_5$ exiting the wetland is 50 mg L^{-1}, then the percentage is 200% meaning that the value is twice as great as the NPS of 25 mg L^{-1}.

The treatment performance is further summarized by providing a generalized indication as to where in the flow path of wastewater through the wetland the incoming $cBOD_5$ concentration is reduced by half (e.g., 50% reduction) and when the $cBOD_5$ reaches an approximate steady state. These generalized zones of reduction are expressed as a percentage of the total distance the effluent travels through the wetland. For example, if the total length of the wetland is approximately 100 m and the $cBOD_5$ concentration is reduced by half (e.g. 50% reduction) after traveling the first 30 m into the wetland then this values is expressed as "30% of the total distance of the wetland's length is required to achieve a reduction of 50% in the strength of the wastewater parameter". Likewise, if the $cBOD_5$ values are generally stable for the last quarter of the wetland's length, then this is expressed as "75% of the total distance of the wetland's length is required to achieve steady state". Note that the steady state can vary amongst wetlands and therefore it does not represent a standardized performance value.

Table 5.7 Overview of wetland treatment performance in the reduction of cBOD5

Performance Measure / **Wetland Site**	Paulatuk	Pond Inlet	Edzo	Fort Providence	Gjoa Haven	Ulukhaktok	Taloyoak
Water Licence Conc. (BOD5 mg L^{-1})	100	100	30	100	80	120	unknown
Wetland - Conc. In (cBOD5 mg L^{-1})	40	70	26	60	113	94	80
Wetland - Conc. Out (cBOD5 mg L^{-1})	2	50	2	32	2	5	25
% Reduction between in & out	95	29	92	47	98	95	69
% of NPS for cBOD5 (25 mg L^{-1})	8	200	8	128	8	20	100
% Wetland length to achive 50% reduction	25%	***	50%	***	20%	30%	50%
Wetland length to achieve 50% reduction (m)	70	***	150	***	150	160	240
% Wetland length to achive steady state	50%	***	85%	***	60%	80%	70%
Wetland length to achieve steady state (m)	140	***	260	***	450	425	335
Size of Wetland (m^2)	14600	5800	21300	8700	169000	72900	61200
Approximate length of wetland (m)	275	250	300	160	750	530	480

Legend: *** means that <50% reduction was achieved

In all wetlands, except for Pond Inlet and Fort Providence, a 50% reduction in $cBOD_5$ was achieved within the first half (e.g., inlet side) of the wetland and in the case of larger wetlands such as Gjoa Haven and Ulukhaktok this reduction was achieved within the first 20 to 30 percent of the wetland. All wetlands met or exceeded the NPS of 25 mg L^{-1} 'for $cBOD_5$ except for Pond Inlet and Fort Providence. The $cBOD_5$ removal rates were even greater in Taloyoak than what is shown in Table 5.7 when sampled from the stream exiting the Taloyoak wetland. The $cBOD_5$ concentrations of approximately 2 - 3 mg L^{-1} are observable within the appended data tables for this stream location. However, this stream area was not considered in the mapping of the Taloyoak wetland and is therefore not incorporated into the interpolated maps for Taloyoak. The $cBOD_5$ treatment appears to be poorer in areas associated with high moisture content, or in areas of standing water, particularly in the Taloyoak wetland. The underlying cause for this association is unknown, but may be related to a greater influence of surface water flow and less subsurface flow which may in turn be related to shorter HTR at those wetter locations. This is however, only speculation at this point.

The poor performance of both Pond Inlet and Fort Providence may be related to their relatively smaller size. The steep slope of the Pond Inlet wetland facilitates a rapid travel of the effluent down the slope leading to the assumption that the HRT at Pond Inlet is very short. In the case of the Fort Providence wetland it was assessed in 2010 during the decant period and likely a major factor as to why the treatment efficiency was poorer. In addition it should be noted that the the surface water of the adjacent *Typha* marsh was not included as part of the wetland boundary due to the depth of the water which made sample collection difficult. However, this wetland marsh should have likely been included as part of the wetland. It is anticipated that the samples collected from this site would likely have had significantly lower $cBOD_5$ concentrations. Future investigations of the Fort Providence wetland should include the *Typha* marshland. These results also suggest that better treatment may be achieved if the rate of the lagoon decant was slower, allowing for a greater time for wetland treatment.

Total Suspended Solids

The current water licence agreements for total suspended solids amongst the eight sites varies from a low of 35 mg L^{-1} for Edzo to a high of 180 mg L^{-1} for Ulukhaktok. Individual limits are summarized in Table 5.8. The pattern of TSS is variable within and amongst most wetland sites and it is therefore difficult to assess how well individual wetlands are performing in the removal of TSS. In some locations there appears to be an association between higher TSS values and higher relative soil moisture content. This association may be due in part to how the samples were collected. Water samples in drier areas were, for the most part, collected from sampling wells inserted into the wetland that provided access to subsurface water samples and hence may naturally contain less TSS because of the filtering process occurring with subsurface flow. In wetter locations surface waters were often collected. Wetter locations tended to be in lower points of elevation and located nearer the outflow of the wetland. It is also suspected that the wetter locations may be more influenced by surface flow and thus could be one reason why in some wetlands the concentration of TSS increases rather than decreases as the effluent traverses this area.

A further subdivision of TSS into its components of Fixed Suspended Solids (FSS) and Volatile Suspended Solids (VSS) can be used to provide an indication of the organic component of TSS. Municipal effluents tend to be high in organic content in comparison to the inorganic fraction. Graphing the ratio of VSS to FSS and monitoring the change in this ratio can at times provide a better distinction between the portion of TSS originating from municipal effluents and the portion that could be a natural constituent of the site. Volatile suspended solids were analyzed for all sites except for Paulatuk and Fort Providence.

A review of the ratio of VSS to FSS for the Pond Inlet wetland (Figure 5.3) reveals that the VSS remains relatively constant and thus suggests that this wetland was poor at removing suspended solids from the wastewater effluent. The poor removal of $cBOD_5$ supports the conclusion that relatively little treatment of the effluent in terms of carbon removal was occurring.

A similar graph of VSS to FSS for the Taloyoak wetland shows a changing ratio where the percentage of VSS (the organic portion) decreases with travel length through the wetland suggesting that the wetland is effective in the removal of TSS originating from municipal effluents (Figure 5.4). The trend for the ratio of VSS to FSS in the remaining wetlands is more variable and difficult to interpret as evident in Gjoa Haven and Ulukhaktok (Figure 5.5 and Figure 5.6, respectively). There does not appear to be a clear trend of decreasing VSS with increased travel through the wetland. It should be understood however that VSS is determined by measuring the mass loss after ignition at 550°C.

Table 5.8 Summary of current water licence compliance targets for total suspended solids

Performance Measure / Wetland Site	Paulatuk	Pond Inlet	Edzo	Fort Providence	Gjoa Haven	Ulukhaktok	Taloyoak
Water Licence Conc. (TSS mg L^{-1})	120	120	35	120	100	180	unknown

Overall, the use of TSS as an indicator of treatment performance in wetlands is likely a poor choice for compliance testing. It appears that in some cases, wetlands can be a generator (not a sink) for TSS. Generation of TSS can occur through erosional forces within the wetland, particularly during melt events where the velocities of surface water flows may be strong enough to transport inorganic fines. In other situations wetland may contribute organic constituents to surface flows from the decomposition of plant matter. If

TSS is to be used as a treatment indictor, then it is suggested that the sample be analyzed to determine the proportional composition of organic to inorganic matter (e.g., the ratio of VSS to FSS) in order to gain better insight into how the wetland is functioning in regards to the removal and or addition of these constituents.

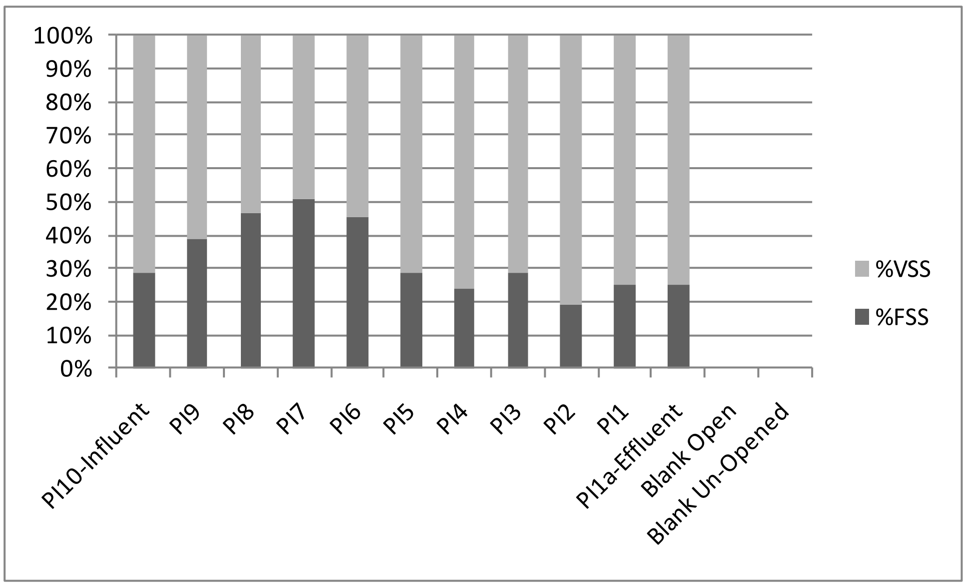

Figure 5.3 Ratio of VSS to FSS at the Pond Inlet wetland. Effluent direction through the wetland is from left to right.

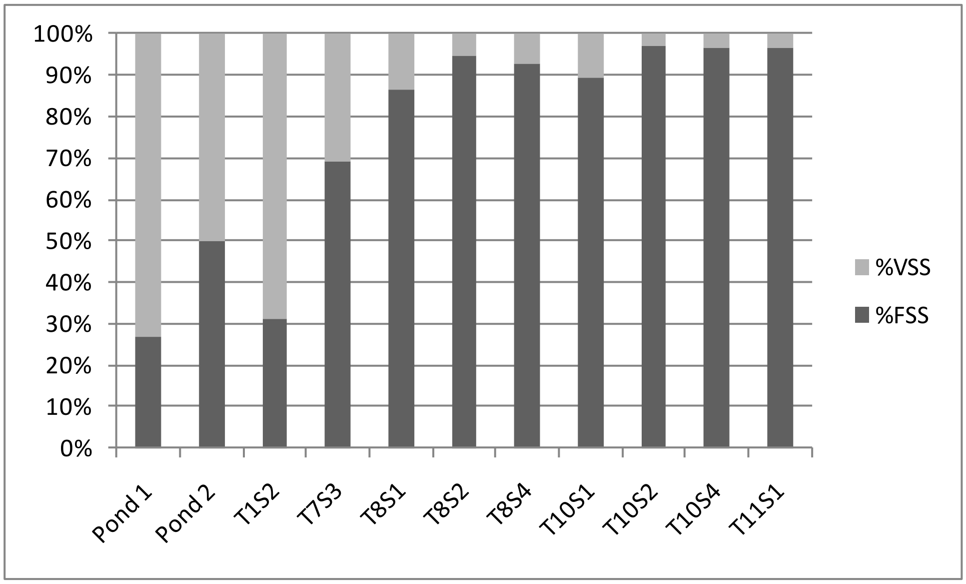

Figure 5.4 Ratio of VSS to FSS at the Taloyoak wetland. Effluent direction through the wetland is from left to right.

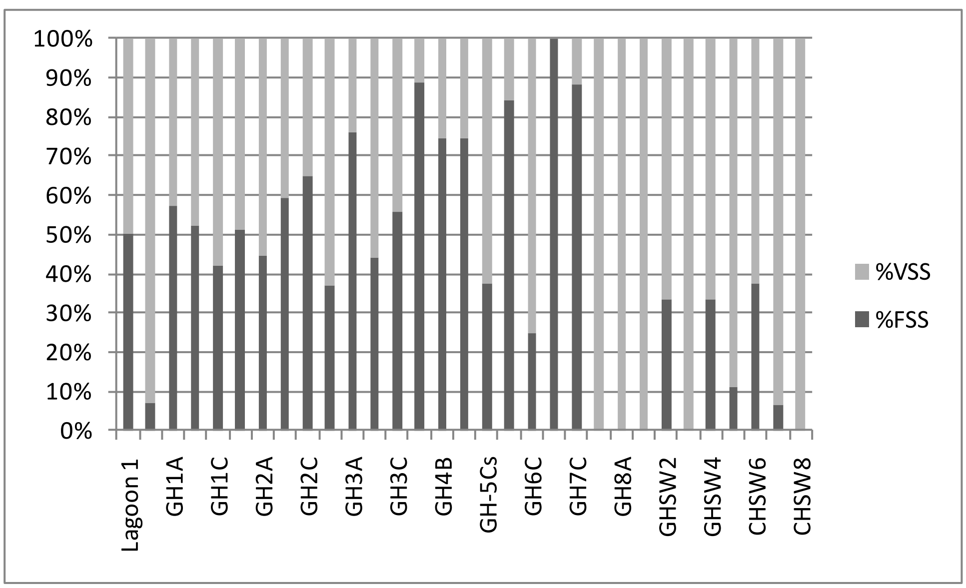

Figure 5.5 Ratio of VSS to FSS at the Gjoa Haven wetland. Effluent direction through the wetland is from left to right.

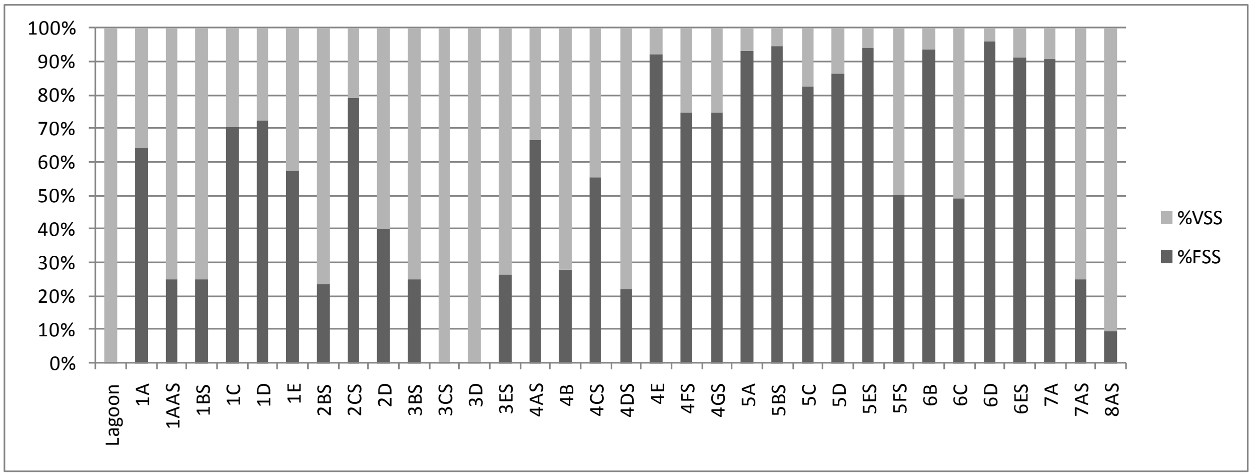

Figure 5.6 Ratio of VSS to FSS at the Ulukhaktok wetland. Effluent direction through the wetland is from left to right.

Ammonia

Ammonia can exist in both an un-ionized form (NH_3) and an ionized form (ammonium NH_4^+). The proportion of these two forms is both pH and temperature dependant with higher percentages of NH_3 favoured with higher pH values. The un-ionized form (NH_3) is toxic to aquatic life forms and as such CCME has set a national performance standard for the concentration NH_3 (measured as N) at 1.25 mg L^{-1} for southern treatment plants. A NSP guideline for northern communities is currently under review.

The ammonia concentrations expressed in this report are expressed as the concentration of nitrogen measured in NH_3. This is written as NH_3-N. However the nitrogen measure from the NH_3 form does not accurately represent the toxic form of NH_3 found in the original environmental sample. The effluent sample in its natural state would contain a fraction of both the un-ionized form (NH_3) and the ionized form (NH_4^+). The effluent sample is analyzed under a basic environment which forces all of the NH_4^+ into the NH_3 form. Thus what is expressed in the value NH_3-N is actually the nitrogen from both the un-ionized and ionized forms. Therefore a better expression of this value is a term called “total nitrogen ammonia” or TAN for short. In order to approach the NPS of 1.25 mg L^{-1} of the toxic un-ionized form (NH_3), a “total nitrogen ammonia” (TAN) concentration of approximately 100 mg L^{-1} in an environment with a pH of 8 and a temperature of 5°C would be needed.

All TAN values (expressed in this manual as NH_3-N) were well below the 100 mg L^{-1} example provided above. The highest concentration of TAN (e.g., 76 mg L^{-1}) was found entering the wetland at Gjoa Haven. The pH of the wetland effluent was less than 8 at all sites except for some locations within the Taloyoak wetland (pH range: 7.1 to 8.6), however, the TAN concentrations at the Taloyoak were below 5 mg L^{-1}. Because of either the relatively non-basic pH values in the wetland or the low TAN concentrations it can be surmised that the concentration of the un-ionized toxic NH_3 would be well below the threshold of 1.25 mg L^{-1} in all areas of the wetland including the effluent exiting the wetland to the receiving water body.

The removal of ammonia was efficient in all wetlands with the exception of Pond Inlet and Fort Providence. Once again, the steep slope and the anticipated short hydraulic retention time at Pond Inlet likely contributed significantly to the poor ammonia removal. The poor performance at Fort Providence may have been related to the fact that this wetland was surveyed during the lagoon decant period and so flows would have been higher than normal with the inflow of fresh effluent. Ammonia removal in all other wetlands was generally ninety percent or greater (Table 5.9) and strongly suggests that the release of NH_3 would be well below the 1.25 mg L^{-1} NPS established for southern Canada.

Table 5.9 Overview of wetland treatment performance in the reduction of total ammonia nitrogen (TAN) expressed as NH3-N

Performance Measure / Wetland Site	Paulatuk	Pond Inlet	Edzo	Fort Providence	Gjoa Haven	Ulukhaktok	Taloyoak
Water Licence Conc. (TAN mg L^{-1})	not set	not set	not set	not set	not set	not set	not set
Wetland - Conc. In (TAN mg L^{-1})	3.2	75.4	16.1	26	76.4	9.6	4.6
Wetland - Conc. Out (TAN mg L^{-1})	0.01	31.6	0.31	18	1	0.1	0.13
% Reduction between in & out	100	58	98	31	99	99	97
% Wetland length to achive 50% reduction	33%	100	50%	***	30%	20%	30%
Wetland length to achieve 50% reduction (m)	90	250	150	***	230	100	150
% Wetland length to achive steady state	70%	***	60%	***	60%	50%	70%
Wetland length to achieve steady state (m)	190	***	180	***	450	270	335
Size of Wetland (m^2)	14600	5800	21300	8700	169000	72900	61200
Approximate length of wetland (m)	275	250	300	160	750	530	350

Legend: *** means that <50% reduction was achieved

Microbial Indicators

When microbial indicators are stipulated for compliance purposes, most water licences base treatment on the reduction of fecal coliforms. For this investigation, total coliforms and E. *coli* were the primary microbial indicators surveyed in all wetlands except for Pond Inlet were microbial parameters were not monitored and in Paulatuk where fecal coliforms were monitored in addition to total coliforms and *E. coli*. Microbial organisms by nature are very heterogeneous in their distribution and thus sample results often reflect high variability. As such, any results generated from this study must be understood as providing only a snap shot of the conditions on that particular sample day with the realization that no attempt was made to quantify the variability in microbial densities at a particular sample locations. Thus the results can at best provide only a generalized impression of treatment efficiencies. The expression of these data into interpolated maps has been challenging since outliers caused from either natural variability or perhaps sample contamination at the time of collection can skew the resulting maps. It should also be understood that *E. coli* is a subset of the microbial density that is normally captured when monitoring the larger body of organisms categorized as fecal coliforms. However, the *E. coli* data does provide an indication of trends in the overall reduction of *E. coli* that likely reflect similar trends that would have been noticed in fecal coliforms should these organisms had been monitored. An overall comparison of the microbial removal by wetland has been provided in Table 5.10.

The information presented in Table 5.10 is intended to provide a high level overview of treatment performance that will allow some generalized trends to be identified amongst the treatment wetlands. This information should not be used for generating specific values since all values presented are rough approximates, particularly when describing approximate lengths within the wetlands associated with a percent reduction in bacterial counts.

Overall, the densities of *E. coli* exiting the wetlands are below the densities stipulated in the water licences for fecal coliforms within all wetlands. It is understood that *E. coli* is only a subset of fecal coliforms and had fecal coliforms been measured, then the microbial densities exiting the wetlands would likely have been higher. In most cases the log reduction of *E. coli* was approximately 2 or greater except for Fort Providence where it was less than 1 log unit.

Table 5.10 Overview of wetland treatment performance in the removal of microbial organisms

Performance Measure / Wetland Site	Paulatuk	Pond Inlet	Edzo	Fort Providence	Gjoa Haven	Ulukhaktok	Taloyoak
Water Licence (Fecal Coliforms - CFU/100mL)	$1x10^4$	$1x10^6$	$1x10^3$	$1x10^5$	$1X10^3$	$1X10^5$	unknown
Wetland - In (E. *coli* - CFU/100mL)	2850		9090	2480	408000	9210	1300
Wetland - Out (E. *coli* - CFU/100mL)	1		1	990	300	1	24
Approximate log reduction	3		4	<1	3	4	1.5
% Reduction between in & out	100		100	60	100	100	98
% Wetland length to achive 50% reduction	20%		50%	80	10%	50%	75%
Wetland length to achieve 50% reduction (m)	50		150	130	50	270	360
% Wetland length to achive steady state	40%		90%	***	20%	60%	85%
Wetland length to achieve steady state (m)	110		270	***	100	320	400
Size of Wetland (m^2)	14600	5800	21300	8700	169000	72900	61200
Approximate length of wetland (m)	275	250	300	160	750	530	480

Legend: *** means that <50% reduction was achieved

Trace elements

The concentration of trace elements in the effluent samples exiting from the wetland is for the most part below the Canadian Water Quality guidelines for the protection of aquatic health. Where elevations are occurring within the wetlands, the primary elements seen above water quality guidelines include iron > copper > zinc. The elevated occurrence of arsenic, chromium and cadmium are less frequent. At the Paulatuk and Edzo sites, iron and copper where the only two elements found in the effluent exiting the wetland.

5.2.3 Discussion

The water quality data for each of the seven sites studied for Environment Canada are presented in the form of interpolated maps in Appendix C of this manual. Note that the raw data files for the interpolated maps are contained in Appendix D. The interpolated maps for most wetlands represent only the more prominent parameters.

The findings from the study funded by Environment Canada indicate that at the time of investigation all wetlands, with the exception of the Pond Inlet and Fort Providence sites, were reducing $cBOD_5$ sufficiently to meet the CCME NPS of 25 mg L^{-1}. Some wetlands like Paulatuk, Edzo, Gjoa Haven and Ulukhaktok were able to lower the values to less than 10 mg L^{-1}. This likely was influenced by both the larger size of the wetlands and the correspondingly lower organic loads entering these sites. Likewise all wetlands with the exception of Fort Providence and Taloyoak (note: Pond Inlet not assessed) were able to achieve a 2 log or greater reduction in *E. coli* counts. All the wetlands studied were, however relatively poor in the removal of total suspended solids. This may be due in part to the phenomenon that wetlands can both remove and generate their own suspended solids, and in particular the organic portion (VSS). Thus it becomes difficult to interpret the TSS findings because the current assessment performed by laboratory methods do not distinguish the portion of TSS originating external to the wetland (e.g., municipal influent) and the TSS generated by the wetland itself. Although the study monitored total ammonia nitrogen (TAN) and not the toxic un-ionized NH_3-N, the values of TAN were low enough in all effluents exiting the wetland to ensure that the concentration of the un-ionized fraction would be well below the NPS of 1.25 mg L^{-1} NH_3-N. Trace elements within effluent samples taken from the wetland were generally below the Canadian water quality guidelines for the protection of aquatic health. Iron, copper and zinc were slightly elevated at or near the discharge of some wetlands. At this stage it is not known if the concentration seen in the effluent samples is a reflection of metal concentration within the sediment portion of the wetland and reflects a buildup of these trace elements above what would be found in nearby reference locations. More study would be needed to be able to better understand the long term impact of land disposal of municipal effluents to these areas.

The data were analyzed to determine if there was an association between the concentration of COD and BOD_5 and $cBOD_5$. If a relationship was found it was speculated that COD may be able to serve as a proxy parameter for the evaluation of BOD_5 and/or

$cBOD_5$. The ability to use a proxy parameter such as COD would prove valuable since the COD sample can be preserved in the field and thus does not have the sample time constraint regarding sample shipment to an analytical laboratory. However, no observable relationship was observed for any of the wetland sites.

Analysis of the data indicated that performance of Pond Inlet and Fort Providence was distinctly poorer than the other five sites. Interestingly the effluent transfer from the pre-treatment lagoons to the wetlands was through decanting. The release of effluent into all other wetlands was via a slower but continuous exfiltration through leaky berms or continuous release from facultative lakes during the frost free season suggesting that better treatment can be achieved when releases are slow and continuous. The impact to treatment process caused by a sudden discharge related to a decant event or spring freshet is unknown. It is anticipated that higher flow volumes can decrease HRTs and increase organic loading to the point that the treatment system is overwhelmed and treatment efficiency decreases. Decanting of lagoons is also typically done at the end of the summer period therefore wetlands have less time to assimilate the nutrients and other pollutants.

A four month summer period (e.g. 122 days) was arbitrarily chosen to represent the average period of time when wetlands could be expected to be unfrozen and when effluents would be expected to be flowing through the wetlands. It is anticipated that the extreme cold during winter months would freeze the municipal effluent exiting the pre-treatment lagoons and effectively stop all treatment by the wetland. The study was for the most part conducted in late summer and so little is known about the effluent flow volumes and concentrations occurring in the early part of summer shortly after the thaw and when effluents started to once again flow to the wetlands. In some cases it may be that the flow volumes overwhelmed the wetland's treatment capacity and yet it could also be that there is such a dilution effect occurring from the melt of winter ice and snow that effluent concentrations were lower than normal. More study is needed in the early part of summer shortly after the thaw in order to better understand the influential conditions occurring at that time.

The mechanisms of action operative in the treatment of effluent are different for waters travelling subsurface and that portion flowing overland. This study attempted to understand the hydraulic dynamics within the wetlands by investigating the hydraulic conductivity and pore size of the sediments as an indirect method to determine the hydraulic retention time for the effluent. The result from these efforts had indicated that flow through the subsurface was quite slow and suggested that a significant portion of the effluent may be traveling overland in preferential flow paths. The proportion of effluent flowing subsurface in comparison to surface has been difficult to assess. For example, the piezometer work undertaken at the Ulukhaktok site would suggest that the vast majority of the effluent volume should be traveling as overland flow, however, at this site, no overland flow or preferential pathways were observed as there was also no observable outflow point where effluent was exiting the wetland. This led to the speculation that most of the effluent loss from the site might be occurring through an evaporation process. However, some debris associated with wastewater was found well into the middle of the wetland area suggesting that higher flow must have occurred at some point in time to have carried the debris this far. This observation once again indicates that more study is needed to better understand the seasonality of wastewater flow.

One of the challenges encountered during the interpretation of the data was identifying a representative exit point for the effluent. In many cases the inflow of effluent to the wetland was diffuse. Exfiltration from the lagoon berm is often variable both in location and the volume of flow. It is common to find preferential channelling or ponding occurring while some of the inflow may also be entering the wetland subsurface and therefore not easily seen. This makes it difficult to directly measure the daily hydraulic loading of the wetlands. Likewise monitoring the outflow can also be challenging. In some situations such as Taloyoak, the wetland flow (at least the overland flow portion) was funnelled into a small stream exiting the wetland; however in other wetlands the exit of surface waters can be more diffuse making it difficult to determine if the sample location chosen is the best site to represent treatment efficiencies. The lack of a clearly defined effluent exit point can make it challenging from a regulatory perspective unless clearly marked static sample locations are chosen and agreed upon in advance.

Despite the challenges and the unknowns associated with wetland treatment sites, it appears that wetlands are significantly improving the water quality of the effluent beyond what is being achieved during the primary treatment process. Wetlands appear to play a critical role as a key component within a hybridized approach to the treatment of municipal effluents in the north that utilizes lagoons or facultative lakes for pre-treatment and storage, and wetlands for secondary treatment during the frost-free season.

5.3 Summary and future research directions

Despite the global wealth of knowledge regarding the use of constructed wetlands for the treatment of municipal wastewater, a review of the published literature suggests that there is a considerable lack of knowledge regarding the overall understanding of natural treatment wetlands in the Arctic (Yates *et al*., 2012; Kadlec and Wallace, 2009; Vymazal, 2011). Current understanding of Arctic systems generated from research conducted by the CAWT and published by Yates *et al*., (2012) has shown that wetlands which received continuous exfiltrates from lagoons or facultative lakes, despite cold ambient air temperature, permafrost soils, minimal soil depth, and a growing season of as little as two months achieved or exceeded performance standards set for southern Canada. However, there are a number of specific research needs that need to be fulfilled as we try to determine appropriate performance standards for wetland treatment systems in the Canadian Arctic.

A greater understanding of the complex roles that the hydrological conditions and biogeochemical interactions play in the overall treatment performance of tundra wetlands is needed in order to better apply this technology to cold climate natural tundra regions. For most natural wetland sites, site specific information regarding subsurface and surface flow is generally lacking. The volume of wastewater entering the wetland can be estimated from the volume of waste hauled to the site; however, determining flow volumes exfiltrating from the lagoon berm and how much of this flow travels overland and what portion travels subsurface is difficult. Determining the volume of new water entering the wetland either via surface or subsurface flow and how this might influence wastewater strength through dilution is also difficult.

The exact location of the wetland outlet is not always obvious for natural wetlands. Water quality can change dramatically in short distances from dilution from non-effluent watershed contributions and other factors. Additionally, the wetland outlet point location can change over the treatment season. This ambiguity in outlet location complicates monitoring and performance assessment of the system. The wetland outlet sample locations, and any other important sample locations, should be strategically located, representative of the waste stream, and be well defined to assure long-term monitoring is consistent. The correct sample location siting may require site-specific hydrodynamic studies such as tracer testing.

The limited amount of information generated from these studies suggest that the level of treatment may vary seasonally, and particularly during the spring freshet when subsurface soils are still frozen and the wastewater that has accumulated over the winter time on top of the wetland surface begins to melt. At this point, there is a lack of understanding regarding early season variability and ability to identify which wetlands are at risk to being overwhelmed by high organic loadings and which wetlands have the capacity to assimilate high spring time loadings. Similarly, the effects of dilution from spring meltwater are unknown. Dilution from meltwater may mitigate concentration based effects.

Tracer testing to determine site-specific HRTs should be conducted at strategic times during the spring freshet or in conjunction with the highest effluent discharge period for decanted systems. Furthermore, the permafrost melt rates and depths of active layers of the subsurface areas receiving effluent would be an important parameter to characterize, especially in relation to HRT.

Further research on the effluent effects on arctic vegetation in the wetland treatment areas is required. Eventually, determination of the threshold HLRs to avoid detrimental effects to the native vegetation would be useful for design purposes.

Since monitoring treatment performance data collected in wetlands is limited, it is rare to have comparable data from one year to the next. As a result, little is known regarding how treatment efficiencies may vary and what factors influence this variability. In the Arctic, this is especially true where climate change is expected, and already is experiencing drastic changes. With increases in mineralization rates of organic matter and nutrients and increases in plant biomass, treatment periods would likely become longer, and performance would only improve (Yates *et al.*, 2012). However, such changes would also require changes in the management strategies, because of changes in the hydrological regime, eutrophication downstream and prolonged increases in pathogens that may have human and ecosystem consequences given the current management of several treatment systems (Yates *et al.*, 2012).

The fulfillment of these research needs would help significantly in both interpreting the results and predicting how the wetland would perform under different organic loading regimes. This would facilitate informed, ecologically responsible and safe incorporation of natural tundra wetlands into the overall northern wastewater management. To meet the research needs outlined above, there is a requirement for hydraulic, treatment performance, and modeling studies on multiple northern wetlands, which entails comprehensive monitoring programs and associated funds.

6.0 Predictive tools

6.1 Treatment wetland design models

The increase use of wetlands for wastewater treatment together with increasingly stricter water quality standards is an ever growing motive for the development of numerical models to be used as predictive process design tools. The main objective of the modeling effort was to increase the predictive insight into the functioning of complex treatment wetlands through the use of process or mechanistic based models that describe in detail transformation and degradation processes (Langergraber et al, 2009). Once reliable numerical models are developed and validated against experimental data, they can be used for evaluating and improving existing design criteria. Most of the literature on models refers to simple first-order decay models (e.g. Stein *et al.*, 2006; Rousseau et al., 2004) or describes the treatment wetland as a black box (e.g. Tomemko *et al.*, 2007; Pastor et al., 2003) acknowledging only a limited understanding of the studied facility. The number of mechanistic or process based models is limited.

There are currently a variety of approaches that can be applied to predict the future capacity of constructed wetlands. However, the options available for modeling the performance of natural tundra wetlands are limited. This is primarily due to the fact that these natural wetlands are not engineered and because of this much less is known regarding media depth, flow rates, the influence of preferential flow paths and infiltration of surface or ground waters and many other characteristics required for model input. The options currently available generally include relatively simple design models like "rules of thumb" and regression equations along with first-order kinetic models or sophisticated 2-dimensional or 3-dimentional models. The best approaches are likely those that incorporate site specific performance data into the model in an attempt to calibrate the model to an individual wetland.

Regardless of whether the wetland is constructed or natural, these tools are needed by on-site managers as well as consulting engineers, regulatory agencies, municipal planners and territorial water boards to allow them the ability to validate a technology and predict future needs as communities expand and regulations change. This chapter discusses some of the more common methods used to determine what the optimal wetland size is for the current and future volume of sewage to be treated.

6.2 Sizing calculations for existing and new sites

There are a variety of methods that can be used to determine the approximate size a wetland must be in order to effectively improve the water quality of the influent (e.g., Domestic sewage) before it is released to the environment. The Canada - wide strategy for municipal effluents prepared by the Canadian Council of Ministers of the Environment (CCME) addresses four water quality parameters (BOD, TSS, ammonia and total residual chlorine).

Sizing tools can be generally categorized under the following headings:

- Rules of thumb (sometimes also called scaling factors)
- Regression equations and loading charts
- Simple first order kinetic models (e.g., *k* – C* model)
- Variable - order, mechanistic or compartmental models (e.g., SubWet 2.0) and sophisticated 2D and 3D models (e.g., HYDRUS, WASP, TABS-2, STELLA)

In general terms, the rules of thumb methods contain the greatest amount of uncertainty and thus are often used primarily as a "first-cut" estimate of wetland size. The variable - order and compartmental models can provide the most precise measurements, but their use is often hampered by the need for a large data set of site specific information which often does not exist or is not easily obtained. Without the calibration of these models to the specific conditions of the site, the results can be quite inaccurate. Figure 6.1 provides an overview of the strength and weaknesses for each major predictive tools category.

6.2.1 Rules of Thumb

Rules of thumb, which are sometimes referred to as "scaling factors", are based on observations from wetlands that exhibit a wide range of climatic, vegetative and physical conditions and water quality types. These generalized observations can be used to predict the behaviour of certain water quality parameters in relation to different physical components of the wetland. From an engineering perspective, rules of thumb are the easiest and fastest method for determining the approximate size needed for a wetland in order to achieve generalized water quality parameters or treatment. Since the rules of thumbs have evolved from a wide range of conditions, they can only be used at best as a very rough approximation. In fact, Rousseau *et al.* (2004) has suggested that they are best used as a method for validation of other more sophisticated sizing methods such as the first order kinetic model k-C* or other variable-order or compartmental type models.

Rules of thumb methods are generally based on either the speed at which the sewage traverses the wetland (e.g., hydraulic retention time), the volume of water entering the wetland per unit size of wetlands (e.g., hydraulic loading rate), the mass of organic loading that is being applied per unit of wetland (e.g., organic loading rate) or are composed of a generalized set of observations that have been compiled over the years from a wide range of wetland conditions.

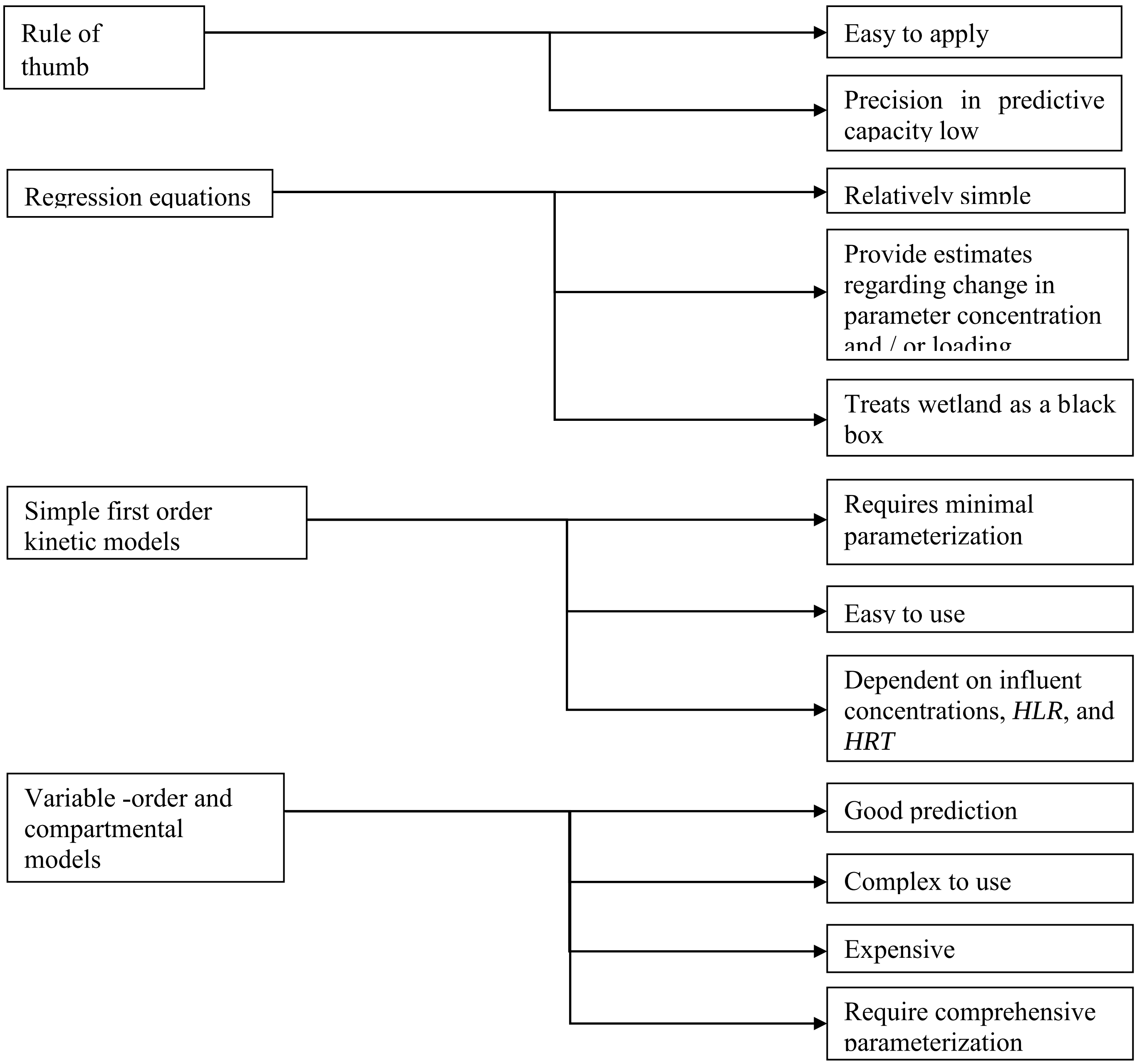

Figure 6.1 Overview of the strength and weaknesses for each major predictive tools category.

6.2.2 Hydraulic Retention Time (HRT)

The hydraulic retention time provides an estimate predicting how long it will take for the water entering the wetland to exit the wetland. Many of the treatment mechanisms within the wetland are biologically and or chemically driven and as such take time to complete. It has been generally accepted that most of the biological and chemical treatment can occur within a 2 to 7 day residency time within wetland. Many of these observations however have been made for temperate wetlands further south than those found in Nunavut and thus some have suggested a more realistic HRT for those wetlands north of 60° latitude might be closer to two weeks.

In many northern situations where natural wetlands are being used to treat domestic sewage, the size of the wetland is fixed by the surrounding landscape and cannot be easily adjusted. In these situations, it will still be important to determine what the actual HRT is for a specific wetland. This can be used to determine if the existing HRT falls within the generally accepted range of 2 to 7 days or preferable longer. If however, the HTR is less than 2 to 3 days then there is a significant chance that the wetland is not large enough to effectively treat the volume of sewage entering the wetland.

The HRT is basically a measure of volume / flow. For example, if the wetland has a volume of 1000 cubic metres and the inflow is 200 cubic metres per day, then the HRT is 1000 m^3 / 200 m^3 per day = 5 days. This is based on the rate of water entering the wetland together with the volumetric capacity of the wetlands, or in other words, how much water can the wetland hold (similar in principle to determining how much volume a pond or lake can hold and how often that water volume is replenished or exchanged).

Determining water volume of the wetland

The water (sewage) holding capacity of a wetland is determined by knowing the wetlands width, length and depth (to the bottom of the permafrost or bedrock). In most tundra wetlands, the water volume above the ground is minimal compared to the volume of water contained in the mineral and organic soils of the wetland. It is important to remember that the saturated portion of the wetland is much like a sponge and as such is composed of both water and sediments. In order to determine the portion of the saturated zone occupied by only the water, the average porosity of the soil needs to be known. The porosity provides an estimate of the pore space between soil particles that is occupied by water. In some wetlands, the porosity is 30% meaning that within 1 cubic metre of soil, 70 percent of the volume would be occupied by soil and 30 percent would be occupied by water which in this case would mean that 300 L of water could be stored with a 1 cubic metre of soil that had a porosity of 30%.

If it were a perfect world, then measuring the water volume of the wetland would be as easy as it is described above, however, in tundra wetlands, the wetland size is often irregular in shape and the depth of the unfrozen zone of soil and rocks can be quite variable, as can be porosity. It is therefore often quite difficult to get accurate measurements, however, the intent here is to get a reasonable approximation of the wetland volume; remembering that rule of thumb methods are by nature imprecise.

Determining the flow of sewage through the wetland

In order to determine the HRT, the flow of water (sewage) into the wetland must be estimated. Typically this is measured as litres of sewage entering per minute or hour, but generally expressed as cubic metres of sewage per day. One cubic metre contains 1000 L and one day contains 1440 minutes per day (e.g., 60 minutes per hour X 24 hours per day = 1440 minutes per day). Depending on the wetland the flow can be estimated in different ways. For those wetlands that have scheduled periods of decanting, the flow can often be measured to provide an estimated flow per day or week. In some communities, the lagoon berm may leak. If leakage is confined to one region, then it may be possible to estimate the approximate discharge rate to the wetland, in other situations, particularly when leakage through the berm is more diffuse, estimates are made from knowing the number of trucks per day discharging sewage to the lagoon and by monitoring water levels within the lagoon itself.

An indirect way to determine flow, but one that is just as valid as those mentioned above is to estimate the volume of sewage generated by the community. In communities with trucked service the volume of drinking water delivered within the community is tracked (recorded) and as such can be used as an indirect measure of sewage produced. The volume of sewage trucked for treatment is generally not tracked. It is also realized that the raw sewage for most communities is temporarily stored in a lagoon prior to disposal to the wetland. The underlying assumption here is that evaporation from the lagoon is minimal and that the discharge to the wetland from the lagoon is consistent in terms of flow volume, even if the decant occurs over an established period of time rather than being continuous.

In communities where it is difficult to get a reasonable estimate of sewage generation or in situations where the future volume of sewage generated by a community is of interest, an estimate can be determined by knowing the population and an estimated volume of water used per individual per day. This estimated volume is often referred to as "personal equivalence or PE". The volume of water consumed per day for an individual varies greatly depending on their location and the availability of water. Note that the PE method does not provide any information regarding what strength of effluent can be treated, nor does it provide any information concerning the quality of treatment. The values generated by the PE method provide information only in regards to the amount of effluent predicted to be produced by a certain population size. The Canadian average (for southern Canada) is 454 L/d per person which is a noticeably high estimate that averages in personal consumption and use by industry. In the USA, the personal equivalents (PE) determined for common households is 190 L per day per person. In developing countries it ranges between 60 to 80 L per day per person. In the Canadian north, the Department of Municipal and Community Affairs (MACA), Government of Northwest territories has developed the following formula to determine the volume of sewage generated from a known population base. The equation is:

$$\text{Water Usage (L/community/d)} = 90 \text{ L/c/d} \times (1.0 + 0.00023 * \text{population})$$

Once the flow rate and hydraulic retention time are known, then an aerial estimate of the wetland size can be determined. A HRT of 1 day would estimate the size of the wetland needed to contain the volume of water (sewage) generated from one day within a community. A HRT of 5 days would estimate the size of the wetland that would have a capacity to hold 5 times the volume generated from one day within a community. Thus it would take 5 days for this sewage to leave the wetland. Likewise a HRT of 7 days would mean that the size of the wetland needed to retain (hold) the sewage for 7 days would have to be 7 times the volume produced from a community during one day.

The following provide some example calculations when determining the HRT.

Step 1: Converting a flow rate of litres per minute to cubic meters per day

$$\frac{\mathrm{m}^3}{d} = \frac{L}{min} X \frac{m^3}{1000\ L} X \frac{60\ min}{h} X\ \frac{24h}{d}$$

For an example of 2.7 L per minute the flow rate expressed in m^3/d is

$$\frac{\mathrm{m}^3}{d} = \frac{2.7L}{min} X \frac{m^3}{1000\ L} X \frac{60\ min}{h} X\ \frac{24h}{d} = 3.88\ cubic\ metres\ per\ day$$

Step 2: Factoring in soil porosity to determine the size of the wetland needed for a one-day HRT

- Using the flow value of 3.88 m^3 above, and a porosity of 30 percent then 3.88 m^3 represents only 30 percent of the wetland size that is needed. In order to determine the total size of the wetland needed the following formula is used:

$$\frac{3.88\ \mathrm{m}^3}{X} = \frac{30\ \%}{100\ \%}$$

Solving for X you determine that X = 12.9 m^3

This means that a wetland with 30 % porosity must be 12.9 m^3 in size in order to hold a daily flow of 3.88 m^3.

Step 3: Determining the size of the wetland needed for a 5-day HRT is as follows

$$\frac{1d\ HTR}{5d\ HTR} = \frac{12.9\ \mathrm{m}^3}{X}$$

Solving for X you determine that X = 64.7 m^3

Step 4: Determining the aerial size of the wetland taking into account the depth of the soil

- If the depth of the wetland soil is 0.2 m then the surface area of the wetland can be determined by:

$$\frac{64.7\ \mathrm{m}^3}{0.2\ m} = 323\ \mathrm{m}^2$$

Converting to hectares

$$323\ m^2 = \frac{1\ \mathrm{ha}}{10000\ m^2} = 0.0323\ ha$$

6.2.3 Hydraulic Loading Rate (HLR)

The hydraulic loading rate is a quick method to determine if the flow through the wetland (distance / time) is within a broad range of values generally considered suitable for the treatment of sewage within wetlands. The range of values for HLR are broad and thus must be interpreted cautiously and considered as only one course indicator to determine if the wetland is receiving an appropriate load. HLR is a measure of flow divided by area. For example an 8000 m^2 wetland which receives a flow of 200 m^3 per day has a HLR of 200 m^3 per d / 8000 m^2 = 0.025 m/d or 2.5 cm / d. The HLR provides a measure of flow velocity and the lower the flow velocity, the greater the chance for solids to settle out.

The HLR is determined as:

HLR = flow (m^3 per day) divided by wetland size (m^2)

$$HLR = \frac{\mathrm{m}^3}{d} X \frac{1}{\mathrm{m}^2}$$

$$HLR = \frac{200\mathrm{m}^3}{d} X \frac{1}{8000\mathrm{m}^2} = 0.025 \frac{m}{d}$$

Often HLR will be expressed in cm/d which can be achieved by multiplying m/d by 100, thus 0.025 m/d = 2.5 cm / d

Commonly accepted ranges for HLR range greatly. Typically, a normal HLR is considered to range between 0.2 to 3.0 cm/day (Wood, 1995) and in colder climates it has been suggested that a more appropriate range is 1 to 2 cm/day (Doku and Heinke, 1993), but others such as Kadlec and Knight (1996) suggest the range to be somewhere between 8 to 30 cm per day.

6.2.4 Organic Loading Rate

Dillon Consulting Limited prepared an assessment of the Kugaaruk, Nunavut treatment wetland in 2009. In that report they cite the work of Doku and Heinke (1993) who states that northern wetlands should not receive an organic loading of greater than 8 kg

BOD_5/ha/d in order to ensure adequate aerobic conditions exist within the wetland. Other investigators have used BOD loadings but more from a water quality perspective. Most uses suggest that BOD loadings should not exceed certain levels in order to ensure defined water quality parameters are not exceeded. For example Wallace and Knight (2006) indicate that BOD loadings should not exceed 80 kg BOD/ha/d to ensure that the water quality of the effluent exiting the wetland has a BOD concentration of 30 mg/L or less. Most of these rule of thumb values have be derived from loading charts which plot the BOD concentration of the water exiting the wetland as a function of the aerial loading rate of the BOD (e.g., kg BOD/ha/d) entering the wetland. The scatter around these regression curves is often large since the loading charts are often developed from the inclusion of data gathered from a wide range of wetland sizes, shapes, flow rates and climatic conditions.

An example of how to calculate the organic loading rate is as follows:

Equations

$$\text{Organic Matter}\left(\text{BOD5}\frac{\text{kg}}{\text{m3}}\right) = \frac{BOD5\,\frac{mg}{L}\ X\ 1000\,\frac{L}{m3}}{1{,}000{,}000\,\frac{mg}{kg}}$$

$$\text{Organic Loading Rate}\left(\frac{\text{kg BOD5}}{\text{ha}\cdot\text{d}}\right) = \frac{Organic\ Matter\left(BOD5\,\frac{kg}{m3}\right)\ X\ Flow\ \left(\frac{m3}{d}\right)}{Area\ (ha)}$$

Calculations

$$\text{Organic Matter}\left(\text{BOD5}\frac{\text{kg}}{\text{m3}}\right) = \frac{120\,\frac{mg}{L}\ X\ 1000\,\frac{L}{m3}}{1{,}000{,}000\,\frac{mg}{kg}}$$

$BOD_5 = 0.12\ kg/m^3$

$$\text{Organic Loading Rate}\left(\frac{\text{kg BOD5}}{\text{ha}\cdot\text{d}}\right) = \frac{Organic\ Matter\left(0.12\,\frac{kg}{m3}\right)\ X\ 314.6\ \left(\frac{m3}{d}\right)}{1.6\ (ha)}$$

Organic Loading Rate = 23.6 kg BOD_5/ ha per day

Once again, these prescriptive rule of thumb methods can at best provide only a rough approximation for anticipated results. The loading rates such as those discussed above will provide rough guidelines for anticipated results, but it should be remembered that most of the rule of thumb approaches have been generated for warmer climates where higher temperature rates are likely more reflective of faster biological and chemical reaction rates. Loading rates such as the above for BOD cannot be used to provide an estimate of the wetland size needed to ensure the desired water quality targets are met. Furthermore, rule of thumb approaches are based on constructed wetlands, not natural wetlands.

Some common scaling factors for BOD are as follows:

Rousseau *et al.*, (2004)

- Max BOD loading rate of 75 kg BOD ha^{-1} d^{-1}

EC/EWPCA Emergent Hydrophyte Treatment System Expert Contact Group and Water Research Centre, (1990) [cf Kadlec and Wallace, 2009]

- 80 kg BOD ha^{-1} d^{-1} to produce an effluent BOD of less than 30 mg/L for primary-treated domestic wastewater

U.S. EPA, (2000a) [cf Kadlec and Wallace, 2009]

- 60 kg BOD ha^{-1} d^{-1} at inlet to produce an effluent BOD of less than 30 mg/L

Wallace and Knight, (2006) [cf Kadlec and Wallace, 2009]

- 80 kg BOD ha^{-1} d^{-1} at inlet to produce an effluent BOD of 30 mg/L
- 50 kg BOD ha^{-1} d^{-1} at inlet to produce an effluent BOD of less than 25 mg/L

Doku and Heinke, (1993) [cf Dillion 2009 KUG]

- 8 kg BOD_5 ha^{-1} d^{-1}

Campbell and Ogden, (1999)
Good estimates for BOD removal in a temperate climate (2.5 kg BOD / m^2 / year)

- In slightly warmer climates, this changes to 3.3 kg / m^2 / year @ 15°C and 4.4 kg / m^2 / year at 20°C

6.2.5 Regression Equations

The majority of the wetland studies appear to measure input and output concentrations, with some measuring input and output loadings. From this limited information many have developed regression equations in an attempt to mathematically describe the processes occurring within the wetland. This overly simplified approach treats the wetland as a black box and does not allow for the input of other influential parameters such as climate, bed material or physical dimensions of the wetland (length, width, depth, etc.). A lack of knowledge concerning these parameters hinders the appropriateness and closeness of fit to site specific wetlands. Wetlands, particularly those classified as natural wetlands being used for treatment, are quite variable in many of the influential parameters such as HLR, HRT, soil type and porosity, wetland dimensions, influent concentrations, climate, etc. and as such the application of generic scaling factors can only be used as a rough estimate of anticipated performance.

Regression equations can provide estimates regarding the change in parameter (e.g., BOD, COD, TSS, etc.) concentration and / or loading but are limited in the ability to be used to determine an estimate of the wetland size needed to meet certain effluent standards unless the regression equation accommodates the input of the hydraulic loading rate which when inputted into the equation Area (m^2) = flow (m^3 / d) / HLR (m / d) allows for the determination of wetland size, or, when a rule of thumb value is available for estimating the removal rate of the parameter of interest (e.g., a good estimate for BOD removal is 2.5 kg BOD m^{-2} y^{-1}).

Area based on HLR

$$A = \frac{Q}{q}$$

Where:

Q = flow (m^3/d)

q = hydraulic loading rate (m/d) [note: the equation used to calculate q is provided above]

Example:

$$A = \frac{200\frac{m3}{d}}{0.2\frac{m}{d}}$$

$$A = 1000\ m^2$$

The following provide some regression equations for HSSF wetlands:

Biological Oxygen Demand

Regression models with concentration or loading only (no HLR) as input parameters

Brix, (1994) [c.f. Rousseau *et al.*, 2004] System = Danish and UK soil-based HSSF

Equation: $C_{out} = (0.11 * C_{in}) + 1.87$

Input Range = $1<C_{in}< 330$ mg L^{-1}; Output Range $1<C_{in}<50$ mg L^{-1}; $q = 0.8<q<22$ cm d^{-1}; $R^2 = 0.74$

Vymazal, (1998) [c. f. Rousseau *et al.*, 2004] System = HSSF in Czech Republic

Equation: $C_{out} = (0.099 * C_{in}) + 3.24$

Input Range = $5.8<C_{in}< 328$ mg L^{-1}; Output Range $1.3<C_{in}<51$ mg L^{-1}; $q = 0.6<q<14.2$ cm d^{-1}; $R^2 = 0.33$

Reed and Brown, (1995) [c.f. Rousseau *et al.*, 2004] System = 14 USA HSSF

Equation: $L_{removed} = (0.653 * L_{in}) + 0.292$

Input Range = $4<L_{in}< 145$ kg ha^{-1} · d^{-1}; Output Range $4<L_{removed}<88$ kg ha^{-1} · d^{-1}; q = not given; $R^2 = 0.97$

Vymazal, (1998) [c.f. Rousseau *et a*l., 2004] System = HSSF in Czech Republic
Equation: $L_{out} = (0.145 * L_{in}) – 0.06$
Input Range = $6<L_{in}< 76$ kg ha^{-1} d^{-1}; Output Range $0.3<L_{out}<11$ kg ha^{-1} · d^{-1}; q = not given; $R^2 = 0.85$

Chemical Oxygen Demand

Regression models with concentration or loading only (no HLR) as input parameters

Vymazal, (1998) [c.f. Rousseau *et al.*, 2004] System = HSSF in Czech Republic
Equation: $L_{out} = (0.17 * L_{in}) + 5.78$
Input Range = $15<L_{in}< 180$ kg ha^{-1} · d^{-1}; Output Range $0.3<L_{out}<11$ kg ha^{-1} · d^{-1}; q = not given; $R^2 = 0.85$

Total Suspended Solids

Regression models with concentration and HLR (q) as input parameters

Reed and Brown, (1995) [c.f. Rousseau *et al.*, 2004] System = 14 USA HSSF
Equation: $C_{out} = C_{in} * (0.1058 + 0.0011 * q)$
Input Range = $22<C_{in}< 118$ mg L^{-1}; Output Range $3<C_{in}<23$ mg L^{-1}; q = not given; R^2 = not given

Regression models with concentration or loading only (no HLR) as input parameters

Vymazal, (1998) [c. f. Rousseau *et al.*, 2004] System = HSSF in Czech Republic
Equation: $C_{out} = (0.021 * C_{in}) + 9.17$
Input Range = $13<C_{in}< 179$ mg L^{-1}; Output Range $1.7<C_{in}<30$ mg L^{-1}; $q = 0.6<q<14.2$ cm d^{-1}; $R^2 = 0.02$

Brix, (1994) [c. f. Rousseau *et al.*, 2004] System = Danish and UK soil-based HSSF
Equation: $C_{out} = (0.09 * C_{in}) + 4.7$
Input Range = $0<C_{in}< 330$ mg L^{-1}; Output Range $0<C_{in}<60$ mg L^{-1}; q = not given; $R^2 = 0.67$

Total Nitrogen

Regression models with concentration and HLR (q) as input parameters

Kadlec and Knight, (1996) [c.f. Rousseau *et al.*, 2004] System = NADB + others

Equation: $C_{out} = 2.6 + (0.46 * C_{in}) + (0.124 * q)$

Input Range = $5.1 < C_{in} < 58.6$ mg L^{-1}; Output Range $2.3 < C_{in} < 37.5$ mg L^{-1}; $q = 0.7 < q < 48.5$ cm d^{-1}; $R^2 = 0.45$

Regression models with concentration or loading only (no HLR) as input parameters

Kadlec *et al.*, (2000) [c.f. Rousseau *et al.*, 2004] System = Danish soil-based HSSF

Equation: $C_{out} = (0.52 * C_{in}) + 3.1$

Input Range = $4 < C_{in} < 142$ mg L^{-1}; Output Range $5 < C_{in} < 69$ mg L^{-1}; $q = 0.8 < q < 22$ cm d^{-1}; $R^2 = 0.63$

Vymazal, (1998) [c.f. Rousseau *et al.*, 2004] System = HSSF in Czech Republic

Equation: $C_{out} = (0.42 * C_{in}) + 7.68$

Input Range = $16.4 < C_{in} < 93$ mg L^{-1}; Output Range $10.7 < C_{in} < 49$ mg L^{-1}; $q = 1.7 < q < 14.2$ cm d^{-1}; $R^2 = 0.72$

Vymazal, (1998) [c.f. Rousseau *et al.*, 2004] System = HSSF in Czech Republic

Equation: $L_{out} = (0.68 * L_{in}) + 0.27$

Input Range = $145 < L_{in} < 1894$ kg $ha^{-1} \cdot d^{-1}$; Output Range $134 < L_{out} < 1330$ kg $ha^{-1} \cdot d^{-1}$; $q = 1.7 < q < 14.2$ cm d^{-1}; $R^2 = 0.96$

Total Phosphorus

Regression models with concentration and HLR (q) as input parameters

Kadlec and Knight, (1996) [c.f. Rousseau *et al.*, 2004] System = USA HSSF

Equation: $C_{out} = 0.23 * (q^{0.6} * C^{0.76}{}_{in})$

Input Range = $2.3 < C_{in} < 7.3$ mg L^{-1}; Output Range $0.1 < C_{in} < 6$ mg L^{-1}; $q = 2.2 < q < 44$ cm d^{-1}; $R^2 = 0.60$

Regression models with concentration or loading only (no HLR) as input parameters
Brix, (1994) [c.f. Rousseau *et al.*, 2004] System = Danish soil-based HSSF
Equation: $C_{out} = (0.65 * C_{in}) + 0.71$
Input Range = $0.5<C_{in}< 19$ mg L^{-1}; Output Range $0.1<C_{in}<14$ mg L^{-1}; $q = 0.8<q<22$ cm d^{-1}; $R^2 = 0.75$

Vymazal, (1998) [c.f. Rousseau *et al.*, 2004] System = HSSF in Czech Republic
Equation: $C_{out} = (0.26 * C_{in}) + 1.52$
Input Range = $0.77<C_{in}< 14.3$ mg L^{-1}; Output Range $0.4<C_{in}<8.4$ mg L^{-1}; $q = 1.7<q<14.2$ cm d^{-1}; $R^2 = 0.23$

Regression equation examples for sizing of wetlands
Example 1: When a rule of thumb removal rate is known

This is an example of BOD removal rates being used along with a regression equation to determine the approximate wetland size that is needed in order to achieve a desired removal rate.

Given:
- BOD concentration entering wetland (120 mg L^{-1})
- BOD regression equation: $C_{out} = (0.11 * C_{in}) + 1.87$
- Volume of effluent entering the wetland (314 $m^3 \cdot d^{-1}$)
- Number of days per year the wetland is functioning (90 $d \cdot y^{-1}$)
- Rule of thumb BOD removal rate (2.5 kg BOD m^{-2} y^{-1})

Step 1: Calculate the expected concentration of BOD exiting the wetland

$$C_{out} = (0.11 * C_{in}) + 1.87$$
$$C_{out} = (0.11 * 120) + 1.87$$
$$C_{out} = 15 \text{ mg } L^{-1}$$

Step 2: Calculate the mass of BOD removed per year (Note: active portion is only 90 days)

BOD removed (kg/yr) = (BOD loss mg/L) * (Flow m^3/d) * (1 g / 1000 mg) * (1 kg / 1000 g) * (1000 L / m^3) * 90 d/y)

BOD removed = (120-15 mg / L) * (314 m^3/d) * (1 g / 1000 mg) * (1 kg / 1000 g) * (1000 L / m^3) * 90 d/y)

BOD removed = (105 mg / L) * (314 m^3/d) * (1 g / 1000 mg) * (1 kg / 1000 g) * (1000 L / m^3) * 90 d/y)

BOD removed = 2967 kg BOD per the 90 day active period of the wetland

Step 3: Calculate the area required based on the rule of thumb (e.g., 2.5 kg/m^2/y). NOTE: in this case a year represents 90 days

Area Required = BOD mass removed / rule of thumb

Area Required = 2967 kg BOD per year / 2.5 kg BOD / m^2 / y

Area Required = 1187 m^2 or 0.1187 ha

Example 2: Regression equation when both influent concentration and HLR are known

This is an example illustrating the use of a regression equation for TP which will allow the determination of the HLR if the concentration of TP is known at both the inlet and outlet. In this example, two equations are being used. One regression equation is used to predict the TP concentration exiting the wetland for a known TP influent concentration. Once the input and output of TP concentrations are known, then a second equation is used to estimate the HLR. A third equation is then used to determine the Area based on knowing the flow entering the wetland and the HLR.

Given:

- Equation used to model TP loss: $C_{out} = (0.65 * C_{in}) + 0.71$
- Equation used to estimate HLR (once TP in and out are known): $C_{out} = 0.23 * (q^{0.6} * C^{0.76}_{in})$
- Equation used to estimate wetland size based on flow and HLR: A = flow / HLR
- Concentration of TP entering the wetland is: 5 mg/L

Step 1: Calculate the concentration of TP exiting the wetland

$$C_{out} = (0.65 * C_{in}) + 0.71$$

$$C_{out} = (0.65 * 5) + 0.71$$
$$C_{out} = 3.96 \text{ mg / L}$$

Step 2: solve for HLR (q)

$$C_{out} = 0.23 * (q^{0.6} * C^{0.76}_{in})$$

$$3.96 \text{ mg / L} = 0.23 * (q^{0.6} * 5^{0.76})$$

$$3.96 = 0.23 * (q^{0.6} * 3.40)$$

$$3.96 / 0.23 = (q^{0.6} * 3.40)$$

$$17.2 / 3.40 = q^{0.6}$$

$5.06 = q^{0.6}$

$5.06^{1/0.6} = q$

$q = 14.6$ cm / d

Step 3: determine size of wetland based on formula:

Area (m^2) = flow (m^3/d) / HLR (cm / d)

Area (m^2) = 314 (m^3/d) / 0.146 m / d   (Note: HLR expressed in m/d not cm/d)

Area = 2151 m^2 or 0.21 ha

6.2.6 First -Order Kinetic Models

The first-order k-C* models are based on areal rate constants (k), flow rates, and wastewater concentrations entering the wetland. They consist of first-order equations which under the influence of ideal plug-flow behaviour and constant conditions (e.g. influent, flow and concentrations) predict an exponential profile between inlet and outlet (Kadlec and Wallace, 2009). The parameters k, C* and θ group a large number of other characteristics representing a complex matrix of interactions in a treatment wetland as well as external influences like weather conditions. Therefore, there can be high variability in reported values for $k_{A,}$ k_V, C* and θ (Rousseau *et al.*, 2004). Many if not most of the areal rate constants used for these models have been developed in more southern locations under warmer climatic conditions and with data generated from constructed wetlands, not natural wetlands similar to those found in the Arctic.

The first-order kinetic models have their own set of limitations and care must be used to acknowledge the underlying assumptions that are being made by the user and to understand the limitations regarding many of the unknowns within a wetland, particularly natural wetlands. Such unknowns can include factors such as preferential flow paths and hydraulic dead zones, inconsistencies in bed medium, hydraulic conductivity, porosity, etc. Many of these uncertainties can also be present in the more sophisticated models when site specific parameters are substituted with generalized parameters gathered from other sites.

Alberta Model

There are many variations of the first - order kinetic model. One that has gained popularity for use in the Canadian north is what is typically called the Alberta model (2000) which was prepared by the Alberta Environment ministry with the help of CH2M Gore and Storries Limited and an Alberta Environment Advisory / Working group. The basic expression of the model is a variant of the k – C* model described by Kadlec and Knight (1996).

This model has been rearranged to allow for the estimation of wetland size using the following expression.

$$\mathrm{A} = \left[\!\left[\frac{0.0365Q}{k}\right]\!\right] xln \left[\!\left[\frac{Ci - C^*}{Ce - C^*}\right]\!\right]$$

Where:

A = area (ha)

k = aerial rate constant @ 20°C, m/yr

Q = design flow (m^3/d)

C_i = influent concentration (mg/L)

C_e = effluent concentration (mg/L)

C* = wetland background limit (mg/L)

This equation can be re-written to determine if the predicted size actually produces the target effluent concentration (C_o). This step is done primarily as a check to make sure the equation is consistent in giving the same answer. The rearrangement of the equation for determining if the size meets the target concentration is:

Where:

C_o = effluent concentration in mg/L

$$\mathrm{Co} = C^* + (Ci - C^*) \exp \left[\!\left[-\frac{kAmax}{0.0365\ Q} \right]\!\right]$$

The Alberta model provides k - values for TSS, BOD, TP, TN, NH_4-N and Org - N, thus allowing size to be based on all of the above water quality parameters.

The Alberta model requires an estimate of the background concentration for the parameter of interest. The model developed for the Alberta Environment Ministry provides regression equations that will allow the background concentrations for TSS and BOD to be estimated. These equations are as follows:

TSS $C^* = 7.8 + 0.063\ C_i$

BOD $C^* = 3.5 + 0.053C_i$

Major drawbacks to the Alberta model appear to be related to the aerial rate constants which do not account for the influence of temperature. Likewise there is no ability to adjust for wetland depth or for differences in bed porosity.

Campbell and Ogden 1999

The first - order kinetics model presented by Campbell and Ogden (1999) enables the size of the wetland to be predicted based on the concentration of the BOD entering and exiting the wetland. It appears to have greater utility in that it will accommodate the influence of temperature and porosity, and yet the model as presented below is for use with BOD only. The Campbell and Ogden (1999) equation is as follows:

$$\text{As} = \frac{Q(\ln Co - \ln Ce)}{Kt \cdot d \cdot n}$$

Where:

As = surface area of the wetland
Q = flow, in m^3/day
Co = influent BOD (mg/L)
Ce = effluent BOD (mg/L)
Kt = temperature – dependent rate constant
d = depth of bed medium
n = porosity of bed medium

The influence of temperature can be accommodated by modifying K_t, the temperature - dependent rate constant using the modified Arrhenius equation (Kadlec and Wallace, 2009, p. 643):

$$K_t = K_{20}\ \theta^{(T-20)}$$

Where:

K_{20} = rate constant at 20°C
Θ = theta, the temperature correction factor set at 1.06
T = temperature of the water in °C

[NOTE: Kadlec and Wallace (2009) provide K_{20} and theta values for BOD_5, Ammonia, TKN, T Nitrogen, T Phosphorus. However, these were given for FWS systems (e.g., free water surface wetlands), and it is not known if they can be used for HSSF systems (e.g., horizontal subsurface flow wetlands)]

[Note: cf Reed, Crites and Middlebrooks 1995, p. 226: K_{20} increases linearly as the organic loading increases, up to an organic loading of 100 kg/ha / d (e.g., at a loading of 100 kg/ha/d the K_{20} is 1.104/d). This is a value for a HSSF wetland. Values for Surface flow wetlands are different and generally lower most likely because surface area is less (e.g., at a loading of 60 kg/ha/d the K_{20} in surface flow wetlands is approx. 0.66/d)]

Campbell and Ogden (1999) also provide sizing equations based on i) TKN and HN_4 and ii) NO_3:

- **TKN / HN_4**

$$ln\,(TKN)/NH_{4eff}) = K_t{*}HRT$$

or

$$HRT = ln\,(TKN)/NH_{4eff})/\,K_t$$

where:

TKN = influent Kjeldahl nitrogen in mg/L

NH_{4eff} = ammonia concentration in the effluent in mg/L

$K_{NH} = 0.01854 + 0.3922(rz)^{2.6077}$

rz = percent of bed depth occupied by roots (a range between 0 and 1; use 1 for 100% occupied)

$K_t = K_{NH} * (1.048)^{(T-20)}$

HRT = hydraulic retention time in days

Example:

Determine the HRT required to drop TKN from 45 mg/L to 4 NH_4 mg /L at a temperature of 5°C

$$HRT = ln\,(TKN/NH_{4eff})/\,K_t$$

1st Step: determine K_t

$$K_t = K_{NH} * (1.048)^{(T-20)}$$

Where

$K_{NH} = 0.01854 + 0.3922(rz)^{2.6077}$

$K_{NH} = 0.01854 + 0.3922(1)^{2.6077}$ (assuming that the root zone penetrates 100% of the bed depth)

$K_{NH} = 0.01854 + 0.3922(1)$ (Note: $(1)^{2.6077} = 1$

$K_{NH} = 0.4107$

Now determine K_t

$K_t = K_{NH} * (1.048)^{(T-20)}$

$K_t = 0.4107 * (1.048)^{(5-20)}$ (at temp = 5°C)

$K_t = 0.4107 * (0.495)$

$K_t = 0.4107 * (0.495)$

$K_t = 0.20$ (note: K_t will range between 0.2 and 0.25 when temp varies between 5 to 10°C)

2nd Step: solve for HRT

$HRT = ln\,(TKN/NH_{4eff})/ K_t$

$HRT = ln\,(45/4)/ 0.2$

$HRT = ln\,(11.25)/ 0.2$

HRT = 2.42 / 0.2

HRT = 12 days

3rd Step: determine the surface area of the wetland needed

NOTE: use the volume based 1st order kinetic equation to determine volume of wetland needed:

Volume = Flow (Q) * HRT (where Q is known. In this example I am using Q = 60.5 m^3/d)

$V (m^3) = Q(m^3/d) * HRT(d)$

$V = 60.5\ m^3/d * HRT$

Re-writing the equation where $V = A_s * d * p$ (where A_s = surface area, d = bed depth, p = porosity)

Solving for Area:

$A_s = [Q(m^3/d) * HRT(d)]/[depth (m) * porosity (unit less)]$ (where bed depth is given as 0.6 and porosity is given as 0.4)

$A_s = [60.5 * 12] / [0.6 * 0.4]$

$A_s = 3{,}025\ m^2$

- **NO_3**

The following formula can be used to determine the surface area of the wetland needed based on a targeted wetland NO3 value:

$ln\ (NO_{3\ inf} / NO_{3\ eff}) = K_t * HRT$

or

$HTR = [\ln(NO_{3\ inf} / NO_{3\ eff})] / K_t$

Where

$K_t = 1.15^{(T-20)}$

$NO_{3\ inf}$ = influent nitrate in mg/L

$NO_{3\ eff}$ = effluent nitrate in mg/L

1st Step: determine Kt at 5°C

$K_t = 1.15^{(T-20)}$

$K_t = 1.15^{(-15)}$

$K_t = 1.15^{(T-20)}$

$K_t = 0.1229$

2nd Step: determine HRT

$HTR = [\ln(NO_{3\ inf} / NO_{3\ eff})] / K_t$

$HTR = [\ln(40 / 23)] / 0.12$

$HTR = [\ln(NO_{3\ inf} / NO_{3\ eff})] / K_t$

$HTR = 0.55 / 0.12$

$HTR = 4.6$

3^{rd} **Step**: determine the surface area of the wetland needed

NOTE: use the volume based 1^{st} order kinetic equation to determine volume of wetland needed:

Volume = Flow (Q) * HRT (where Q is known. In this example Q = 60.5 m^3/d)

$V (m^3) = Q(m^3/d) * HRT(d)$

$V = 60.5\ m^3/d * HRT$

Re-writing the equation where $V = A_s * d * p$ (where A_s = surface area, d = bed depth, p = porosity)

Solving for Area:

$A_s = [Q(m^3/d) * HRT(d)]/[depth (m) * porosity (unit less)]$ (where bed depth is given as 0.6 and porosity is given as 0.4)

$A_s = [60.5 * 4.6] / [0.6 * 0.4]$

$A_s = 1,160\ m^2$

Rousseau *et al.*, (2004) concluded that the first - order kinetic models provided the best method for sizing wetlands. These authors found that rule of thumb methods were very generalized and therefore could not be relied on other than to provide a very rough estimate that could be used to confirm the measurements generated from the first-order kinetic models (used to verify that the model was being employed correctly). Rule of thumb methods were generally found to be overly conservative and overestimated the size of the wetland needed. This may in fact be an advantage in cold climate regions were space constraints are often of little concern and where microbial action during treatment is inhibited by the cold climate which often demands a larger treatment area than typically needed in more temperate regions.

Rousseau *et al.* (2004) also concluded that regression equations were often of limited value, stating that there is a wide range of variation amongst the different equations which is reflective of the site specific conditions under which they were generated. Thus it becomes difficult to find a regression equation that would model a specific wetland, and in particular one in the Canadian arctic. Compounding the problem is the fact that most regression equations model only input and output concentrations without taking into consideration important parameters such as the hydraulic loading rate (HLR). These authors found only a few regression equations which allowed investigators to model both concentrations and HLR in the same equation, thus allowing an estimate of the wetland size to be calculated using the formula: Area (m^2) = flow (m^3/d) / HLR (m/d). Kadlec and Wallace (2009) provides additional comment on regression models (e.g., loading charts) outlining the limitations to these methods.

6.2.7 Sophisticated 2D and 3D models

Other sizing methods exist, such as variable-order, monod-type, mechanistic and compartmentalized models, and more sophisticated 2D and 3D models such as HYDRUS, WASP, TABS-2, STELLA, ANN, BASINS and NPS-WET. However, Rousseau *et al.* (2004) suggest that the main limitations to these models relates to the inherent complexity and parameter requirement which often does not exist for most sites. The lack of site specific parameter data often leads to the use of more generalized parameter data to satisfy the demands of the model which often creates greater uncertainty without much more gain in precision than could be achieved with the simpler first - order kinetic models.

SubWet 2.0

The SubWet 2.0 model is a horizontal subsurface flow modeling program designed to predict the level of treatment that can be expected based on the characteristics of several parameters known to influence treatment (e.g., wetland size, loading rates, etc.). This model has been modified for use within natural wetlands of northern Canada, and is believed to be a good compromise between first-order kinetic models and the more sophisticated 2D, 3D models. SubWet utilizes 16 rate constants in an integrated manner to predict the treatment of BOD, organic nitrogen, ammonium, nitrate and total phosphorus. SubWet also provides the user the ability to calibrate these rate constants to site conditions in order to better reflect actual measured values. The calibration method to some extent accommodates for some of the influential processes that could be occurring within the wetland for which input data do not exist. For example, in most northern tundra wetlands, the area involved in the actual treatment process is likely smaller than the physical borders of the wetland. Modification (calibration) of specific rate constants within SubWet can therefore be used to ensure that simulated results closely match measured results as illustrated in the examples of Chapter 7. Obviously, variability between seasons and years may require more frequent calibrations although it is anticipated that the accuracy of the SubWet predictions will only increase as the data set for the wetland increases, thus providing greater insight into seasonal and yearly variability.

7.0 SubWet 2.0

7.1 General considerations

The SubWet model is a software program package used to simulate the treatment of wastewater in subsurface horizontal flow artificial wetlands. This model was originally developed by the United-Nations Environment Programme-Division of Technology, Industry and Economics-International Environmental Technology Centre (UNEP-DTIE-IETC). The model is distributed by the United-Nations as free-ware and can be found on the home web page for UNEP-IETC. Initially developed for warm climate applications and after being successfully used as a design tool in 15 cases in Tanzania, SubWet was upgraded for use within cold climates for both artificial and natural treatment wetlands. The Centre for Alternative Wastewater Treatment of Fleming College worked in collaboration with UNEP-DTIE-IETC and Sven Jørgensen (the originator of the model) to developed SubWet 2.0, a new version to accommodate temperate and cold climatic conditions including summer Arctic and temperate winter conditions. SubWet was modified for use in cold climates by calibrating the model with data originating from the natural tundra wetlands investigated during the International Polar Year study detailed earlier in this manual. The application of this software to natural tundra wetlands is beyond the original purpose it was designed for. However, the calibration of SubWet with Arctic data has demonstrated its ability to model treatment performance within natural tundra wetlands and thus provide an additional predictive tool to aid northern stakeholders in the treatment of municipal effluents.

7.2 Model structure

SubWet incorporates the influence of several factors at one time while empirical equations are generally not able to consider more than two factors at one time and usually in isolation of the other influential parameters. The model has causality: this means that the process behind the model is known and can therefore be modelled by a mathematical equation. The model employs 25 differential process equations and 16 parameters (e.g., rate coefficients such as the temperature coefficient of nitrification). Readers desiring to know more about the design parameters of the SubWet model are directed to Foundations of Ecological Modelling (4th Ed.) edited by Sven Erik Jørgensen and Brian D. Fath (2011). Chapter 7.6 of this edition (Jørgensen and Gromiec, 2011) profiles the SubWet model and provides an in-depth description of differential process equations, default parameters, forcing functions and output parameters. The SubWet model was originally designed by Sven Jørgensen and colleagues as part of the Danida project, promoting cooperation between Copenhagen and Dar es Salaan University in Tanzania. Software for this model was later developed by the United Nations Environmental Programme, International Environmental Technology Centre (UNEP-IETC), so that it could be used in developing countries to design subsurface flow constructed wetlands for the treatment of domestic wastewaters. In 2009, the SubWet model was further developed by Sven Jørgensen and the Centre for Alternative Wastewater Treatment, Fleming College, Canada for use with natural tundra wetlands of the Canadian arctic.

SubWet suggests default parameters for both warm climate and cold climate scenarios; however each parameter can be modified to improve the simulation for site specific conditions. The design input values of the model are used to specify the wetland width, length, depth, slope, % particulate matter, precipitation factor, hydraulic conductivity and selected flow rate (in cubic meters per day). The forcing functions outlining the operational parameters include wetland volume, flow of wastewater, porosity, average oxygen concentration, average temperature, the input of $cBOD_5$, ammonium, nitrate, total phosphorus, and organic nitrogen along with the fraction of $cBOD_5$, phosphorus, and organic N as suspended matter. The model calculates the simulated output values for $cBOD_5$, nitrate, ammonium, total phosphorus and organic nitrogen in milligrams per liter and the corresponding removal efficiencies in percentage.

7.3 Model calibration

The procedure used to calibrate SubWet 2.0 to site conditions has been outlined by Chouinard *et al.* (in press). In brief, the calibration is achieved by comparing wastewater effluent concentrations measured exiting the wetland site against the simulated concentrations generated by the SubWet 2.0 model. Rate coefficients, referred to as parameters in the SubWet model, are then selectively adjusted within defined limits to bring simulated values closer to measured values. Thus the model is calibrated to each individual wetland; however, calibration can take place only when site specific measured data exists. The use of measured concentrations to calibrate SubWet integrates, in a limited manner, some of the unknown processes influencing treatment performance; lessening the need to know specific details concerning individual influencing processes. Therefore the burden to know precise details regarding factors such as soil depth and the influence of melt waters becomes less demanding since the model is comparing a simulated integrated treatment response to a measured integrated treatment response. It should be noted that the cold climate default rate coefficients embedded within the cold climate operations mode of SubWet do provide simulated output values that are generally with approximately 25 % of the measured values for most wetlands we have investigated. The calibration procedure as outlined by Chouinard *et al.*, (in press) generally reduces the difference between measured and simulated values to approximately 10 % or less. The work by Chouinard *et al.* (in press) and the SubWet user manual (Appendix E) provides a step by step overview in how the SubWet model is operated.

7.4 Predictive tool based on different scenarios

SubWet can be used to allow managers to predict the impact to treatment efficiency based on different scenarios involving an alteration to the HRT, aerial loading rates and the desired level of influent treatment. Furthermore, the model can be used as a predictive tool to help managers determine the size of a wetland needed to meet treatment objectives. This will assist managers in determining if the current wetland size can accommodate projected growth in population and anticipated effluent volumes. The model can be used to predict treatment performance anticipated from alterations to the size of the treatment area that could be increased through the construction of infiltration/dispersion ditches and structures that divert flow to other parts of the wetland that are not currently involved in treatment of the influent. Ultimately, SubWet can be used by resource managers to demonstrate the treatment benefit acquired from the use of designated treatment wetlands and can also be used as a predictive tool to forecast the potential these areas could provide from the application of selected management operations. This will help resource managers in cost benefit analysis when planning for future needs. Chouinard *et al.*, (2014) present the analysis of five different hypothetical scenarios to demonstrate how SubWet 2.0 can provide Arctic municipal wastewater managers with a tool to adapt to changing treatment conditions as well as the impact to treatment when wetland systems are altered. The simulated scenarios show that despite reducing wetland size, or increasing discharge volumes, as well as reducing temperature regimes the tundra wetlands provide excellent treatment potential, both on their own, or as an integrated/hybridized system with either a lagoon or facultative lake.

7.5 Field trials from eleven natural tundra wetlands in Arctic Canada

In addition to the work described by Chouinard *et al.*, (in press), the collected data sets in this chapter are used to illustrate how SubWet 2.0 can be calibrated to model the performance of eleven individual northern municipal treatment tundra wetlands in the Canadian Arctic. As stated in Chapter 6, treatment wetlands in Whale Cove, NU, Coral Harbour, NU, Arviat, NU, Repulse Bay, NU, Paulatuk, NT, Pond Inlet, NU, Edzo, NT, Fort Providence, NT, Gjoa Haven, NU, Ulukhaktok, NT and Taloyoak, NU were monitored by the Center for Alternative Wastewater Treatment (CAWT), Fleming College, Lindsay, Ontario under contract with Environment Canada and through the IPY study. The data that were generated during the surveys are used to refine the calibration of SubWet.

7.5.1 Whale Cove, NU data set

The following example with the Whale Cove data set illustrates how SubWet 2.0 c an be calibrated to this tundra wetland. Table 7.1 compares the values simulated by SubWet to the measured treatment values observed in the field, and provides the percent deviation of concentration values before calibration. It is generally accepted that the standard deviation around sampling and analytical procedures typically is between 10-12% and thus the standard deviation to be expected for comparisons between measured values and model simulated values can generally be expected to be in the range of 15 to 20 %. In the following comparisons, we will try to target a percent deviation of concentration values below 5% by altering the input variables in the model (a sample calculation of the percent deviation of concentration values is presented for this data set in Appendix F).

An examination of the values in Table 7.1 reveals that there is discrepancy between the simulated to the observed results for all parameters. The values indicate that SubWet may be overestimating the decomposition of organic matter (e.g., removal of BOD_5) while underestimating the phosphorus adsorption capacity and underestimating the rate of nitrification. This suggests that the coefficients for the decomposition of organic matter and for the inverse phosphorus adsorption capacity are too high and should be lowered, and that the coefficient for the rate of nitrification is too low and should be increased.

Table 7.1: Comparison of simulated and observed values before calibration for the Whale Cove, NU data set

	Unit	Simulation Results	Observed Values	% deviation of concentration values
BOD_5	mg O_2/L	8.60	21	64
Ammonium-N	mg N/L	0.90	0	10
Phosphorus	mg P/L	1.46	0.1	34

The magnitude by which these coefficients are altered was approached in a trial and error manner where one coefficient at a time is altered and the simulation re-run and the graphical expression of the simulated to observed values re-examined, such as described by Chouinard *et al.*, (in press). It has been determined that for this data set a change in decomposition rate of organic matter (OC) from 0.25 to 0.05, a change in the inverse phosphorus adsorption capacity (AF) from 0.36 to 0.2 and a change in the nitrification rate (NC) from 0.9 to 2.5 produces simulation values for BOD_5 ammonium-N and total phosphorus that are much closer to the observed values (see the Glossary of symbols applied in SubWet 2.0 for a description of these coefficients in Appendix E). Table 7.2 shows the simulation results and the percent deviation of concentration values after calibration. The simulated parameters values are now closer to the observed values, and the percent deviations of concentration value all are below 5%.

Table 7.2: Simulation results after calibration for the Whale Cove, NU data set

	Unit	Simulation Results	Observed Values	% deviation of concentration values
BOD_5	mg O_2/L	20.9	21	0.52
Ammonium-N	mg N/L	0.14	0	1.56
Phosphorus	mg P/L	0.23	0.10	3.25

7.5.2 Coral Harbour, NU data set

Table 7.3 compares the values simulated by SubWet to the measured values observed in the field, and provides the percent deviation of concentration values before calibration. An examination of the values in Table 7.3 reveals that for all parameters monitored there is discrepancy between the simulated and the observed results. The values indicate that SubWet may be overestimating the decomposition of organic matter (e.g., removal of BOD_5) and the rate of nitrification (e.g., conversion of ammonium to nitrate), and underestimating the rate of ammonification and the inverse phosphorus adsorption capacity. This suggests that the coefficients for the decomposition of organic matter and nitrification rate are too high and should be lowered, and the coefficients for the ammonification rate and the inverse phosphorus adsorption capacity should be increased.

With a percent deviation of concentration value of 4.52 %, calibration of BOD_5 was not necessary, but was performed to demonstrate how close it is possible to get the simulated value to the observed value with the model. It has been determined that for this data set a change in OC from 0.25 to 0.17 and a change in NC from 0.9 to 0.1, a change in AC from 0.9 to 1.5, and a change in AF from 0.36 to 0.38 produces simulation values for BOD_5, ammonium-N and TP that are much closer to the observed values. Table 7.4 shows the simulation results and the percent deviation of concentration values after calibration.

Table 7.3: Comparison of simulated and observed values before calibration for the Coral Harbour, NU data set

	Unit	Simulation Results	Observed Values	% deviation of concentration values
BOD_5	mg O_2/L	6.45	14	4.52
Ammonium-N	mg N/L	0.09	2.8	14.3
Phosphorus	mg P/L	0.43	0.8	7.90

Table 7.4: Simulation results after calibration for the Coral Harbour, NU data set

	Unit	Simulation Results	Observed Values	% deviation of concentration values
BOD_5	mg O_2/L	14.6	14	0.35
Ammonium-N	mg N/L	3.12	2.8	1.68
Phosphorus	mg P/L	1.04	0.8	0.20

The simulated parameters values are now closer to the observed values, and the percent deviations of concentration value all are very low. The default values gave acceptable results that could be used for wetland design and predictive management needs; however, as shown, calibration can improve the model's ability to produce simulated values that are very close to the observed values, and by extension, very close to the real values and therefore producing a model that is more realistic in its predictive capabilities.

7.5.3 Arviat, NU data set

The data set from Arviat, NU is interesting in that the ammonium concentration of the effluent entering the wetland are much higher (11 mg/L) than normally encountered in municipal wastewater effluents (similar to the Baker Lake case study presented in Chouinard et al., in press). As shown in Table 7.5, the simulated total phosphorus values are relatively close to the observed values for this parameter. However, the values for BOD5 and ammonium-N are not acceptable, but can be improved when SubWet is calibrated for this specific site. Table 8-5 summarizes the differences between the values from the effluent after the wetland treatment observed in the field and the simulated results and provides the percent deviation of concentration values before calibration. The values in Table 7.5 indicate that SubWet may be overestimating the decomposition of organic matter (e.g., removal of BOD5), the rate of nitrification (e.g., conversion of ammonium to nitrate) and the rate of denitrification (for an explanation of the modification of the rates, see the Baker Lake data set under section 19.3.1.2 in Chouinard et al., in press). This suggests that the coefficients for the decomposition of organic matter, nitrification and denitrification rate are too high and should be lowered. In the Canadian Arctic, denitrification is in all likelihood a combination of bacterial conversion and plant uptake.

Table 7.5: Comparison of simulated and observed values before calibration for the Arviat, NU data set

	Unit	**Simulation Results**	**Observed Values**	**% deviation of concentration values**
BOD_5	mg O_2/L	0	16	18.4
Ammonium-N	mg N/L	6.42	11	7.40
Phosphorus	mg P/L	2.5	2.3	2.22

It has been determined that for this data set a change in OC from 0.25 to 0.05, a change in NC from 0.9 to 0.6 and a change in the denitrification rate coefficient (DC) from 3.5 to 0.2 produces simulation values for BOD_5 and ammonium-N that are much closer to the observed values. The unusually high ammonium present in the wastewater resulted in the need for the calibration of the denitrification rate constant. This type of wastewater typically forms high nitrate content in the anaerobic zone, which can induce higher denitrification under the proper conditions (mainly temperature and presence of sufficient organic carbon as substrate). In the case of the Arviat's system, the lagoon is massive and very anaerobic; treatment is minimal, and the wetland is undersized. Table 7.6 shows the simulation results and the percent deviation of concentration values after calibration.

The Arviat, NU data set provides an example of one of the more challenging calibration exercises. Despite the unusually high strength of the waste stream, the calibration of SubWet demonstrated that this model can provide a reasonable approximation of treatment efficiencies. The calibration efforts significantly improved the BOD_5 and ammonium-N values, and the percent deviations of concentration value are now well within the acceptable limit for the model. Furthermore, since this wetland has variable flow paths, the model is capable of accommodating these differences in tundra wetland operation, despite the variability in the wetland type and operation.

Table 7.6: Simulation results after calibration for the Arviat, NU data set

	Unit	**Simulation Results**	**Observed Values**	**% deviation of concentration values**
BOD_5	mg O_2/L	12.2	16	4.32
Ammonium-N	mg N/L	11.8	11	1.30
Phosphorus	mg P/L	2.5	2.3	2.22

7.5.4 Repulse Bay, NU data set

Table 7.7 compares the values simulated by SubWet to the values from the effluent after the wetland treatment observed in the field for Repulse Bay, NU, and provides the percent deviation of concentration values before calibration. An examination of the values in Table 7.7 reveals that for all parameters there is discrepancy between the simulated and the observed results. However, the percent deviations of concentration values are relatively low (all below 5%). Nevertheless, we can utilize this example to see how closely the observed and simulated values can be matched. The values indicate that SubWet may be overestimating the decomposition of organic matter (e.g., removal of BOD_5) and the rate of nitrification (e.g., conversion of ammonium to nitrate), and underestimating the inverse phosphorus adsorption capacity. This suggests that the coefficients for the decomposition of organic matter and nitrification rates are too high and should be lowered, and the coefficients for the inverse phosphorus adsorption capacity should be increased.

It has been determined that for this data set a change in OC from 0.25 to 0.15, a change in NC from 0.9 to 0.23 and a change in AF from 0.36 to 0.45 produces simulation values for BOD_5, ammonium-N and TP that are much closer to the observed values. Table 7.8 shows the simulation results and the percent deviation of concentration values after calibration.

The simulated parameters values are now closer to the observed values, and the percent deviations of concentration value all are extremely low, and show that by improving the precision of the calibration, simulation is in turn improved.

Table 7.7: Comparison of simulated and observed values before calibration for the Repulse Bay, NU data set

	Unit	Simulation Results	Observed Values	% deviation of concentration values
BOD_5	mg O_2/L	7.34	25	5
Ammonium-N	mg N/L	0.17	2.8	3.9
Phosphorus	mg P/L	1.07	1.4	4.23

Table 7.8: Simulation results after calibration for the Repulse Bay, NU data set

	Unit	Simulation Results	Observed Values	% deviation of concentration values
BOD_5	mg O_2/L	25.3	25	0.10
Ammonium-N	mg N/L	2.8	2.8	0.00
Phosphorus	mg P/L	1.31	1.4	1.15

7.5.5 Paulatuk, NT data set

Table 7.9 compares the values simulated by SubWet to the values from the effluent after the wetland treatment observed in the field in Paulatuk, NT, and provides the percent deviation of concentration values before calibration. An examination of the values in Table 7.9 reveals that there is discrepancy between the simulated and the observed results for BOD_5 and ammonium-N. The values indicate that SubWet may be underestimating the decomposition of organic matter (e.g., removal of BOD_5), the rate of nitrification (e.g., conversion of ammonium to nitrate), and the rate of ammonification. This suggests that the coefficient for the decomposition of organic matter, the nitrification rate and the coefficient for the ammonification rate are too low and should be increased.

Table 7.9: Comparison of simulated and observed values before calibration for the Paulatuk, NT data set

	Unit	Simulation Results	Observed Values	% deviation of concentration values
BOD_5	mg O_2/L	13.2	2	29.5
Ammonium-N	mg N/L	0.36	0.01	9.75
Phosphorus	mg P/L	0.03	0.04	0.41

It has been determined that for this data set a change in OC from 0.25 to 0.88, a change in NC from 0.9 to 2.5 and a change in AC from 0.9 to 2 produces simulation values for BOD_5 and ammonium-N that are much closer to the observed values, and percent deviation concentration values which are reasonable. Table 7.10 shows the simulation results and the percent deviation of concentration values after calibration.

Table 7.10: Simulation results after calibration for the Paulatuk, NT data set

	Unit	Simulation Results	Observed Values	% deviation of concentration values
BOD_5	mg O_2/L	1.9	2	0.26
Ammonium-N	mg N/L	0.08	0.01	2.20
Phosphorus	mg P/L	0.03	0.04	0.41

7.5.6 Pond Inlet, NU data set

Table 7.11 compares the values simulated by SubWet to the values from the effluent after the wetland treatment observed in the field at Pond Inlet, NU and provides the percent deviation of concentration values before calibration. An examination of the values in Table 7.11 reveals that there is discrepancy between the simulated and the observed results for $BOD_{5,}$ ammonium-N and total phosphorus. As with Repulse Bay, NU, the percent deviations of concentration values for these parameters are relatively low (below 5%). Nevertheless, we will also utilize this example to see how closely the observed and simulated values can be matched through calibration. The values indicate that SubWet may be overestimating the decomposition of organic matter (e.g., removal of BOD_5), and the rate of nitrification (e.g., conversion of ammonium to nitrate), and underestimating the inverse phosphorus adsorption capacity. This suggests that the coefficients for the decomposition of organic matter and nitrification rate are too high and should be lowered, and that the coefficient for the inverse phosphorus adsorption capacity should be increased.

Table 7.11: Comparison of simulated and observed values before calibration for the Pond Inlet, NU data set

	Unit	Simulation Results	Observed Values	% deviation of concentration values
BOD_5	mg O_2/L	7.34	25	4.90
Ammonium-N	mg N/L	0.17	2.8	3.90
Phosphorus	mg P/L	1.07	1.4	4.23

It has been determined that for this data set a change in OC from 0.25 to 0.15, a change in NC from 0.9 to 0.23 and a change in AF from 0.36 to 0.45 produces simulation values for BOD_5, ammonium-N and total phosphorus that are much closer to the observed values. Table 7.12 shows the simulation results and the percent deviation of concentration values after calibrations; which are now extremely low and therefore quite acceptable.

Table 7.12: Simulation results after calibration for the Pond Inlet, NU data set

	Unit	Simulation Results	Observed Values	% deviation of concentration values
BOD_5	mg O_2/L	25.35	25	0.10
Ammonium-N	mg N/L	2.79	2.8	0.01
Phosphorus	mg P/L	1.31	1.4	1.15

7.5.7 Edzo, NT data set

Table 7.13 compares the values simulated by SubWet to the measured values observed in Edzo, NT, and provides the percent deviation of concentration values before calibration. An examination of the values in Table 7.13 reveals that for all parameters there is discrepancy between the simulated and the observed results. The values indicate that SubWet may be underestimating the rate of nitrification (e.g., conversion of ammonium to nitrate) and the inverse phosphorus adsorption capacity and either overestimating or underestimating the rate of denitrification. This suggests that the coefficients for the nitrification and the inverse phosphorus adsorption capacity are too low and should be increased, and that the denitrification rate is too high or too low and should be modified. The value for the decomposition of organic matter (e.g., removal of BOD_5) suggests that the model overestimated the coefficient for the decomposition of organic matter. Through calibration of the other parameters, it has been determined that no calibration of this specific coefficient was necessary; calibration of the other parameters was sufficient to improve the discrepancy between the simulated and observed values for BOD_5.

Table 7.13: Comparison of simulated and observed values before calibration for the Edzo, NT data set

	Unit	Simulation Results	Observed Values	% deviation of concentration values
BOD_5	mg O_2/L	0	2	8.30
Ammonium-N	mg N/L	2.67	0.31	15
Phosphorus	mg P/L	0.08	0.16	9.20

It has been determined that for this data set a change in NC from 0.9 to 2.5, a change in DC from 3.5 to 0.1, and a change in AF from 0.36 to 0.55 produces simulation values for BOD_5, ammonium-N and TP that are much closer to the observed values. Table 7.14 shows the simulation results and the percent deviation of concentration values after calibration.

The calibration efforts significantly improved the parameters values, and the percent deviations of concentration values are now within the acceptable limit for the modeling for these parameters.

Table 7.14: Simulation results after calibration for the Edzo, NT data set

	Unit	Simulation Results	Observed Values	% deviation of concentration values
BOD_5	mg O_2/L	2.41	2	1.71
Ammonium-N	mg N/L	0.41	0.31	0.63
Phosphorus	mg P/L	0.16	0.16	0

7.5.8 Fort Providence, NT data set

Table 7.15 compares the values simulated by SubWet to the values from the effluent after the wetland treatment observed in the field for Fort Providence, NT, and provides the percent deviation of concentration values before calibration. An examination of the values in Table 7.15 reveals that for all parameters there is discrepancy between the simulated and the observed results.

Table 7.15: Comparison of simulated and observed values before calibration for the Fort Providence, NT data set

	Unit	Simulation Results	Observed Values	% deviation of concentration values
BOD_5	mg O_2/L	9.77	32	79.39
Ammonium-N	mg N/L	5.28	18.5	56.73
Phosphorus	mg P/L	5.10	8.94	56.25

The values indicate that SubWet may be overestimating the decomposition of organic matter (e.g., removal of BOD_5), and the rate of nitrification (e.g., conversion of ammonium to nitrate), and underestimating the inverse phosphorus adsorption capacity. This suggests that the coefficients for the decomposition of organic matter and nitrification rate are too high and should be lowered, and the coefficient for the inverse phosphorus adsorption capacity should be increased. It has been determined that for this data set a change in OC from 0.25 to 0.2, a change in NC from 0.9 to 0.1, and a change in AF from 0.36 to 2.5 produces simulation values for BOD_5, ammonium-N and total phosphorus that are much closer to the observed values. Table 7.16 shows the simulation results and the percent deviation of concentration values after calibration.

Table 7.16: Simulation results after calibration for the Fort Providence, NT data set

	Unit	Simulation Results	Observed Values	% deviation of concentration values
BOD_5	mg O_2/L	33.8	32	6.40
Ammonium-N	mg N/L	19.2	18.5	9.73
Phosphorus	mg P/L	8.88	8.94	2.80

The simulated parameters values are now closer to the observed values; however, in this case BOD and ammonium-N are not within the 5% range targeted, especially ammonium-N. Considering the unusually high ammonium-N content in the wastewater, this is the best percent deviation concentration value that could be obtained with the model for both cases. Furthermore, these values are still within the acceptable 15% of the modeling standards.

7.5.9 Gjoa Haven, NU data set

Table 7.17 compares the values simulated by SubWet to the values from the effluent after the wetland treatment observed in the field for Gjoa Haven, NU, and provides the percent deviation of concentration values before calibration. An examination of the values in Table 7.17 reveals that there is a discrepancy between the simulated and the observed results for total phosphorus. The values indicate that SubWet may be overestimating the inverse phosphorus adsorption capacity. This suggests that the coefficient for the inverse phosphorus adsorption capacity is too high and should be lowered.

With a percent deviation of concentration value of 3.31% for ammonium-N, calibration was not necessary, but was performed to demonstrate how close it is possible to get the simulated value to the observed value with the model. It has been determined that for this data set a change in AF from 0.36 to 0.3 and a change in NC from 0.9 to 2.5 produces simulation values for total phosphorus and ammonium-N that are closer to the observed values. Table 7.18 shows the simulation results and the percent deviation of concentration values after calibration.

Table 7.17: Comparison of simulated and observed values before calibration for the Gjoa Haven, NU data set

	Unit	Simulation Results	Observed Values	% deviation of concentration values
BOD_5	mg O_2/L	9.60	7	1.82
Ammonium-N	mg N/L	1.79	0.12	3.31
Phosphorus	mg P/L	1.31	0.78	12

Table 7.18: Simulation results after calibration for the Gjoa Haven, NU data set

	Unit	Simulation Results	Observed Values	% deviation of concentration values
BOD_5	mg O_2/L	9.60	7	1.82
Ammonium-N	mg N/L	0.16	0.12	0.08
Phosphorus	mg P/L	0.55	0.78	5.20

The simulated parameters values are now closer to the observed values, and the percent deviations of concentration value are well within acceptable limits for the model.

7.5.10 Ulukhaktok, NT data set

Table 7.19 compares the values simulated by SubWet to the values from the effluent after the wetland treatment observed in the field for Ulukhaktok, NT, and provides the percent deviation of concentration values before calibration. An examination of the values in Table 7.19 reveals that for all parameters there is discrepancy between the simulated and the observed results. The values indicate that SubWet may be underestimating the decomposition rate of organic matter, the rate of nitrification (e.g., conversion of ammonium to nitrate), and the rate of ammonification and overestimating the inverse phosphorus adsorption capacity. This suggests that the coefficients for the decomposition rate of organic matter, nitrification rate and ammonification are too low and should be increased, and the coefficients for the inverse phosphorus adsorption capacity should be decreased.

Table 7.19: Comparison of simulated and observed values before calibration for the Ulukhaktok, NT data set

	Unit	Simulation Results	Observed Values	% deviation of concentration values
BOD_5	mg O_2/L	8.03	5	4.50
Ammonium-N	mg N/L	1.09	0.09	16
Phosphorus	mg P/L	1.47	0.2	10.5

It has been determined that for this data set that a change in OC from 0.25 to 0.31, NC from 0.9 to 2.5, a change in AC from 0.9 to 1.5, and a change in AF from 0.36 to 0.24

produces simulation values for BOD_5, ammonium-N and total phosphorus that are much closer to the observed values. Table 7.20 shows the simulation results and the percent deviation of concentration values after calibration.

With a percent deviation of concentration value of 4.50 %, calibration of BOD_5 was not necessary, but was performed to demonstrate how close it is possible to get the simulated value to the observed value with the model. The simulated parameters values are now closer to the observed values, and the percent deviations of concentration value all are within acceptable limits for the model.

Table 7.20: Simulation results after calibration for the Ulukhaktok, NT data set

	Unit	Simulation Results	Observed Values	% deviation of concentration values
BOD_5	mg O_2/L	5.03	5	1.14
Ammonium-N	mg N/L	0.12	0.09	0.31
Phosphorus	mg P/L	0.19	0.2	0.12

7.5.11 Taloyoak, NU data set

Table 7.21 compares the values simulated by SubWet to the values from the effluent after the wetland treatment observed in the field for Taloyoak, NU, and provides the percent deviation of concentration values before calibration. An examination of the values in Table 7.21 reveals there is discrepancy between the simulated and the observed results for BOD_5 and phosphorus. The values indicate that SubWet may be overestimating the decomposition of organic matter (e.g., removal of BOD_5) and underestimating the inverse phosphorus adsorption capacity. This suggests that the coefficients for the decomposition of organic matter is too high and should be lowered, and that the coefficient for the inverse phosphorus adsorption capacity is too low and should be increased. With a percent deviation of concentration value of 1.80 %, calibration of ammonium-N was not necessary, but was again performed to demonstrate how close it is possible to get the simulated value to the observed value with the model. It has been determined that for this data set a change in OC from 0.25 to 0.17, a change in AF from 0.36 to 0.83 and a change in NC from 0.9 to 1.2 produces simulation values that are much closer to the observed values. Table 7.22 shows the simulation results and the percent deviation of concentration values after calibration.

Table 7.21: Comparison of simulated and observed values before calibration for the Taloyoak, NU data set

	Unit	Simulation Results	Observed Values	% deviation of concentration values
BOD_5	mg O_2/L	16.7	25	15.1
Ammonium-N	mg N/L	0.21	0.13	1.80
Phosphorus	mg P/L	0.00	0.32	8.94
Nitrate	mg N/L	0.03	0.02	0.89

Table 7.22: Simulation results after calibration for the Taloyoak, NU data set

	Unit	Simulation Results	Observed Values	% deviation of concentration values
OD_5	mg O_2/L	25.4	25	0.75
Ammonium-N	mg N/L	0.13	0.13	0
Phosphorus	mg P/L	0.32	0.32	0
Nitrate	mg N/L	0.03	0.02	0.89

The simulated parameters values are now closer to the observed values, and the percent deviations of concentration value all are within acceptable limits for the model.

7.5.12 Summary of the coefficient changes

Table 7.23 summarizes the changes that were made to the cold climate default parameters of the SubWet 2.0 model. The coefficient changes column reflects which coefficient has been modified, and provides the new value after calibration. The coefficient range and default coefficient values refer to the coefficients required by the differential equations that SubWet uses to model wetland processes. The range for each coefficient has been identified from published literature. The default parameters fall within the normal range and are embedded within the SubWet model before calibration. The range of coefficient changes column reflects the proposed new range found after calibration of the 11 sites: some of the ranges have stayed the same, others have changed (i.e. the initial coefficient range for DC is: 0.00-5 and after calibration of all 11 sites, the proposed new range for DC is: 0.1-0.2).

Even though a 15% difference between simulated and measured values is generally considered acceptable, it was shown in the previous calibration models that most simulated values could be calibrated to approximately 5% deviation. A review of the SubWet 2.0 simulations revealed that the cold water default parameters were poorly suited for the Fort Providence wetland. This may be in part related to the fact that the wastewater is decanted from the lagoon to the wetland in a concentrated period of time, unlike the slow continuous release that occurs from the exfiltration of leaky lagoon berms or the release from facultative lakes. The impact to treatment process caused by a sudden discharge related to a decant event or spring freshet is unknown. It is anticipated that higher flow volumes can decrease HRTs and increase organic loading to the point that the treatment system is overwhelmed and treatment efficiency decreases. Decanting of lagoons is also typically done at the end of the frost free period; therefore wetlands have less time to assimilate the nutrients and other pollutants. This could have an effect on the model simulations and may be why there is discrepancy between observed and simulated values. The simulated values (before calibration) from Whale Cove, NU and Paulatuk, NT are also moderately poor. These two sites are the only locations where pre-treatment of the wastewater is through a facultative lake, and thus it appears that the default cold climate default parameters of SubWet 2.0 may always need calibration to measured values for wetlands receiving wastewaters pre-treated in these lake systems.

Table 7.23: Summary of the coefficient changes for the 11 tundra treatment wetlands from the Canadian Arctic presented

11 Tundra Treatment Wetlands from the Canadian Arctic	Coefficient changes	Coefficient range and default coefficient values used in calibration	Range of coefficient changes
Whale Cove, NU	OC: 0.05 AF: 0.2		
Coral Harbour, NU	OC: 0.17 AF: 0.38 NC: 0.1 AC: 1.5		
Arviat, NU	OC: 0.05 NC: 0.6 DC: 0.2	AC: 0.05- 2.0 0.9 (1/24h) NC: 0.1- 2.5 0.9 (1/24h) OC: 0.05- 2.0 0.25 (1/24h) DC: 0.00-5 3.5 (1/24h) AF: 0-100 0.36	AC: 0.5- 2.0 NC: 0.1- 2.5 OC: 0.05- 1.7 DC: 0.1-0.2 AF: 0.2-2.5
Repulse Bay, NU	OC: 0.15 AF: 0.45 NC: 0.23		
Paulatuk, NT	OC: 0.88 NC: 2.5 AC: 2		
Pond Inlet, NU	OC: 0.15 NC: 0.23		
Edzo, NT	AF: 0.55 NC: 2.5 DC: 0.1		
Fort Providence, NT	OC: 0.2 AF: 2.5 NC: 0.1		
Gjoa Haven, NU	AF: 0.3		
Ulukhaktok, NT	OC: 0.31 AF: 0.34 NC: 2.5 AC: 1.5		
Taloyoak, NU	OC: 0.17 NC: 1.2		

The main challenges in modeling tundra treatment wetlands in the far north is that they are extremely heterogeneous (patchy systems, with both preferential flow and dead zones), have fast and slow retention times and good and poor conductivity. Furthermore, there is the problem of measuring these variables and parameters. In some cases hidden dilution from groundwater might be a problem. Because permafrost exists at nearly all wetland sites it is assumed that melt water may be the primary source of any subsurface flow that could cause wastewater dilution with the treatment zone. Each wetland system is unique and therefore it is always best to calibrate SubWet to measured values when possible. The measured water quality parameter values along with the calibration values reflect the conditions for only one short time period. These values do not reflect the seasonal variation that can occur throughout the frost free period, nor do they capture the year to year variability that likely occurs. The values do however; provide a relative indication of the type of treatment that may be expected. It is anticipated that with the inclusion of subsequent years of measured data the uncertainties regarding season and year to year influences will be better understood, thus providing greater confidence in modelled results.

It should be remembered that some of the modelled water quality parameters such as ammonium are actually influenced by more than one process. For example the treatment of ammonium reflects the ammonification of organic nitrogen and the nitrification of ammonium and can also be influenced by the oxygen demand related to BOD. Thus, the calibration of SubWet may require changing more than one rate coefficient.

7.6 Summary and possible future modifications

A variety of approaches can currently be applied to predict the performance of constructed wetlands, however, only and a few numerical models are available as a predictive tool for horizontal subsurface flow treatment wetlands. All numeric models can be problematic when applying to natural wetlands; which nature are often open and diffuse systems, with poorly defined boundaries, flow patterns and permeable borders (Kadlec and Wallace, 2009). These conditions present challenges for wastewater regulators who require well defined points of control. The best approach is to incorporate site specific performance data (when available) into the model in an attempt to calibrate the model to the unique characteristics of the particular wetland. This was the approach taken with the application of the SubWet model to the natural tundra wetlands.

The calibration of SubWet with the eleven northern wetlands in the Canadian Arctic clearly demonstrates its ability to model treatment performance within natural tundra wetlands and thus provide an additional predictive tool to aid northern stakeholders in the treatment of municipal effluents. It was demonstrated that even during periods of wastewater decanting, SubWet was robust enough to provide moderately good treatment predictions. Likewise it has also been demonstrated that SubWet is able to provide good predictions for those municipalities that produce a high strength wastewater (e.g., Baker Lake and Arviat).

It is recognized however, that our present knowledge regarding year to year variability in wetland performance and seasonal influences is lacking and future monitoring will be needed to improve temporal predictions.

8.0 Summary

The study results outlined in the preceding chapters demonstrates the wastewater treatment services that are provided by the eleven natural tundra wetlands investigated. For the most part, the concentration of cBOD5, ammonia, phosphorus and microbial pathogens were significantly reduced with final treated effluent values well below the CCME NPS for southern Canada. Treatment performance was poorer at some wetland sites such as Whale Cove, Pond Inlet and Fort Providence where the wetlands were either undersized or the slope and hydraulic retention times were too steep or short. Total suspended solids did not appear to be a good indicator of wastewater treatment since some wetlands generate TSS that does not originate in the wastewater influent. It is suggested that a monitoring of fixed suspended solids (FSS) and volatile suspended solids (VSS) and a comparison of their contribution to TSS may provide more insight into treatment performance. In some wetlands that generated TSS it was found that the VSS component of the wastewater decreased as it traversed the wetland, suggesting that the organic fraction of TSS was being removed by sedimentation, filtration and or microbial oxidation while the FSS (inorganic portion) increased, suggestive that erosional forces were mobilizing inorganic particles into the effluent.

The IPY study investigated treatment performance over the course of an entire arctic summer. Although these results indicate that treatment performance remained high during the summer, more investigation is needed during the spring freshet where flows are anticipated to be higher because of the influx of melt waters and influent strength is expected to be stronger with the release of the frozen wastewaters that accumulated over the winter time. Treatment performance during the spring freshet is not well documented but is expected to be variable depending on the inherent characteristics of individual wetlands which vary in their capacity to accommodate increased volumes and influent strengths. The Environment Canada funded study looked at treatment performance at multiple locations within the wetland in an attempt to better understand the progression of treatment as effluents traversed the site. It was found that in most cases the wetlands had the capacity to accommodate either higher flows or loading rates. Both studies (IPY & EC) did indicated that a slow steady release of effluent into the wetland resulted in better treatment performance than if effluents were released quickly over a short period of time during a scheduled lagoon decant. This information suggests that wetland treatment is enhanced if the lagoon exfiltrates rather than being decanted quickly. A better management practice may be to decant smaller volumes more frequently rather than release a large volume all at once.

It was found that the SubWet 2.0 modelling program provided simulated results that were much closer to measured results than any of the other readily accessible predictive tools that currently exist. SubWet was successfully calibrated to all eleven wetlands and after calibration the simulated (predicted) values were generally within 10% of the measured values. SubWet can provide wastewater managers the ability to predict the outcome of a variety of simulated operational scenarios and in doing so determine which management options are anticipated to provide the best treatment. This should be of great utility for those operators wanting to know how much of the lagoon's effluent can be released to the wetland and how frequently this can be done while still maintaining a desired level of treatment. SubWet can also be used to predict the capacity of existing wetlands to accommodate future population growth and associated increases in wastewater volume.

It is hoped that this document will be useful to wastewater managers, regulatory agencies and consulting engineers and planners. The work contained in this document has attempted to provide greater insight into the performance of natural wetlands for the treatment of domestic effluent and in doing so to remove some of the barriers that may have prevented a greater formal utilization of natural wetlands as part of an overall wastewater strategy for northern Canada.

9.0 References

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Appendix A. Overview of basic treatment processes within wetlands

Appendix A1 Wastewater Constituents

BOD_5 / $cBOD_5$

Wetlands play an important role in the cycling of carbon and provide carbon exports from the wetland to receiving ecosystems. Carbon imports and the carbon formed from decomposition processes supply many internal wetland processes.

The added wastewater in treatment wetlands frequently contains large supplies of carbon. In wetland carbon processes, degradable carbon compounds are rapidly utilized. Simultaneously, a variety of wetland decomposition processes produce available carbon (Kadlec and Wallace, 2009). The carbon export is the balance between uptake and production. The amounts of carbon cycled in the wetland are generally comparable to the quantities added in domestic wastewater. Carbon dioxide (CO_2) is required for photosynthesis associated with the growth of wetland plants. A variety of organisms release CO_2 as a product of respiration (Kadlec and Wallace, 2009). Many pathways result in the microbial production of CO_2, as well as methane (CH_4): to a limited extent, both gases dissolve in water, so there are active transfers of carbon to and from the atmosphere. In terms of treatment, good carbon reductions is therefore found for the added wastewater, accompanied by nonzero background levels of various carbon compounds and the related BOD (Kadlec and Wallace, 2009).

Any of several measures of carbon content may be made; however, in the treatment of municipal wastewater, biochemical oxygen demand (BOD) is most frequently used. Biochemical oxygen demand (BOD) is a measure of the oxygen consumption of microorganisms in the oxidation of organic matter. The greater the BOD, the more rapidly oxygen is depleted in the water causing ecosystem changes (Kadlec, 1995). The result of a BOD test indicates the amount of water-dissolved oxygen (expressed as parts per million or milligrams per litre of water) consumed by microbes for a specified period; normally five days which would then be specifically designated as BOD_5. The BOD_5 value has been used and reported for many applications, most commonly to indicate the effects of sewage and other organic wastes on dissolved oxygen in surface waters (Kadlec and Wallace, 2009).

Sometimes it is advantageous to measure just the oxygen demand exerted by organic (carbonaceous) compounds, excluding the oxygen demand exerted by the nitrogenous compounds. To accomplish this, the nitrifying organisms can be inhibited from using oxygen by the addition of a nitrification inhibitor to the samples. The result is termed "Carbonaceous Biochemical Oxygen Demand", or cBOD. Wetlands are effective in the reduction of BOD_5, as long as the BOD_5 coming in exceeds the natural level at which the wetland operates (Kadlec and Wallace, 2009).

Ammonia (NH_3) and Ammonium (NH_4^+)

Among the principal constituents of concern in wastewater are the nitrogen compounds, because of their role in eutrophication, their effect on the oxygen content of receiving waters, and their toxicity to aquatic invertebrate and vertebrate species (Kadlec and Wallace, 2009). Plant growth is also augmented by these compounds, which in turn stimulates the biogeochemical cycles of the wetland. Ammonia is the preferred nitrogen-containing nutrient for plant growth. Ammonia can be converted to nitrite (NO_2) and nitrate (NO_3) by bacteria, and then used by plants. Nitrate and ammonia are the most common forms of nitrogen in aquatic systems (Kadlec and Wallace, 2009). Nitrate predominates in unpolluted waters. Ammonia is excreted by animals and produced during decomposition of plants and animals, thus returning nitrogen to the aquatic system. Ammonia can exist in both an un-ionized form (NH_3) and an ionized form (ammonium NH_4^+). The proportion of these two forms is both pH and temperature dependant with higher percentages of NH_3 favoured with higher pH values. The un-ionized form (NH_3) is toxic to aquatic life forms at low concentrations, typically at concentrations >0.2 mg/L (Kadlec and Wallace, 2009). The combined concentration of NH_3 and NH_4^+ is typically expressed as Total Ammonia Nitrogen (TAN) since the analytical procedure often used forces all NH_4^+ to NH_3 under basic conditions.

Total nitrogen in the natural state can fall into two basic groups, total Kjeldahl nitrogen (TKN) and oxidized nitrogen (NOx). The most important forms of inorganic N compounds include ammonium (NH_4^+), plus oxidized nitrogen in the form of nitrite (NO_2^-), nitrate (NO_3^-), gaseous forms such as di-nitrogen (N_2) and nitrous oxide (N_2O). These compounds are the end products of specific biological reactions (Kadlec and Wallace, 2009). Nitrogen may also be present in wetlands in many organic forms including urea, amino acids, amines, purines, and pyrimidines (Vymazal, 1995). A number of processes transfer nitrogen compounds from one nitrogen state (e.g., nitrogen species) to another in wetlands. These processes include ammonia volatilization, ammonification, nitrification, nitrate ammonification, denitrification, fixation, plant and microbial uptake, ammonia adsorption, organic nitrogen burial, and ANAMMOX (Kadlec and Wallace, 2009). Figure A-1 shows the principal components of the nitrogen cycle in wetlands.

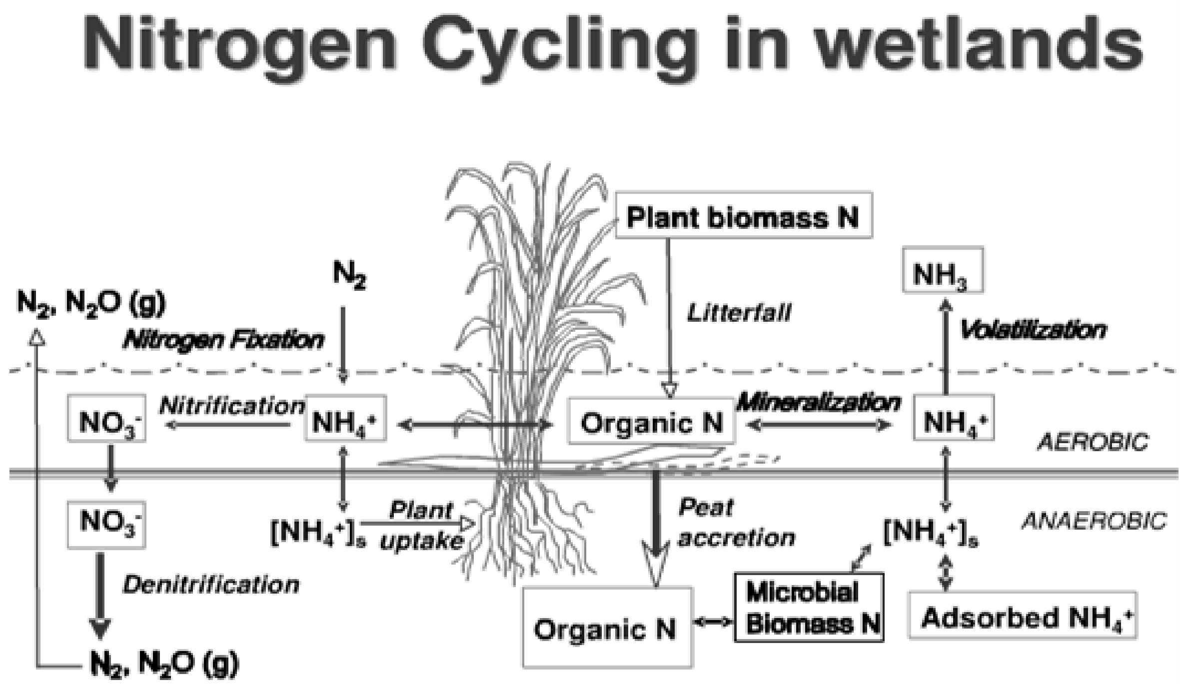


Figure A-1: Principal components of the nitrogen cycle in wetlands (Docstoc, 2013).

Phosphorus

Phosphorus is a nutrient required for plant growth, and is frequently a limiting factor for vegetative productivity. It is also known to cause eutrophication in freshwater systems (Kadlec and Wallace, 2009). Phosphorus can exists in either inorganic or organic forms. The predominant organic form is orthophosphate (PO_4-P) which can be readily used by algae and macrophytes. Phosphorus readily combines with, and may be part of, dissolved organic materials, and in that form has the designation of dissolved organic phosphorus (DOP). DOP has been characterized in great detail for treatment wetland situations, and found to consist of several kinds of organics (Kadlec and Wallace, 2009). Some of them are readily hydrolyzed by soil enzymes, and together with PO_4-P are called soluble reactive phosphorus (SRP); the organic components of SRP can move readily in soils and sediments (Kadlec and Wallace, 2009). Phosphorus also may be associated with suspended particles, and is called particulate phosphorus. Wetlands provide an environment for the interconversion of all these forms of phosphorus, with the eventual sink being one or more of the wetland solid compartments (Figure A-2). Naturally occurring inputs of phosphorus are from surface inflows, and atmospheric deposition that consists of both wet deposition and dryfall. Outputs may be in the form of surface outflows or infiltration to groundwater. Inputs from groundwater and gaseous release to the atmosphere are less common or probable (Kadlec and Wallace, 2009).

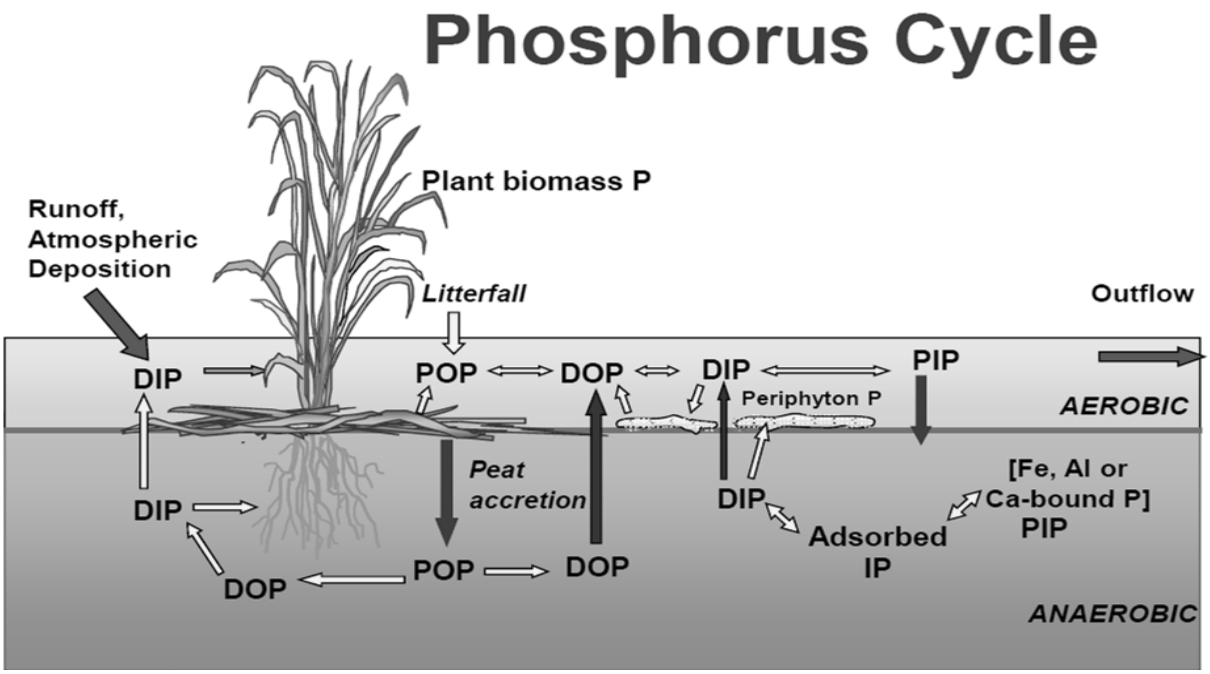


Figure A-2: Phosphorus cycling processes: Dissolved inorganic phosphorus (DIP); dissolved organic phosphorus (DOP); particulate organic phosphorus (POP); particulate inorganic phosphorus (PIP); inorganic phosphorus (IP) (Reddy, 2008).

Phosphorus transformations in wetlands are: soil accretion, adsorption/absorption, precipitation/ dissolution, plant/microbial uptake, fragmentation and leaching, mineralization and burial. Thus, when evaluating a wetland ecosystem to retain phosphorus, all these components should be quantified (Vymazal, 2006). Soil adsorption and peat accretion control long-term phosphorus sequestration in wetlands. However, sorption as well as storage in biomass are saturable processes, meaning they have a finite capacity and therefore cannot contribute to long-term sustainable removal (Vymazal, 2006).

Total suspended solids

The removal of suspended sediments from water moving through the wetland is a major aspect of wetland technology application (Caselles-Osorio, 2007). Sewage entering the wetland can often have a high amount of fine particles suspended in the water; this suspended material is called “Total Suspended Solids” or TSS. Many pollutants are associated with the incoming suspended matter, such as metals and organic chemicals, which partition strongly to suspended matter. Wetlands are generally very efficient in removing suspended solids, but particle resuspension due to wind, wave, or animal activity can play an important role in the sediment cycle of wetlands. Phytoplankton production can also increase the concentration of suspended sediments in wetlands.

A further subdivision of TSS into its components of Fixed Suspended Solids (FSS) and Volatile Suspended Solids (VSS) provides an indication of the organic component of TSS. The suspended solids entering a treatment wetland may display widely varying characteristics, according to the source water involved. Municipal effluents tend to be high in organic content in comparison to the inorganic fraction. For natural wetlands, TSS alone may not be the best regulatory standard since these wetlands may be sources of inorganic TSS that has nothing to do with effluent treatment. Perhaps a better approach would be to measure TSS along with VSS. Graphing the ratio of VSS to FSS and monitoring the change in this ratio could at times provide a better distinction between the portion of TSS originating from municipal effluents and those that are a natural constituent of the site. Suspended solids removal in wetlands occurs through sedimentation, aggregation, and filtration/interception.

Dissolved oxygen

Dissolved oxygen (DO) is an important participant in some pollutant removal mechanisms in treatment wetlands, and can be a regulatory parameter for discharges to surface waters. DO is the driver for nitrification and for aerobic decomposition of cBOD; which is critical for the survival of fish and other aquatic organisms, and for the general health of receiving water bodies (Shutes, 2001). After entering the wetland, several competing processes affect the concentrations of oxygen, BOD, and nitrogen species.

To meet wetland oxygen requirements, DO is depleted in four major categories: sediment/litter oxygen demand, respiration requirements, dissolved carbonaceous BOD, and dissolved nitrogenous oxygen demand (NOD) (Kadlec and Wallace, 2009). Decomposing detritus in the wetland is the result of sediment oxygen demand, as well as decomposition of accumulated organic solids which entered with the water. The NOD is utilized primarily by ammonium nitrogen; but ammonium may be lost by the mineralization of dissolved organic nitrogen. Decomposition processes in the wetland also contribute to NOD and BOD. Microorganisms that are primarily attached to solid and emerged surfaces, mediate the reactions between DO and the oxygen consuming chemicals (Kadlec and Wallace, 2009). Oxygen transfers from air, and generation within the wetland, supplements any residual DO that may have been present in the incoming water. Three routes have been documented for transfer from air: direct mass transfer to the water surface, convective transport down dead stems and leaves, and convective transport down live stems and leaves. The latter two combine to form the plant aeration flux, (PAF). These transfers are largely balanced by root respiration, but may contribute to other oxidative processes in the root zone (Shutes, 2001).

pH

pH is a measure of how acidic or basic water is, and is important because it affects many chemical and biological processes that occur in wetlands. The pH scale measures the logarithmic concentration of hydrogen (H^+) and hydroxide (OH^-) ions, which make up water ($H^+ + OH^- = H_2O$). pH is measured on a scale that ranges from 0 to 14; when both types of ions are in equal concentration, the pH is 7.0 or neutral. Below 7.0, the water is acidic (there are more hydrogen ions than hydroxide ions). When the pH is above 7.0, the water is alkaline, or basic (there are more hydroxide ions than hydrogen ions). Since the scale is logarithmic, a drop in the pH by 1.0 unit is equivalent to a 10-fold increase in acidity. As an example, a water sample with a pH of 5.0 is 10 times as acidic as one with a pH of 6.0, and pH 4.0 is 100 times as acidic as pH 6.0. pH can be used as a proxy of water quality conditions since water pH is easily changed by chemical pollution.

Different organisms flourish within different ranges of pH: the largest variety of aquatic organism prefer a range of 6.5-8.0. pH outside this range can decrease the survival of aquatic organisms and lead to loss of wetland ecosystem diversity (Caselles-Osorio, 2007). High pH levels can occur when algae and aquatic vegetation use CO_2 for photosynthesis. Low pH can be cause by aquatic vegetation when they respire or from bacterial decay of organic matter in the water producing high levels of CO_2. Low pH can also allow toxic compounds and elements to become mobile and available for uptake by aquatic plants and animals. This can produce conditions that are toxic to aquatic life. Changes in acidity in wetland can be caused by atmospheric deposition (acid rain), surrounding rock, and certain wastewater discharges.

Microbial

Pathogens are typically present in runoff waters from animal sources as well as in untreated domestic wastewaters. These microorganisms range from submicroscopic viruses to parasitic worms visible to the unaided eye. If left untreated, these microorganisms could cause wide spread sickness within a community though the contamination of drinking water supplies and food sources. The water and other constituents of the sewage are eventually released into the environment, whether that is the final run off of the liquid into the ocean or other surface water areas, or into ground water. It is therefore important that the sewage is treated to remove or eliminate harmful microorganisms before it is released to areas that could impact human and wildlife health. It should be noted that the majority of microorganisms found within a wetland and a pre-treatment lagoon / pond are not pathogenic (causing sickness) and are in fact beneficial to the treatment of sewage. Many of the microorganisms are involved in the natural breakdown of solids and are therefore needed for the efficient treatment of the sewage.

Waterborne pathogens are functionally divided in groups: viruses, bacteria and protozoan. Their density in raw wastewater varies geographically (Truu *et al.*, 2009). Viruses are defined as submicroscopic, nonliving particles of genetic material that are enclosed in a sheath. They cannot reproduce or divide alone, but they have the ability to infect host organisms and reproduce to very large populations at the expense of the host organisms. In human feces, over 100 types of viruses are known to occur, with the minimum infective dose for some species as low as one organism (Truu *et al.*, 2009).

Bacteria, which are universally present in human feces, have a normal population of about 10^{11} organisms per gram. Despite the fact that most of these organisms live symbiotically with their hosts, a number of species are known human pathogens and occur in large frequency in individuals that are infected (Faulwetter et al., 2009). Of the three types of waterborne pathogens, bacteria are the group that are most often monitored. Common water quality testing often includes the assessment indicator groups with some of the most commonly used being "total coliforms and "*E. coli*". Both of these parameters provide an assessment of the bacterial population within the sewage or test water. Total coliforms, often abbreviated to "TC" provide a general indication of the relative abundance of soil-associated bacteria and thus an indication of recent contamination by this large and widely diverse group of bacteria. Fecal coliforms, a subset of total coliform bacteria, are more fecal-specific in origin (human or animal), and are another category often used as bacterial indicator group. These types of bacteria can come from a wide range of sources. *E. coli*

(*Escherichia coli*) is one bacterial organism that is routinely monitored since it can only originate from the digestive gut of a warm blooded animal or human. In this way, *E. coli* is different from TC in that TC provides a general indication of the presence of bacteria that could have originated from a wide variety of source, while *E. coli* can only come from warm blooded animal sources. The reason *E. coli* is so important to monitor is because its occurrence provides an indication that other human pathogens may be present. It is difficult to test for all the different types of bacterial organisms that can cause disease and sickness. Many of the most contagious and harmful pathogenic bacteria come from humans and sometimes wildlife. Lowering or eliminating the number of *E. coli* can provide a reasonable assurance that most of the many other types of harmful bacteria have also been lowered in numbers.

Protozoans are human parasites that derived from wastewater-related infections. *Entamoeba histolytica* and *Giardia lamblia* are two common protozoan parasites that causes diarrhea in infected humans. Protozoans and in particular viruses are difficult to analyze and require specialized testing. Many of the harmful protozoans and viruses originate from the same sources. The reduction or elimination of bacterial counts as the sewage is treated in the wetland may provide some indication that protozoans and viruses are also being eliminated. It should be understood however, that a reduction in bacterial counts may not always provide a good indication of how effectively other pathogens are being removed, particularly viruses which tend to be longer lived and because of their smaller size may not be physically filtered out of the water as easily as some of the larger bacterial and protozoans.

Factors influencing the removal of pathogenic microorganisms

Survival characteristics and resilience to environmental stressors varies considerably among bacteria, protozoans and viruses, and even among individual species within each of these major grouping. In general terms bacteria appear to be less adapted to survival outside of the host in comparison to viruses and protozoans.

Many factors influence survival. For example, sedimentation will play a vital role in the settling out of microorganisms within the pre-treatment lagoon / pond. Larger organisms such as protozoans can settle out on their own. Other smaller organisms generally settle out when attached to other solids. Once within the wetland, filtration plays an important role, particularly for the larger protozoans and bacteria. The longer the microorganisms are retained within the wetland either through entrapment via filtration or the slow rate of travel of the sewage through the wetland, the greater chance these pathogenic organisms will either die naturally or will be preyed upon by other microorganisms (nematodes, rotifers and non-pathogenic protozoans) common to the wetland. The water chemistry in terms of nutrients status, pH, and oxygen can also influence the survival of the pathogenic organism. The influence of many of these water quality parameters is often organism specific meaning that it is difficult to identify common water quality parameters that generally influence of microorganisms as a whole.

Temperature and nutrient status however, do appear to be two parameters about which general statements can be made. It is generally believed that survival of pathogenic organism is associated with lower water temperatures and increased nutrient status, two conditions common to northern wetlands and yet predation is generally greater with higher water temperatures. Sunlight can degrade or convert many waterborne substances. Biofilms on plants can also form sticky traps that trap some pathogenic organism.

Additional wastewater quality parameters routinely include alkalinity, hardness, metals, organic compounds, DOC and COD; however, these parameters are utilized less frequently for regulatory compliance purposes.

Appendix A2 Major treatment processes within wetlands

Numerous wetland processes may contribute to the removal or reduction of any given pollutant. In this section, some of the most important processes are presented for the most common wastewater constituents of interest.

Microbial

Many wetland reactions are mediated microbially; meaning that they are the result of the activity of bacteria or other microorganisms. The majority of these important microorganisms are found attached to various services within the wetland and often collectively referred to as the biofilm. A smaller percentage exists as free floating organisms. The number of biofilm organisms present is often sufficient to form relatively thick coatings on immersed surfaces (Kadlec and Wallace, 2009). The first step in the overall microbial removal mechanism is the transfer of a chemical from water to immersed solid surfaces. Those surfaces contain the biofilms responsible for microbial processing, and the binding sites for sorption processes. Mass transfer takes place both in the bulk water phase and in the biofilm. Roots are responsible for nutrient and chemical uptake by the macrophytes, and modulated by diffusion and transpiration rates. The sediment-water interface is an important zone for biochemical processes while the litter and stems within the water column comprise the dominant wetted area in free water surface (FWS) wetlands. Dissolved materials must move from the bulk of the water to the vicinity of the solid surface, then diffuse through a stagnant water layer to the surface, and penetrate the biofilm while undergoing chemical transformation (Kadlec and Wallace, 2009).

Microbes are very important in the carbon cycle. Many photoautotrophs (terrestrial and wetland species) are responsible for the initial fixing of carbon dioxide (CO_2) into useful sugars that can be used for energy. Aside from primary production, decomposition is also a function of microbial communities in wetland soils. However, many wetland soils can be anaerobic and thus decomposition rates under these conditions can be slow, resulting in high soil organic matter (SOM) content (USDA, 2004). Microbial communities in hypoxic conditions have the ability to transform this organic matter into usable forms of mineralized DOC (Figure A-3). This process allows plants and other organisms to use these substrates once again for energy. If mineralization did not occur, then carbon would stay in an organic form and be unusable to plants. Microbial communities in the soil can mineralize the SOM into inorganic forms of carbon, like carbon dioxide, that plants can then use for photosynthesis once again (USDA, 2004).

Under extremely reduced conditions, where terminal electron accepters are limited, microbes can use CO_2. These methanogenic bacteria use the CO_2 as a terminal electron acceptor resulting in the production of methane (CH_4) also known as swamp gas (USDA, 2004). Another group of bacteria, known as methanotrophs, use methane as their energy source and oxidize it to CO_2. In general, methanotrophs are obligate aerobes, meaning that in hydric soils, they will be active right above the aerobic/anaerobic dividing line (USDA, 2004). Methane is a major greenhouse gas, but because of the placement of methanotrophs, up to 90% CH_4 generated in hydric soils can be consumed before it reaches the atmosphere. Soil organic matter accumulates when biomass additions to the soil exceed microbial degradation. The organic matter content of a hydric soil will depend on the rate of primary biomass production and the duration of anaerobic condition year; however, in general, wetland can be considered to be C sinks (USDA, 2004).

The principal microbial processes that transform nitrogen from one form to another are: ammonification (mineralization), nitrification and denitrification. Ammonification is the process where organic nitrogen is converted to ammonia. The process is biochemical and involves the release of energy which some microorganisms utilize for growth and new biomass (Vymazal,

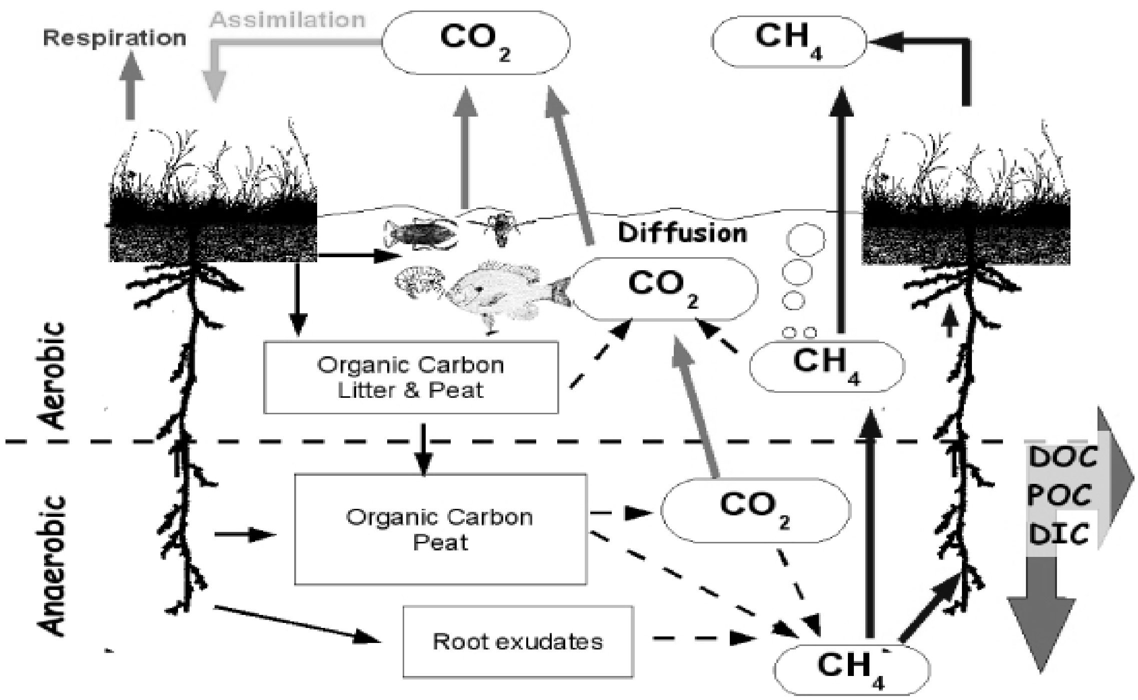


Figure A-3: A representation of the carbon cycle in wetlands. Dissolved inorganic carbon (DIC); dissolved organic carbon (DOC); particulate organic carbon (POC), methane (CH_4); carbon dioxide (CO_2) (Lloyd et al, 2013).

2006). Up to 100% of organic nitrogen is converted to ammonia through a complex process involving the catabolism of amino acids. The process converts amino acids into ammonia by means of aerobically, anaerobically, and obligate anaerobically mediated processes. The majority of ammonification is done by anaerobic and obligate anaerobic mineralization (Kadlec and Wallace, 2009). The rates of ammonification depend on temperature, pH, C/N ratio, available nutrients, and soil conditions. The optimal ammonification temperature is reported to be 40-60°C and optimal pH between 6.5 and 8.5 (Vymazal, 2006). This step is crucial before ammonium is then absorbed by plants, solubilized and returned to the water column, converted to gaseous ammonia, or aerobically nitrified by aerobic organisms.

Once organic nitrogen is in the form of ammonium, nitrification can take place where ammonium is biologically oxidized to nitrite and then finally to nitrate. Heterotrophic and autotrophic organisms utilize this process in the same manner. Nitrifying bacteria utilize CO_2 as a carbon source and oxidize ammonia or nitrite to derive energy (Kadlec and Wallace, 2009). Nitrification is carried out by two types of nitrifying organisms. The first step converts ammonium to nitrite and the second converts nitrite to nitrate. The first step is performed aerobically; the organisms depend on oxidizing the ammonia for cell growth and energy. Soil organisms include *Nitrosospira, Nitrosovibrio, Nitrosolobus, Nitrosococcus*, and *Nitrosomonas*. The carbon source is mostly found from CO_2 but carbonate can be used as well. The second step converts nitrite to nitrate and is accomplished by facultative chemolitrotrophic bacteria which can utilize organics for cell growth and energy (Vymazal, 2006). The only organism found in soils of freshwater systems that can oxidize nitrites is *Nitrobacter*. Nitrification also is influenced by temperature, pH, alkalinity, and DO. The pH values range from 6.6 to 8.8 and proper amounts of alkalinity and dissolved oxygen must be present. Nitrification consumes 4.3 mg of oxygen and 8.64 mg of alkalinity per mg of ammonia oxidized (Vymazal, 2006).

In denitrification, denitrifying bacteria decrease oxidized nitrogen such as nitrate and nitrite into nitrogen gas (Lee *et al.*, 2009). Denitrifying bacteria (denitrifiers) can be classified into two major species, heterotrophs and autotrophs. Heterotrophs are microbes that need organic substrates to obtain their carbon source for growth and evolution, and get energy from organic matter. In contrast, autotrophs utilize inorganic substances as an energy source and CO_2 as a carbon source (Lee *et al.*, 2009). Denitrification can only take place in the anoxic zones of the systems, as the presence of DO suppresses the enzyme system required for this process. High concentrations of nitrate in the inlet zones can lead to more vigorous and robust populations of denitrifiers within the inlet sediments (Lee *et al.*, 2009). Sufficient organic carbon is needed as an electron donor for nitrate reduction, which provides an energy source for denitrification microorganisms. This carbon source can be available in reed beds from organic pollutants of wastewater or cell materials of microorganisms (Kadlec and Wallace, 2009). The rate of denitrification is influenced by many factors, including nitrate concentration, microbial flora, type and quality of organic carbon source, hydroperiods, different plant species residues, the absence of O_2, redox potential, soil moisture, temperature, pH value, presence of denitrifiers, soil type, water level, and the presence of overlying water (Lee *et al.*, 2009; Kadlec and Wallace, 2009, Vymazal, 2006).

Phosphorus removal can be done by biological means but this process does not allow for much storage. The uptake of phosphorus by microorganisms is rather fast because bacteria, fungi, and algae are able to multiply quickly. The drawback is that they are unable to store large amounts of phosphorus, and is more of a temporary solution since the phosphorus is released in the water once the organism begins to decay (Vymazal, 2006).

Volatization

Various processes in wetland create product gases that are released from the wetland environment to the atmosphere, such as ammonia, hydrogen sulfide, di-nitrogen, nitrous oxide, and methane. Wetlands also take in atmospheric carbon dioxide for photosynthesis and expel it from respiratory processes (Kadlec and Wallace, 2009).

Ammonia volatilization is the process where ammonium is in equilibrium with gas and hydroxyl forms. Usually if the pH is lower than 8.0, ammonia volatilization does not occur. If the pH reaches as high as 9.3, then ammonia and ammonium ions present exist in a one to one ratio. This means that the losses from volatilization can be significant. A larger pH can be observed when plants undergo photosynthesis during the day (Vymazal, 2006).

Sedimentation / Filtration

Sedimentation is a treatment process where the water quality in wetlands can be improved by holding or storing it undisturbed and without mixing long enough for larger particles to settle out or sediment by gravity in a settling basin or pond. Storing water for as little as a few hours will sediment the large, dense particles, such as inorganic sands and silts, large microorganisms and any other microorganisms associated with larger, denser particles. Clay particles and smaller microorganisms not associated with large or dense particles will not settle under these conditions. For turbid waters containing non-settable solids, sedimentation will be ineffective and alternative methods of particle removal, such a filtration, are needed. Filtration is the process of removing solids from a fluid by passing it through a porous medium, such as sand. As the water passes through the filter, floc and impurities stay in the medium and the water goes through.

It is important to remove the fine particles that are suspended within the water part of the sewage, mainly because many of the harmful items within the sewage, such as pathogens, metals and chemicals are attached to the suspended solids in the wastewater. Sediments of wetlands tend to accumulate as vast amounts of coliforms and bacteria. Viruses tend to attach to colloidal material which takes longer to settle out and eventually settle out in a loose layer above sediment (Kadlec and Wallace, 2009). Filtering out most of the suspended solids therefore also filters out many of the harmful items in the sewage. Suspended solids, if not filtered out, can over time build up in the environment that receives the water from the wetland and cause problems to aquatic organisms. The necessary connection to solids removal is the quantification of sorption. Most particulate organic nitrogen in wetlands is removed by sedimentation. Particulates may settle on the wetland floor or may adhere to plant stems (Lee *et al.*, 2009).

Adsorption / Absorption

In wetlands, adsorbed ammonia is bound loosely to the substrates and can be released easily when water chemistry conditions change. When the ammonia concentration in the water column is reduced as a result of nitrification, some ammonia will be adsorbed to re-establish equilibrium with the new concentration. If the ammonia concentration in the water column is increased, the adsorbed ammonia will also increase (Vymazal, 2007). If the wetland substrates are exposed to oxygen, adsorbed ammonium may be oxidized to nitrate by periodic draining. The ammonium ion is generally adsorbed as an exchangeable ion on clays, and adsorbed by humic substances. The rate and extent of these reactions are influenced by several factors, such as the type and amount of clay, alternating submergence and drying patterns, characteristics of soil organic matter, submergence period, and the presence of vegetation (Lee *et al.*, 2009).

The ability of soils and sediments to retain phosphorus can depend on processes of phosphorus sorption and precipitation with different forms of Fe, Al and Ca. (Kadlec and Wallace, 2009; Vymazal, 2006). Sorption refers to both adsorption on solid surfaces and absorption into solid phases of Al and Fe oxides and other mineral surfaces. Phosphorus adsorbs to mineral surfaces and once all surface sites are filled, P begins to diffuse into the particle via absorption (Vymazal, 2006). Sorption is important for phosphorus during the start-up period for a treatment wetland. If phosphorous is initially absent in the sediments, it will be stored until the existing soils and sediments reach equilibrium with the overlying water. If phosphorous is initially present, it may be released. Sorption processes are temporally dependent, pH controlled and process rates decrease with time. It may also be partially irreversible, due to mineralization of sorbed materials, or to the formation of very strong chemical bonds (Kadlec and Wallace, 2009; Vymazal, 2006).

Accretion

Not all the dead plant material undergoes decomposition: some small portions of both aboveground and belowground necromass resist decay, and form new stable accretions. Such new stores of chemicals are presumed to be resistant to decomposition. The origins of new sediments may be from remnant macrophyte stem and leaf debris, remnants of dead roots and rhizomes, and from undecomposable fractions of dead microflora and microfauna (algae, fungi, invertebrates, bacteria) (Kadlec and Wallace, 2009).

Through the accretion process, organic nitrogen is incorporated into the soil of a wetland. This nitrogen that is buried in soil then undergoes processes that ends up in peat. The long term solution to removing phosphorus is through accretion but will only be effective if there is lots of biomass (Vymazal, 2006).

Plant uptake

Plants take up nutrients to sustain their metabolism, and they may also take up trace chemicals found in the root zone, which may then be stored, or in some cases, expelled as gases. Uptake is by the roots, which are most often located in the wetland soils, although roots may sometimes be found in the water column. Submerged plants may absorb nutrients and metals from the water column into stems and leaves.

An important part of nitrogen transfer in wetlands is plant uptake and assimilation. This refers to biological processes that convert inorganic nitrogen to organic nitrogen. The organic nitrogen is then used for energy and cell growth. Assimilated forms of nitrogen are ammonia and nitrate. Factors effecting nutrient uptake of plants is growth rate of plants, concentration of nutrients in the plant tissues and climatic conditions. The major portion of the nitrogen removal is through bacterial conversion as compared to nutrient uptake by plants (Vymazal, 2006).

The majority of phosphorus removal is done by uptake from plant roots. The absorption through leaves and plant parts are usually very low and thus removal of phosphorus from the wetland by macrophytes is generally confined to the growing season. The storage of phosphorus in plants varies between the type of plant and storage below ground is usually longer than storage above ground. Phosphorus is released after a plant dies and begins to decay. The decaying plant matter above ground release phosphorus into the water while decaying roots secrete phosphorus into the soil (Vymazal, 2006).

Appendix A3 Major factors impacting treatment processes

Loading rates / Pre-treatment

In generic terms the hydraulic loading rate (HLR, or q) is defined as the rainfall equivalent of the flow under consideration. It does not imply uniform physical distribution of water over the wetland surface. The defining equation is:

$$q = Q/A$$

where:

q= hydraulic loading rate (HLR), m/d
A= wetland area (wetted land area), m^2
Q= water flow rate, m^3/d

The definition is generally applied to the volume of wastewater added to the inlet of the wetland (Kadlec and Wallace, 2009). Some constructed wetlands are operated with intermittent feed: under these circumstances, the term hydraulic loading rate refers to the time average flow rate. The loading rate during a feed portion of a cycle is *the instantaneous hydraulic loading rate*, which is also called the *hydraulic application rate*. Some wetlands are operated seasonally, for instance, during warm weather conditions in northern climates. Although these are in some sense intermittently fed, common usage is to refer to the loading rate during operation and not to average over the entire year (Kadlec and Wallace, 2009). This means the instantaneous loading rate is used and not the annual average loading rate.

Wastewaters with solids content greater than two percent should undergo pre-treatment to allow solids to settle prior to flowing into the treatment wetlands. Pre-treatment can be accomplished by storage in either waste stabilization ponds (e.g., lagoons) or in facultative lakes. Discharge of waste waters with a high solids content can cause premature fouling of the interstitial spaces within the subsurface media of the wetland. Pre-treatment can extend the life of the treatment wetland and ultimately enhance treatment efficiency.

Hydraulic retention time (HRT) / Flow rates / TSS loading of influent

Hydraulic retention time refers to the length of time water remains in the treatment wetland, expressed as mean volume (of the stored waste water) divided by mean outflow rate. It is closely related to hydraulic loading rate. Efficiency of the system is generally shown to increase with longer retention times and lower hydraulic loading rates. High water velocities can wash out rooted vegetation and scour deposited sediments. The longer water remains in the wetland the greater chance of sedimentation, adsorption, biotic processing and retention of nutrients.

The flow rate of the wastewater entering the wetland and the amount of suspended solids in the raw sewage can affect how well the wetland filters. All wetlands have a limit as to how fast they can accept suspended solids. If the amount of suspended solids is coming too fast, then the pore space between the soil particles can become plugged and a greater portion of the wastewater flows overland. When the wetlands are frozen, no filtering takes place. Periods of rapid melt may also add water to the wetland and reduce the amount of wastewater that can be released to the wetland before it overflows or flow rates through the wetlands are too rapid to allow proper filtration and removal of suspended solids.

Hydraulic conductivity / Porosity

The hydraulic conductivity (or permeability) is the ability of the soil to conduct water under hydraulic gradients. It depends on soil characteristics such as type (i.e. clay or sand), size, shape, and packing. Hydraulic conductivity can be estimated in a number of ways: it can be roughly estimated, given the soil composition and texture, or calculated based on a soil size analysis (Carter and Novitzki, 1986) or directly measured with the use of a permeameter. In wetlands, the hydraulic conductivity will strongly influence the subsurface flow rate of the wastewater within the wetland media.

Porosity or pore space is the amount of air space or void space between soil particles and represents the potential area through which water can flow. Porosity greatly influences the filtering action in wetlands. Not all particles are spheres or round, they exist in many shapes and these shapes pack in a variety of ways that may increase or decrease porosity. Generally, a mixture of grain sizes and shapes, results in lower porosity, because the smaller grains fill the openings created by the larger grains. A mixture of grain sizes and shapes (i.e., pore sizes) will be different for different wetlands. Other factors that can influence the porosity in wetlands include the amount of plant roots along with dead and decaying plant material that can fill the pore spaces between the individual grains of sand and gravel. The porosity or pore space determines the volume of wastewater the wetland media can hold and this value; combined with hydraulic loading will determine the hydraulic retention potential of the wetland.

Bed media

Bed media is one of the most important physical components of wetlands. Depth, mineral composition, organic matter content, moisture regime, temperature regime and chemistry have strong influence over vegetation and soil organisms (Gerakis, 1992). The biological and physico-chemical conditions within the soil or sediment are important in determining whether toxicants and nutrients remain fixed to particulate matter. Amount, particle size, density and ion-exchange characteristics are particularly important determinants of decomposition and sorption properties. For example, clay-hummus complexes have the capacity to absorb nutrients and toxins in very much larger quantities than silt-sized particles. In comparison, sands generally have lower chemical exchange capabilities (Gerakis, 1992).

Factors influencing microbial processes (temperature, DO, pH, C/N ratios)

Temperature

Water temperature controls many of the microbially mediated biogeochemical reactions in the water column. Variations in temperatures are reflected in the ranges of values for various water quality parameters and in the productivity of periphyton and vegetation. Variation per degree change is typically greater at the lower end of the temperature scale (<15°C) than observed at higher temperatures (20-35°C) (Kadlec and Wallace, 2009). Processes regulating the decomposition of organic matter are also affected by temperature. Likewise, all nitrogen cycling reactions (mineralization, nitrification, and denitrification) are affected by temperature.

Temperature is the greatest factor directly limiting the treatment of wastewater in an Arctic environment by negatively impacting on a number of process functions important for the mineralization of organic matter and nutrient cycling (Yates *et al.*, in press). Vymazal (2006) explained that organic matter removal from wastewater through anaerobic and aerobic bacteria can remain active to 5ºC; however, prolonged temperatures below 5ºC can limit the wetland's treatment efficiency. Performance may be indirectly or directly affected by environmental variables such as freezing (ice), reduction in microbial community biomass, plant dynamics and the mineralization of organics (Yates *et al.*, in press). During the summer months in natural Arctic environments, microbial communities are at their lowest population levels. The reason for this is a lack of available nutrients, after microbial communities have used much of the available C and N in the soil in the early spring (Edwards and Jefferies, 2010). Conversely, treatment wetlands are an environment enriched with nutrients and carbon, and N and C should not be the limiting factor of microbial growth. In a treatment wetland environment, temperature and oxygen are therefore the most likely causes of reduced decomposition of organic matter and other wastewater contaminants (Yates *et al.*, in press).

DO

Water temperature can affect the DO content, an important water characteristic that strongly affects many aquatic organisms. Concentration of DO in the water column readily responds to anthropogenic impacts. Highly degraded wetlands may have wide shifts in DO concentrations. For example, wetlands receiving waters containing carbonaceous and nitrogenous oxygen demand can exhibit oxygen depletion in the water column. Oxygen production by algae can increase daytime DO concentrations and may result in low DO concentrations during the night. Oxygen is consumed during biological and chemical processes operative in the water column. Plant, animal, and microorganisms consume oxygen during respiration. Similarly, nitrification and oxidation of reduced substances such as sulfides, methane, and reduced iron and manganese consume oxygen.

pH

The pH of the water column also affects many biogeochemical processes. The pH of the water column within natural systems can be highly variable; often depending on wetland type. Photosynthesis results in depletion of CO_2 in the water column, shifting the carbon dioxide – bicarbonate – carbonate equilibrium (Kadlec and Wallace, 2009). However, during the night, high rates of respiration increase the production of protons, thus resulting in decreased pH of the water column. Changes in pH resulting from the wastewater can influence the water chemistry of the treatment wetland. For example, as pH increases, smaller amounts of ammonia are needed to reach a level that is toxic to fish. As pH decreases, the concentration of metal may increase because higher acidity increases its ability to be dissolved from sediments into the water.

C:N ratio

The C:N ratio or carbon-to-nitrogen ratio is a ratio of the mass of carbon to the mass of nitrogen in the treatment wetland. The C/N ratio of the organic material entering the wetland influences the rate of decomposition of organic matter and this result in the release (mineralisation) or immobilization of nitrogen in the system. If the organic material entering the wetland contains more nitrogen in proportion to the carbon, then nitrogen is released into the wetland from the decomposing organic material. On the other hand, if the organic material contains a smaller amount of nitrogen in relation to the carbon then the microorganisms will utilize the nitrogen for further decomposition and the wetland nitrogen will be immobilized and will not be available.

Short circuiting

Velocity heterogeneity is characteristic of wetland systems and results in some influent water remaining in the wetland for less than the expected residence time on the basis of volume and flow rate. This phenomenon, known as short-circuiting, alters the distribution of the chemical and biological transformations that occur within the wetland (Lightbody, 2008). In treatment wetlands, such heterogeneity nearly always results in reduced contaminant removal. Moreover, high degree of short-circuiting can mean that uniform flow is a poor approximation for the flow through the wetland (Lightbody, 2008).

Plants

In wetlands, plant growth provides a vegetative mass that deflects flows and provides attachment sites for microbial development; death creates litter and releases organic carbon to fuel microbial metabolism. In addition, plants stabilize substrates while enhancing its permeability, and a dense stand of vegetation appears to moderate the effects of storms. Not all wetland species are suitable for wastewater treatment since plants for treatment wetlands must be able to tolerate the combination of continuous flooding and exposure to wastewater or stormwater containing relatively high and often variable concentrations of pollutants.

Yates *et al.*, (2012) reported that the greatest responses in plant communities in Arctic environments were observed when the addition of N and P were combined. The authors explained that in Arctic systems many nutrients become locked and unavailable to plant and microbial communities in frozen or partially frozen soils. In wet-sedge tundra where soils were supplemented with additional nutrients (particularly N and P) plant communities quickly utilize the nutrients; often resulting in promoting growth and observable changes in community structure. As a result of the addition of readily available nutrients from sewage, plants and microbial communities rapidly remove much of the nutrients in the wastewater as it passes through the wetland. (Yates *et al.*, 2012)

UV irradiation (sunlight, photolytic compounds)

Many microorganisms, including pathogenic bacteria and viruses, can be killed by ultraviolet radiation. The effectiveness is presumptively determined by the radiation dose rate as well as the concentration of organisms. Direct photolysis involves the breakdown of the molecule, usually by the ultraviolet component of the sunlight (Kadlec and Wallace, 2009). This becomes an important treatment process in arctic tundra wetlands were a significant portion of the flow of wastewater is above ground where it is exposed to intended hours of sunlight.

Appendix B. Contact information for analytical laboratories utilized

Table B-1: Contact information for analytical laboratories utilized

Laboratory	Address	Phone	Website	Contact Email
Agat Laboratories	2910 12th Street NE Calgary, AB T2E 7P7	(403) 735-2005	http://www.agatlabs.com/	
Environment Canada Canada Centre for Inland Waters	867 Lakeshore Rd Burlington, ON L7R 4A6	(905) 336-4999	www.nwri.ca	nwriscience.liaison@ec.gc.ca
Test Mark Laboratories Ltd.	7 Margaret Street Garson, ON P3L 1E1	1-888-282-0422	http://www.testmark.ca/	customer.service@testmark.ca
Centre for Alternative Wastewater Treatment, Fleming College	200 Albert St Lindsay, ON K9V 5E6	(705) 324-9144 x3226	http://appliedresearch.flemingc.on.ca/cawt/	bwootton@flemingc.on.ca
Taiga Environmental Laboratory Renewable Resources & Environment Indian and Northern Affairs Canada	4601 52nd Avenue Yellowknife, NT X1A 2R3	(867) 669-2788	http://nwt-tno.inac-ainc.gc.ca/taiga/index_e.htm	taiga@inac.gc.ca
Caduceon Environmental Laboratories	285 Dalton Ave Kingston, ON K7K 6Z1	(613) 544-2001	http://www.caduceonlabs.com/	sburrows@caduceonlabs.com

Appendix C: Interpolated maps

The interpolated maps for most wetlands represent only the more prominent parameters. All interpolated maps are orientated in a manner where the top of the figure represents a North direction. The values identified on the elevation map identify the individual sampling locations and correspond to the sample identification codes within the raw data tables of the appendix. A generalized flow direction in terms of the influent in / effluent out of the wetland is identified on the interpolated maps identifying the relative moisture contents of the wetland soils

.

Paulatuk, NT (Full survey - Sample date: September 2-3, 2009). Interpolated data maps of effluent water quality parameters

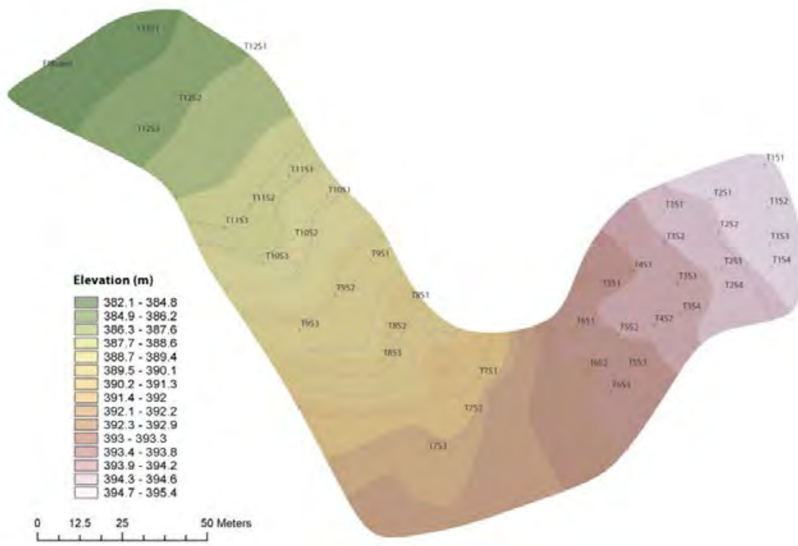


Figure C-1: An elevation map of the Paulatuk wetland showing sampling locations. Note: the flow of wastewater is from right to left.

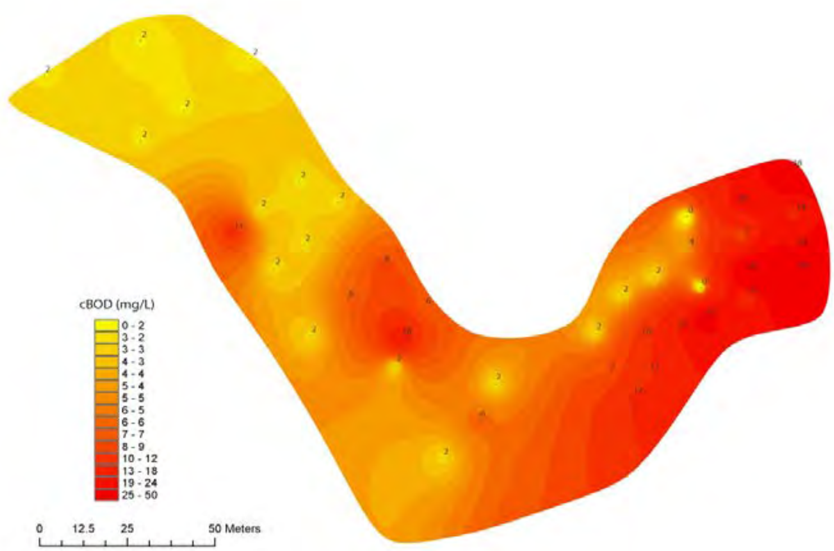


Figure C-2: Carbonaceous biochemical oxygen demand (5 day) of effluent in the Paulatuk wetland. Note: the flow of wastewater is from right to left.

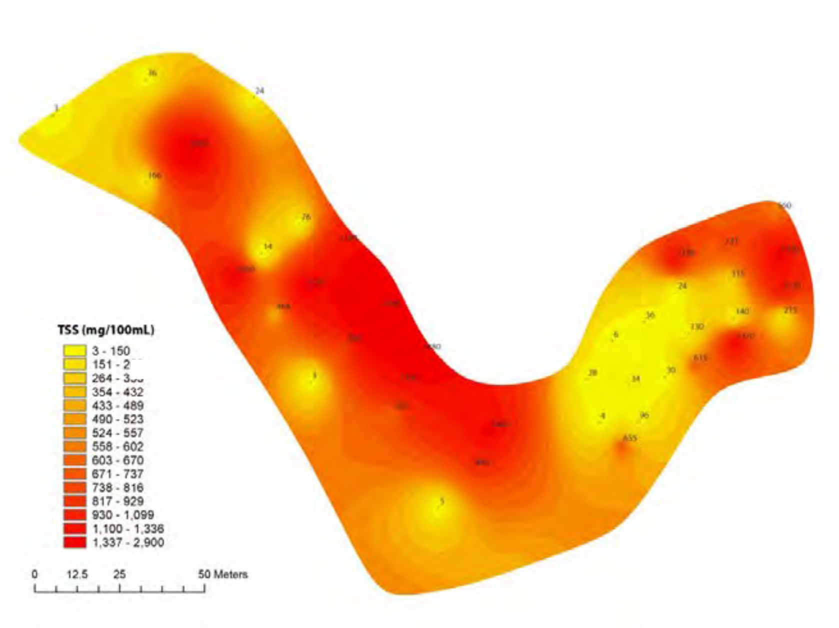


Figure C-3: Total suspended solids of effluent in the Paulatuk wetland. Note: the flow of wastewater is from right to left.

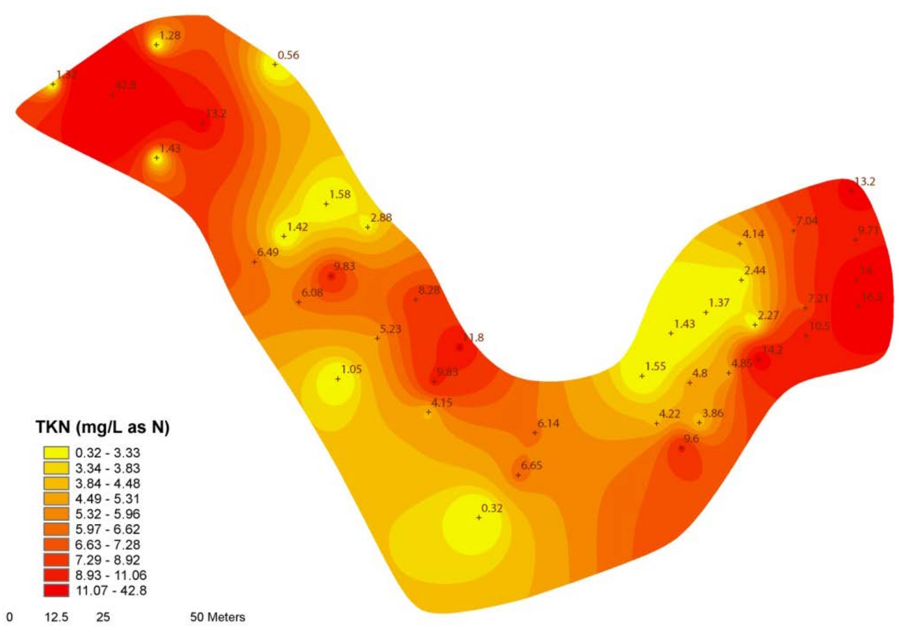


Figure C-4: Total Kjeldahl nitrogen of effluent in the Paulatuk wetland. Note: the flow of wastewater is from right to left.

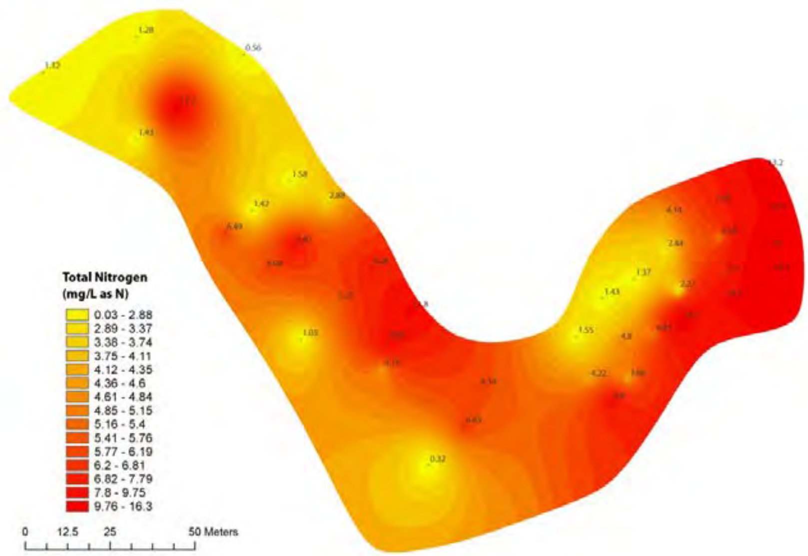


Figure C-5: Ammonia (NH_3 as N) of effluent in the Paulatuk wetland. Note: the flow of wastewater is from right to left.

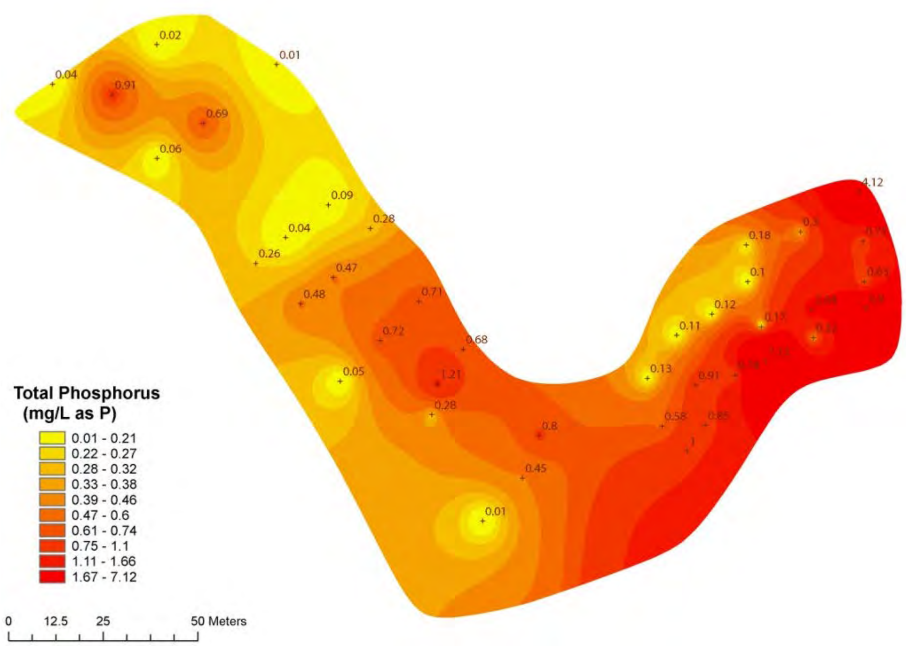


Figure C-6: Total phosphorus of effluent in the Paulatuk wetland. Note: the flow of wastewater is from right to left.

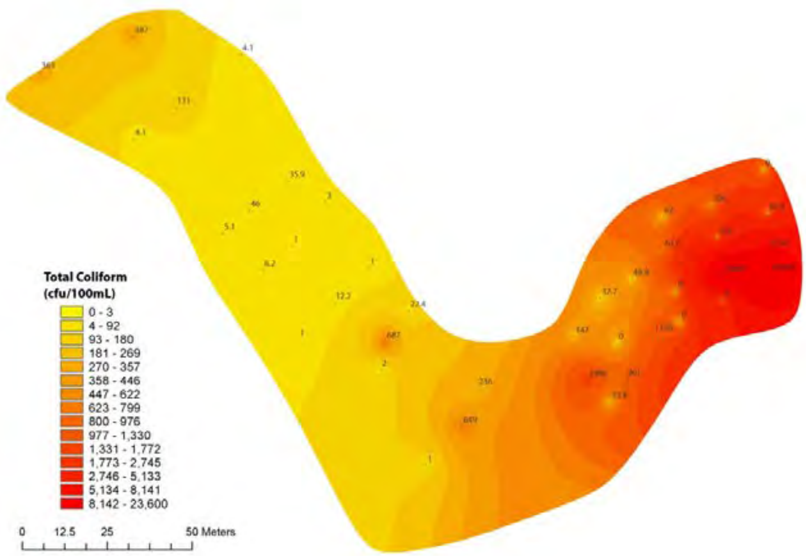


Figure C-7: Total coliform count of effluent in the Paulatuk wetland. Note: the flow of wastewater is from right to left.

Pond Inlet, NU (Full survey - Sample date: September 13-14, 2009). Interpolated data maps of water quality parameters

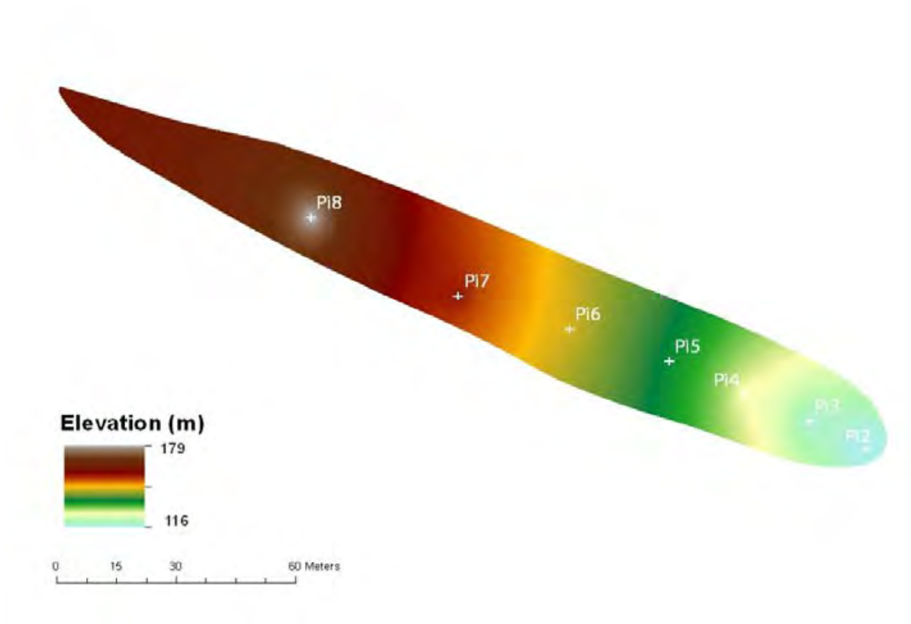


Figure C-8: An elevation map of the Pond Inlet wetland showing sampling locations. Note: the flow of wastewater is from left to right.

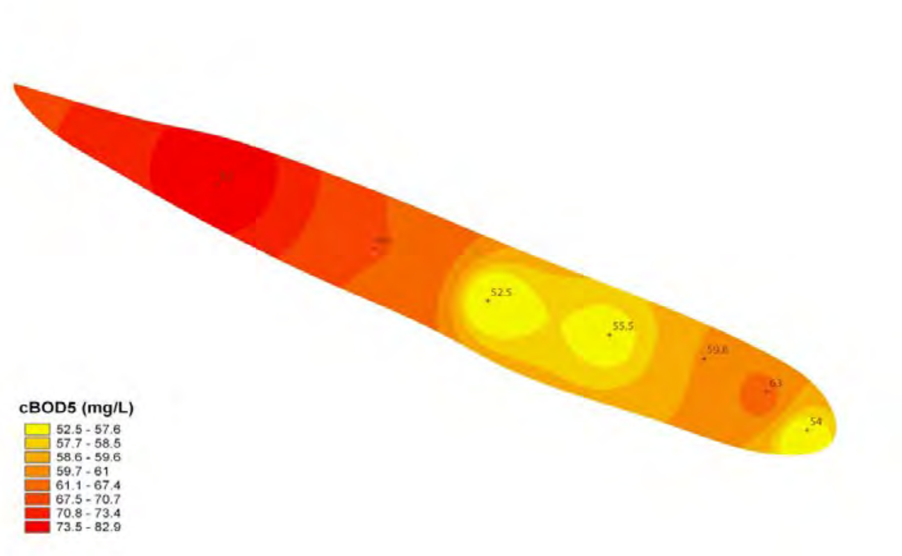


Figure C-9: Carbonaceous biochemical oxygen demand of effluent in the Pond Inlet wetland. Note: the flow of wastewater is from left to right.

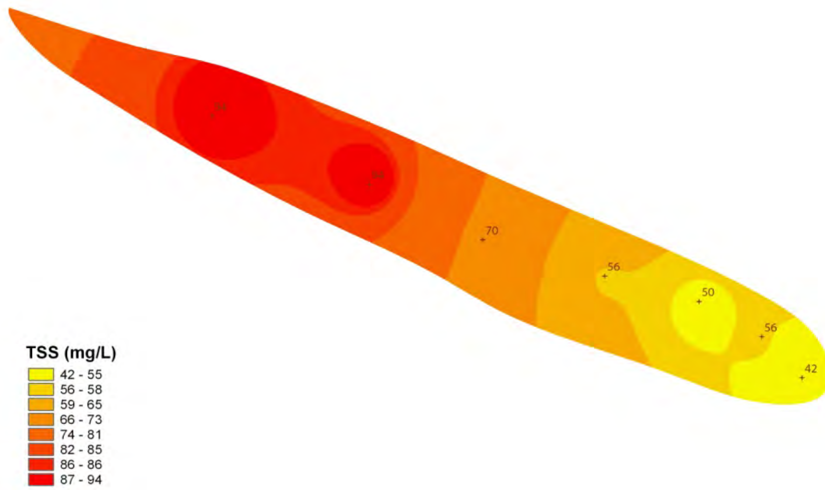


Figure C-10: Total suspended solids of effluent in the Pond Inlet wetland**.** Note: the flow of wastewater is from left to right.

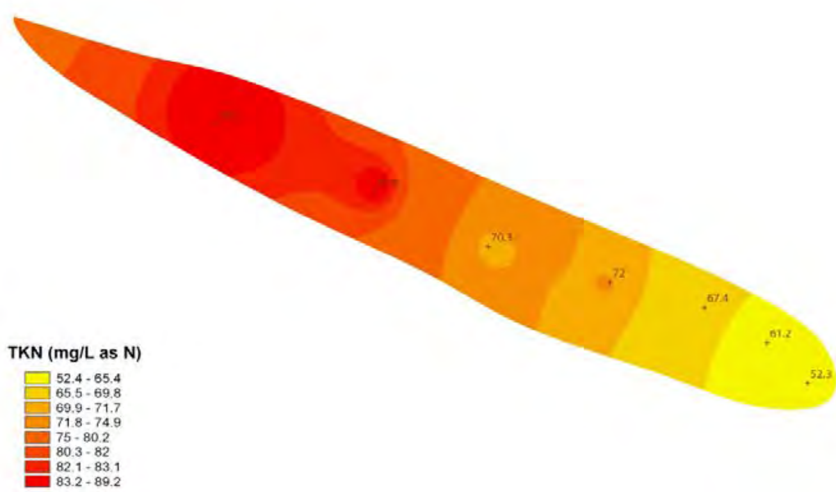


Figure C-11: Total Kjeldahl nitrogen of effluent in the Pond Inlet wetland. Note: the flow of wastewater is from left to right.

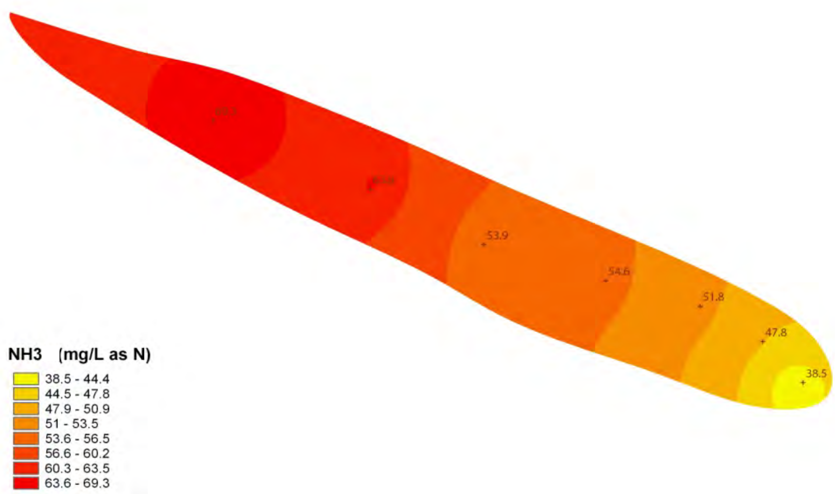


Figure C-12: Ammonia (NH_3 as N) of effluent in the Pond Inlet wetland. Note: the flow of wastewater is from left to right.

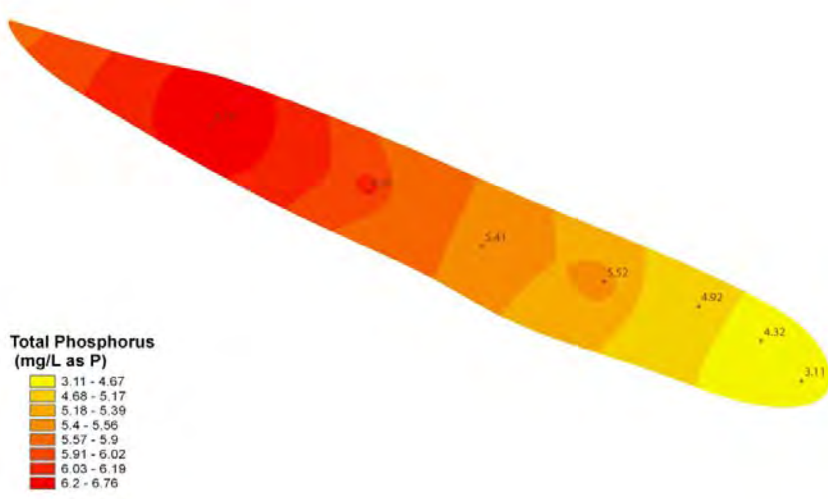


Figure C-13: Total phosphorus of the effluent in the Pond Inlet wetland. Note: the flow of wastewater is from left to right.

Edzo, NT (Full survey - Sample date: September 2-5, 2011; rapid survey data for September 15-16, 2010 is in tabular form in appendix). Interpolated data maps of water quality parameters

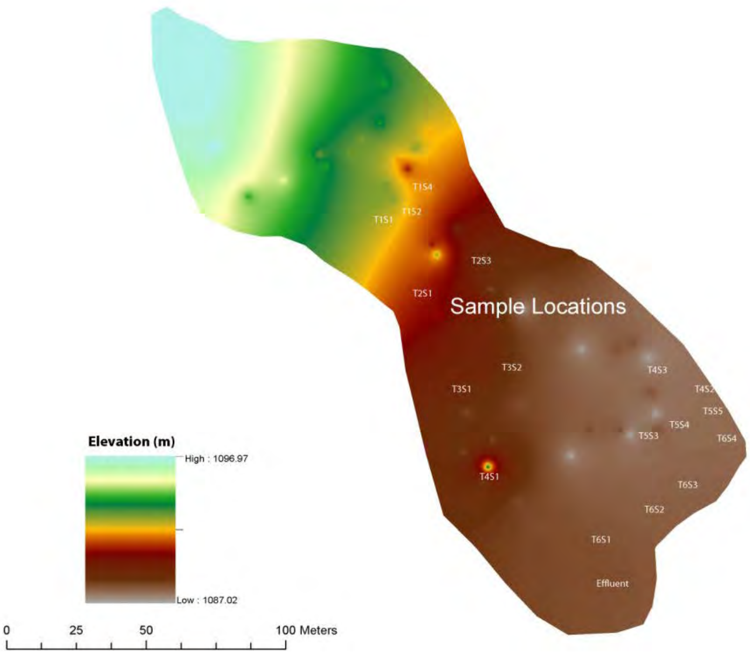


Figure C-14: Elevation map of the Edzo wetland. Note: flow of wastewater is from top to bottom.

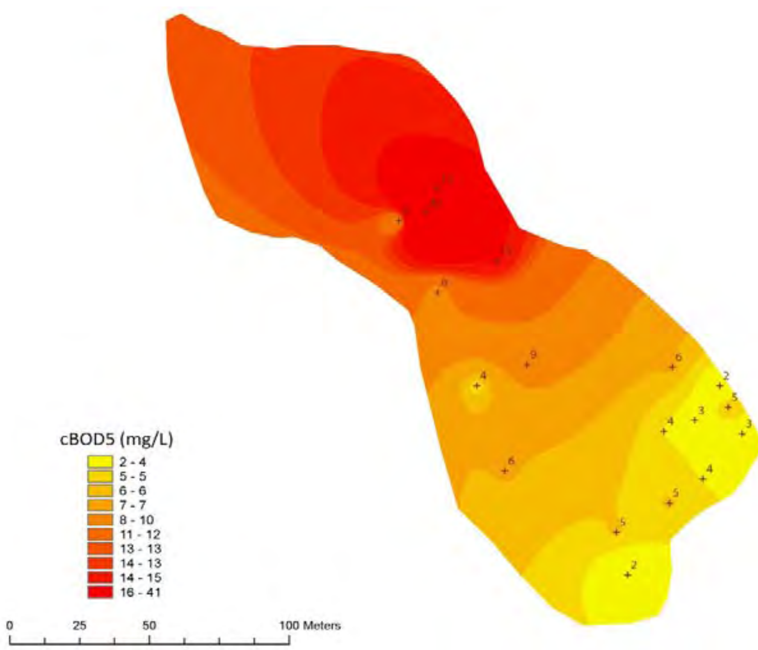


Figure C-15: Carbonaceous biochemical oxygen demand of effluent in the Edzo wetland. Note: flow of wastewater is from top to bottom.

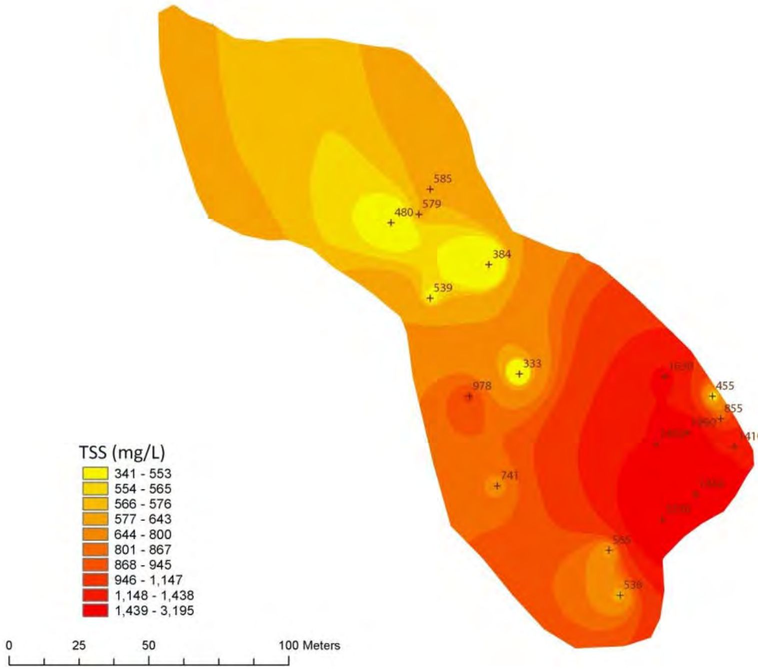


Figure C-16: Total suspended solids of effluent in the Edzo wetland. Note: flow of wastewater is from top to bottom.

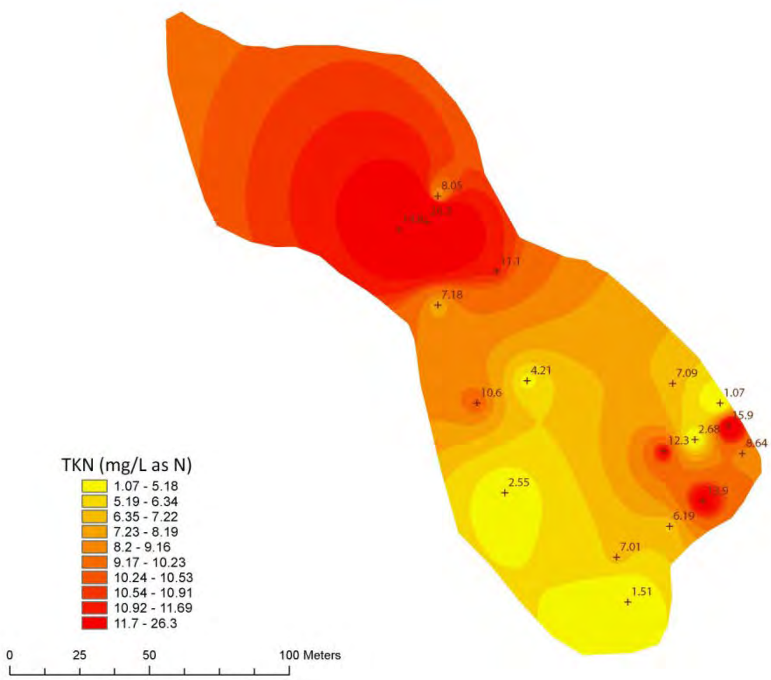


Figure C-17: Total Kjeldahl nitrogen of the effluent in the Edzo wetland. Note: flow of wastewater is from top to bottom.

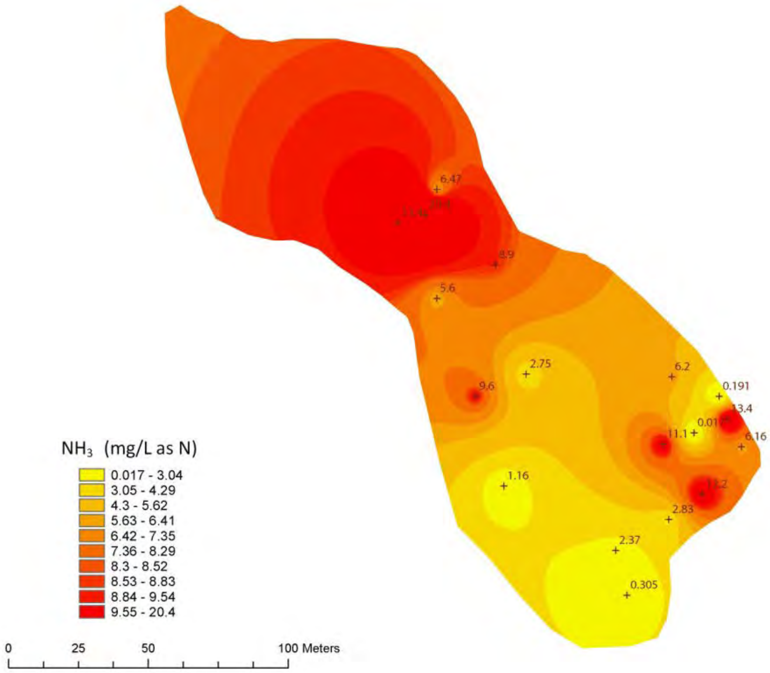


Figure C-18: Ammonia (NH_3 as N) of effluent in the Edzo wetland. Note: flow of wastewater is from top to bottom.

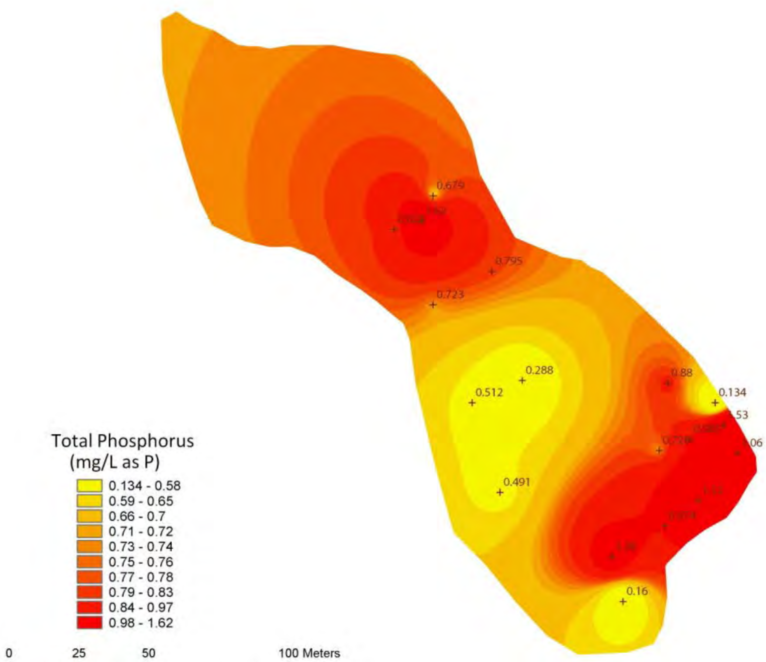


Figure C-19: Total phosphorus of the effluent in the Edzo wetland. Note: flow of wastewater is from top to bottom.

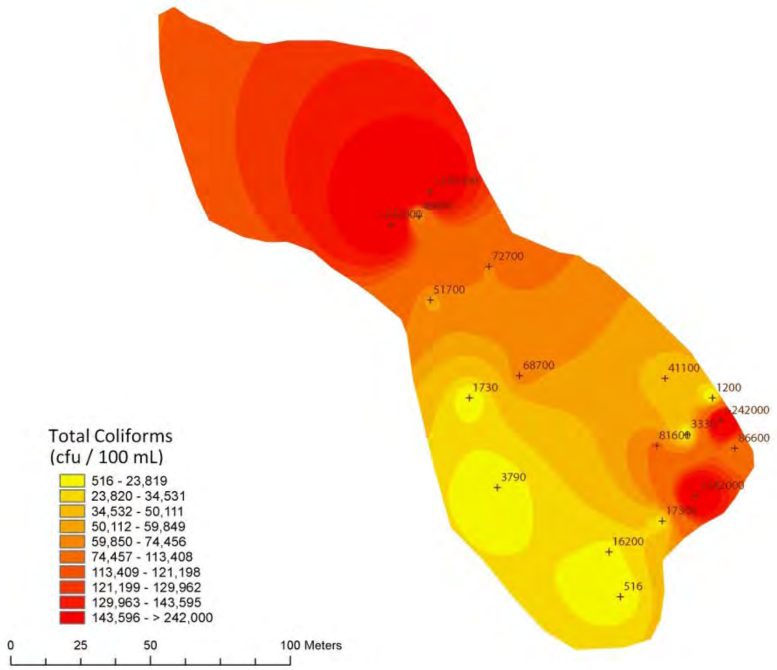


Figure C-20: Total coliform counts of effluent in Edzo wetland. Note: flow of wastewater is from top to bottom.

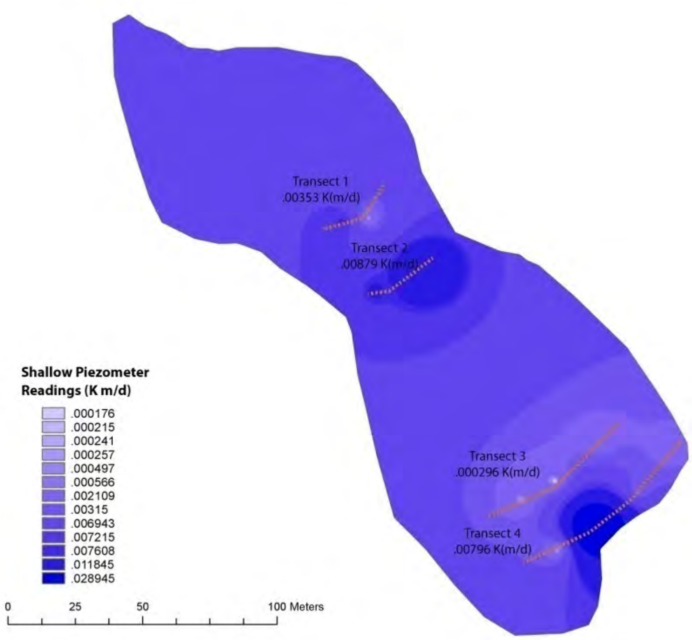


Figure C-21: Hydraulic conductivity of the Edzo sediments expressed as K (m/d), which indicates the rate of water travel through the subsurface sediment. Note: flow of wastewater is from top to bottom.

Fort Providence, NT (Rapid survey - Sample date: September 12-14, 2010). Interpolated data maps of water quality parameters

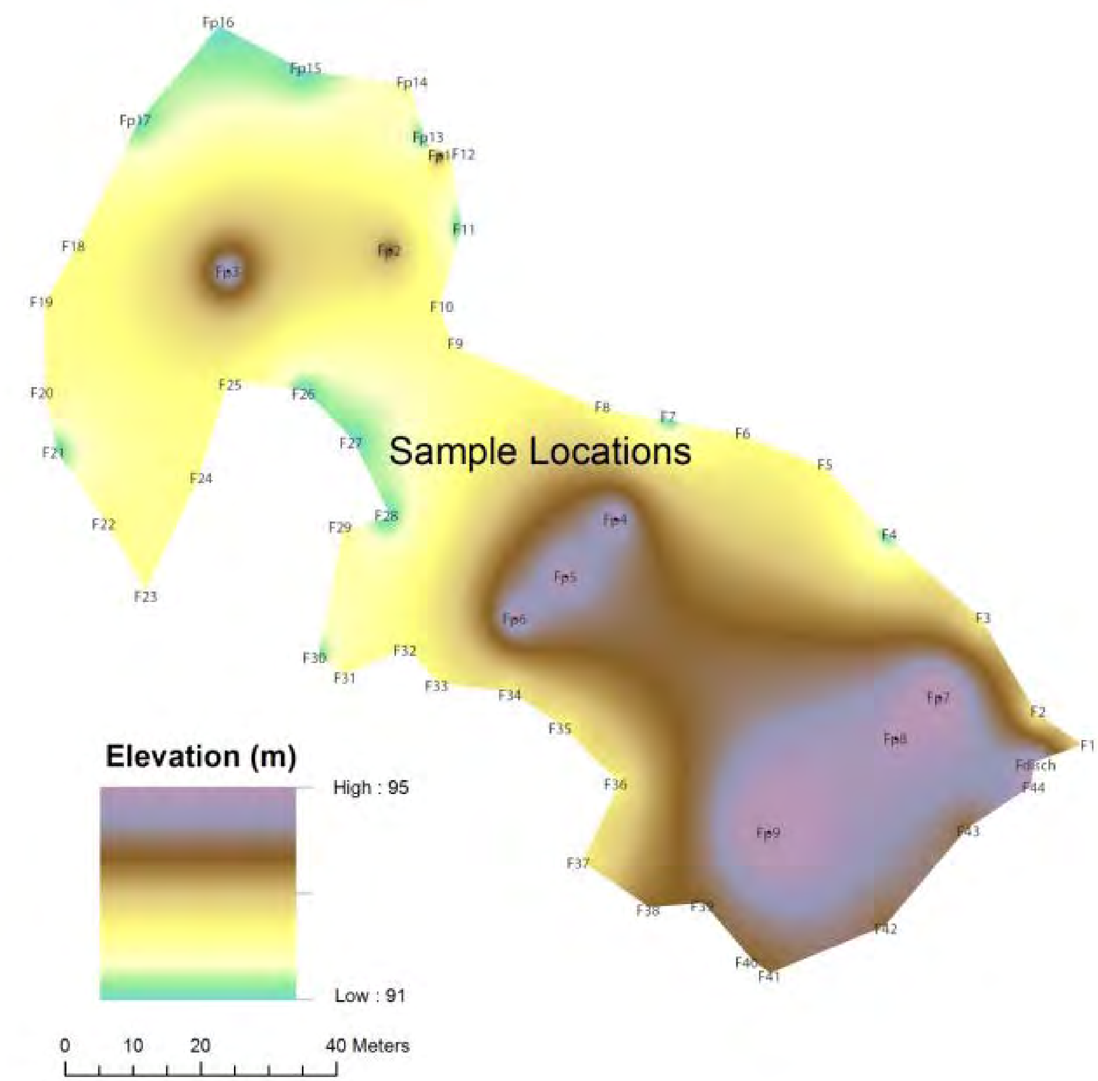


Figure C-22: Elevation map for the Fort Providence wetland. Note: flow of wastewater is from bottom to top.

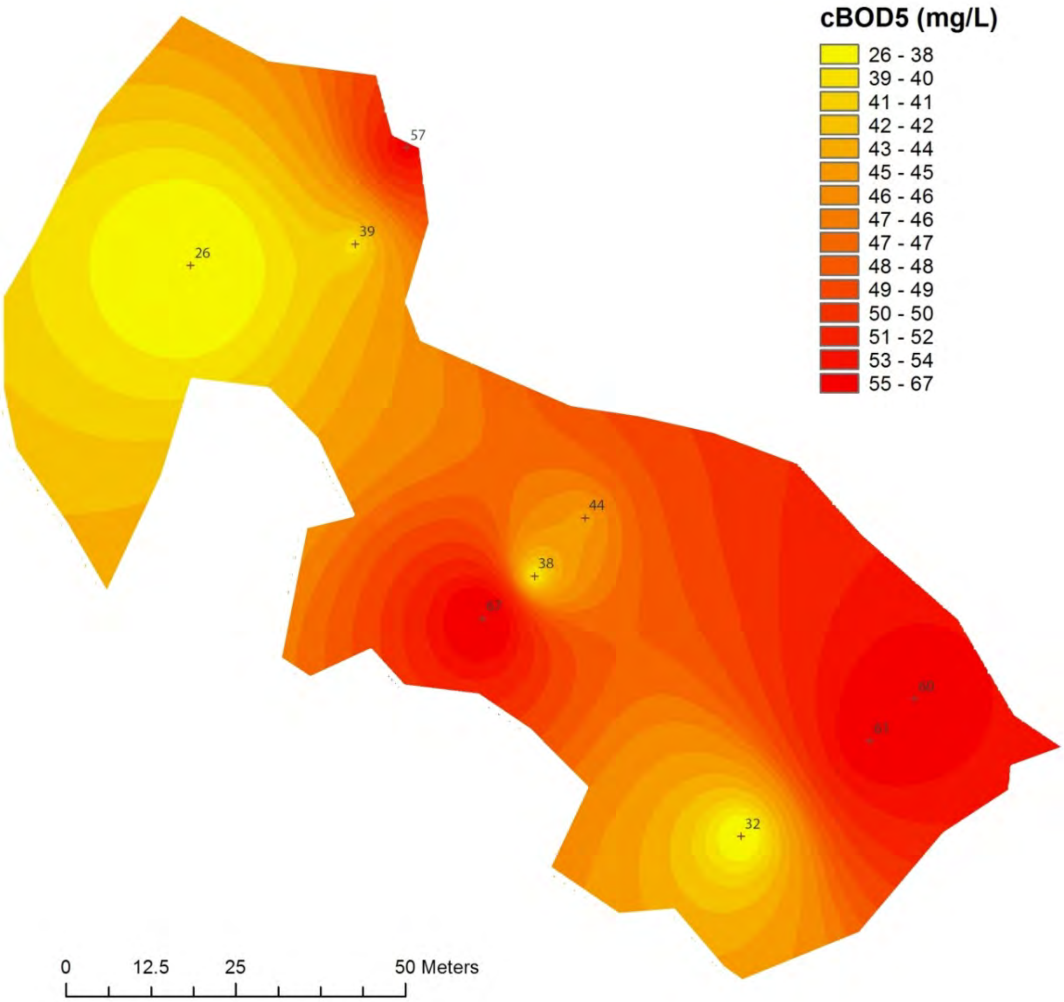


Figure C-23: Carbonaceous biochemical oxygen demand (5 day) of effluent in the Fort Providence wetland. Note: flow of wastewater is from bottom to top.

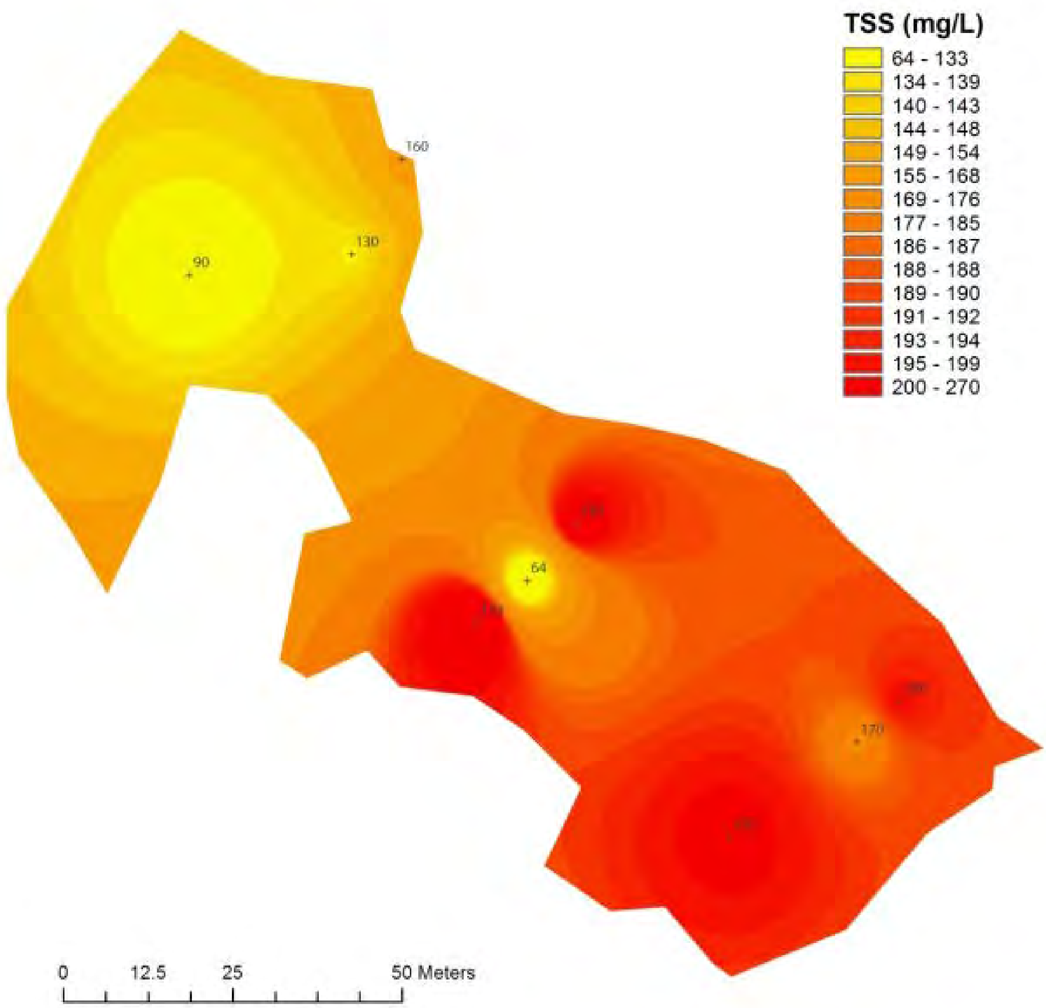


Figure C-24: Total suspended solids of the effluent in the Fort Providence wetland. Note: flow of wastewater is from bottom to top.

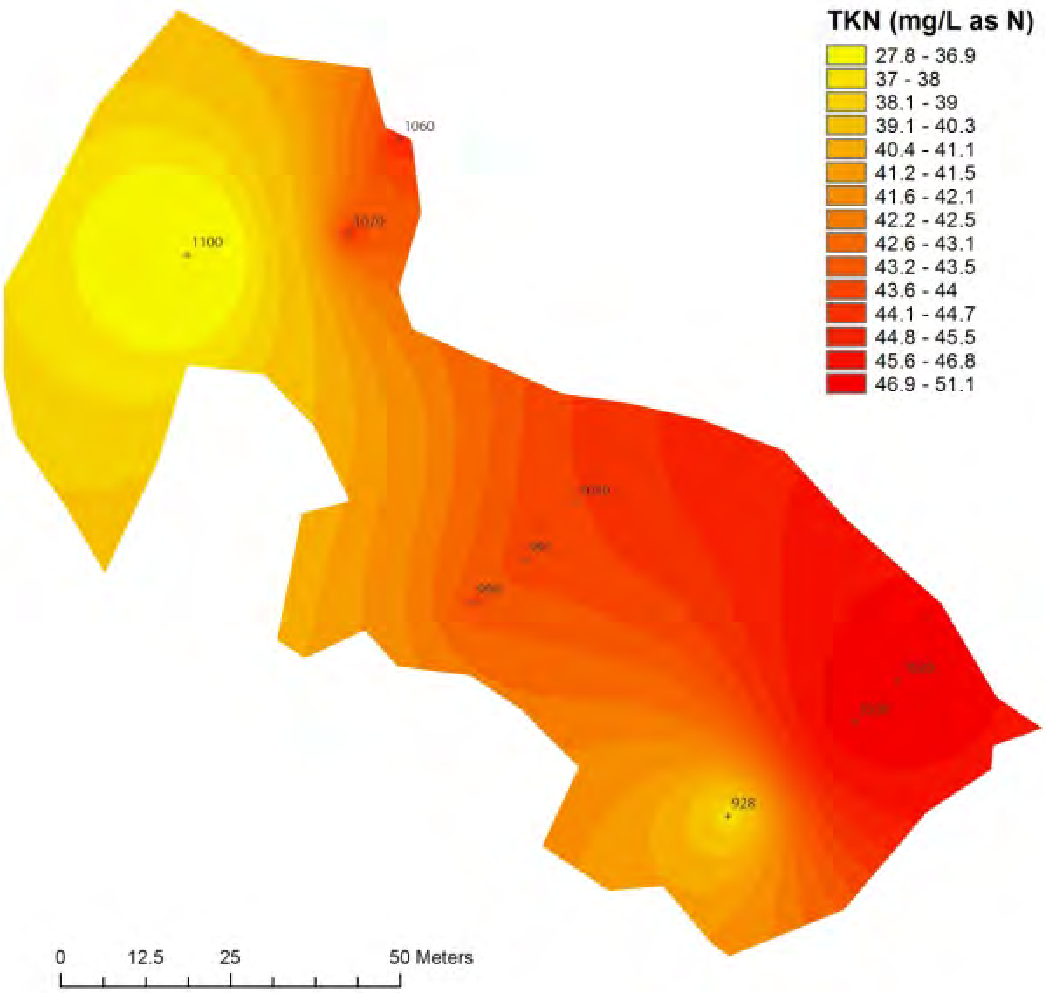


Figure C-25: Total Kjeldahl nitrogen of the effluent in the Fort Providence wetland. Note: flow of wastewater is from bottom to top.

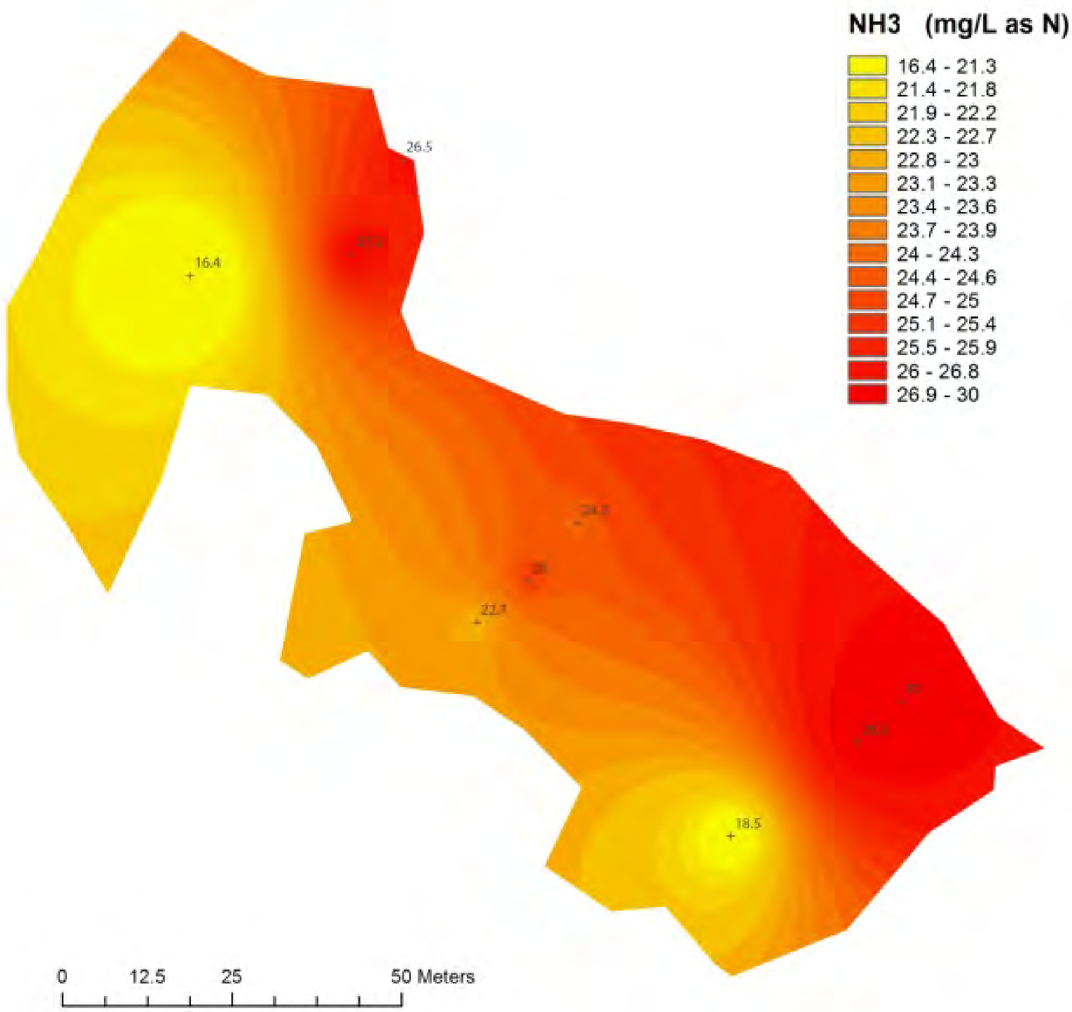


Figure C-26: Ammonia (NH_3 as N) of effluent in the Fort Providence wetland. Note: flow of wastewater is from bottom to top.

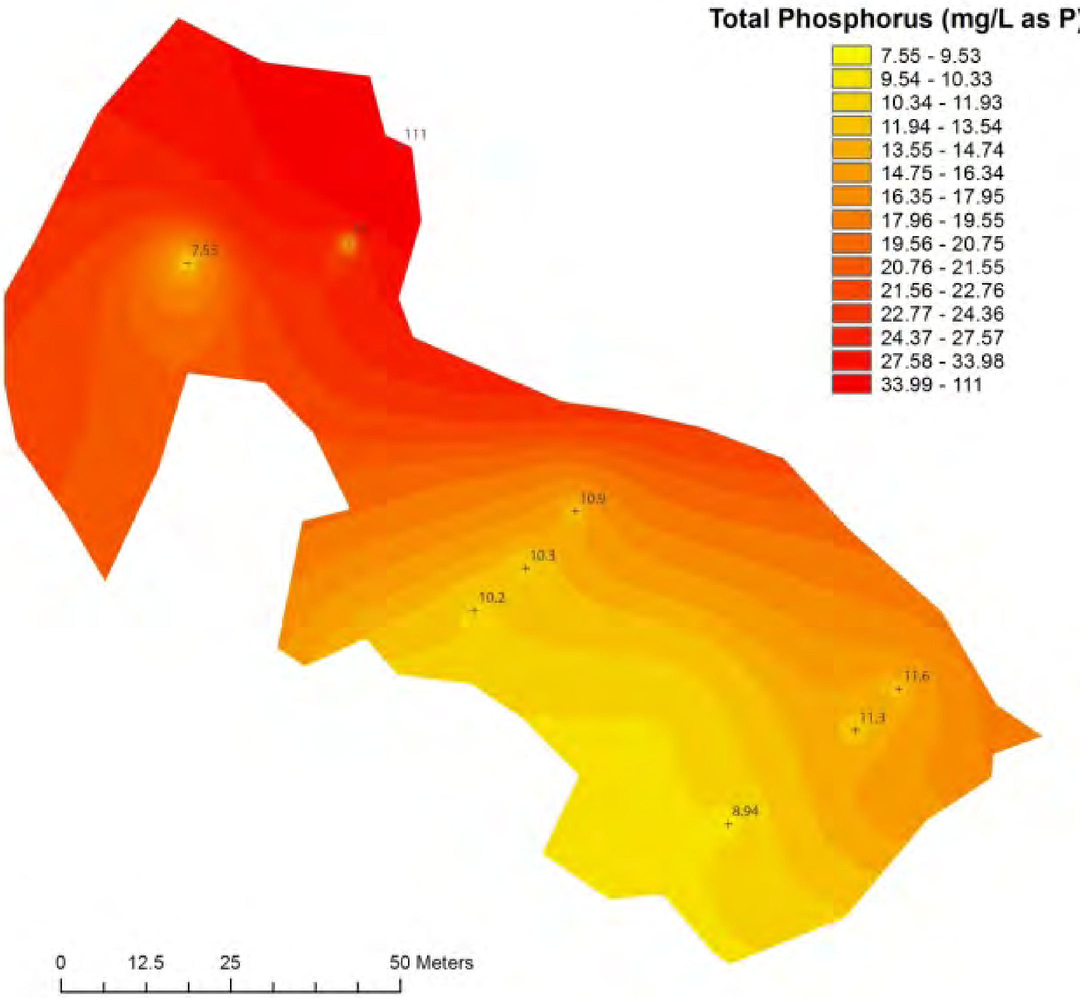


Figure C-27: Total phosphorus of the effluent in the Fort Providence wetland. Note: flow of wastewater is from bottom to top.

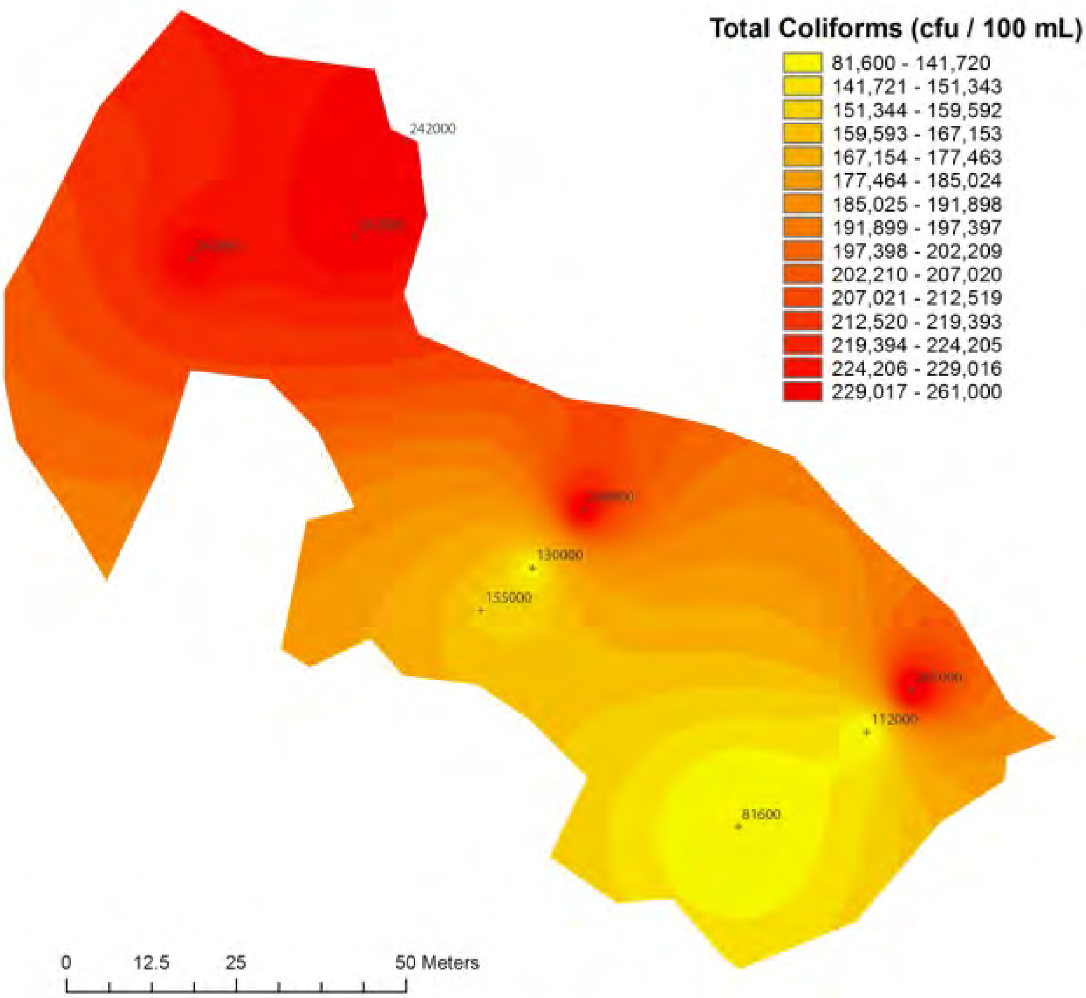


Figure C-28: Total coliform counts of effluent in the Fort Providence wetland. Note: flow of wastewater is from bottom to top.

Gjoa Haven, NU (Full survey - Sample date: August 4-7, 2010)

Interpolated data maps of water quality parameters

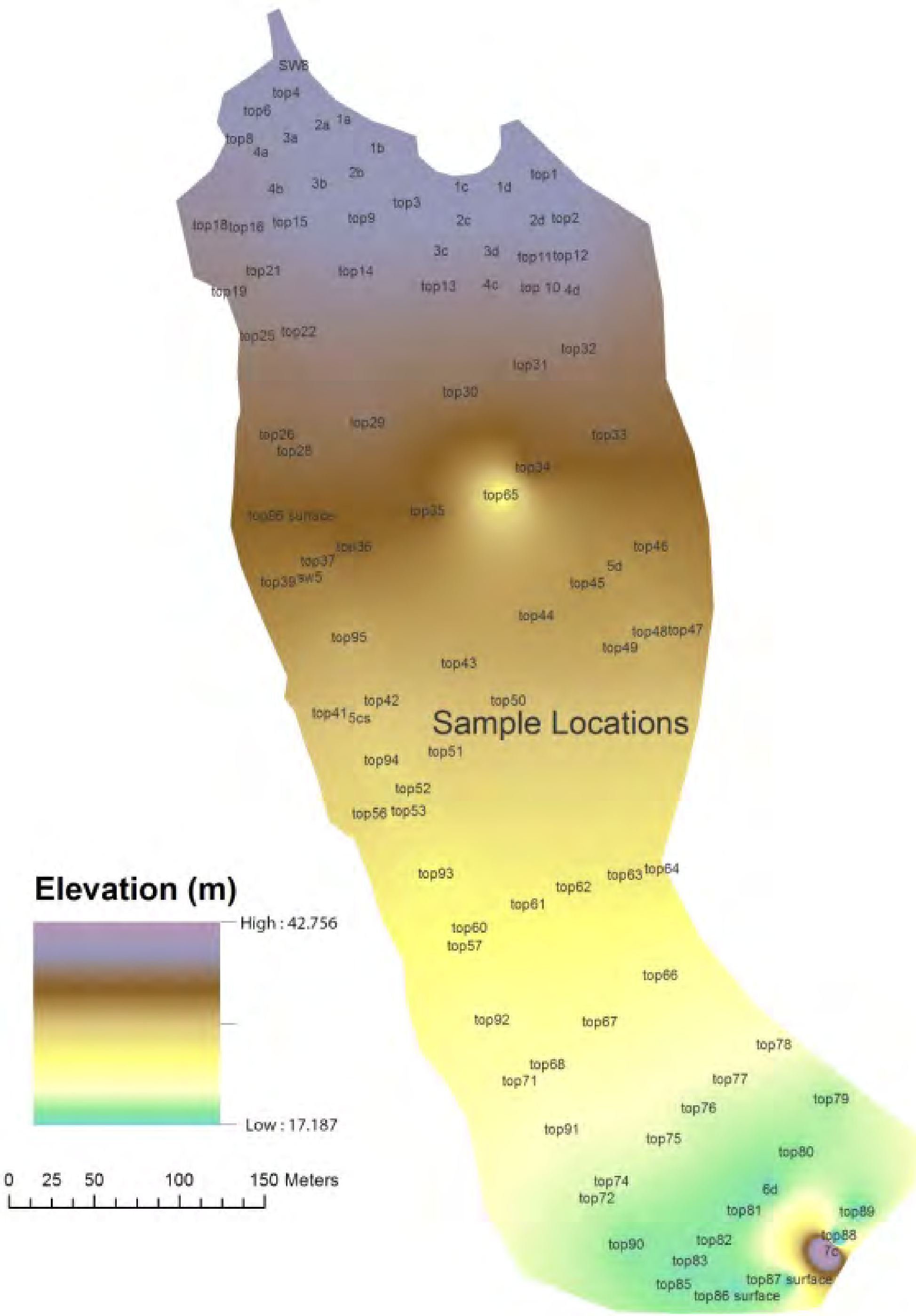


Figure C-29: An elevation map for the Gjoa Haven wetland. Note: flow of wastewater is from top to bottom.

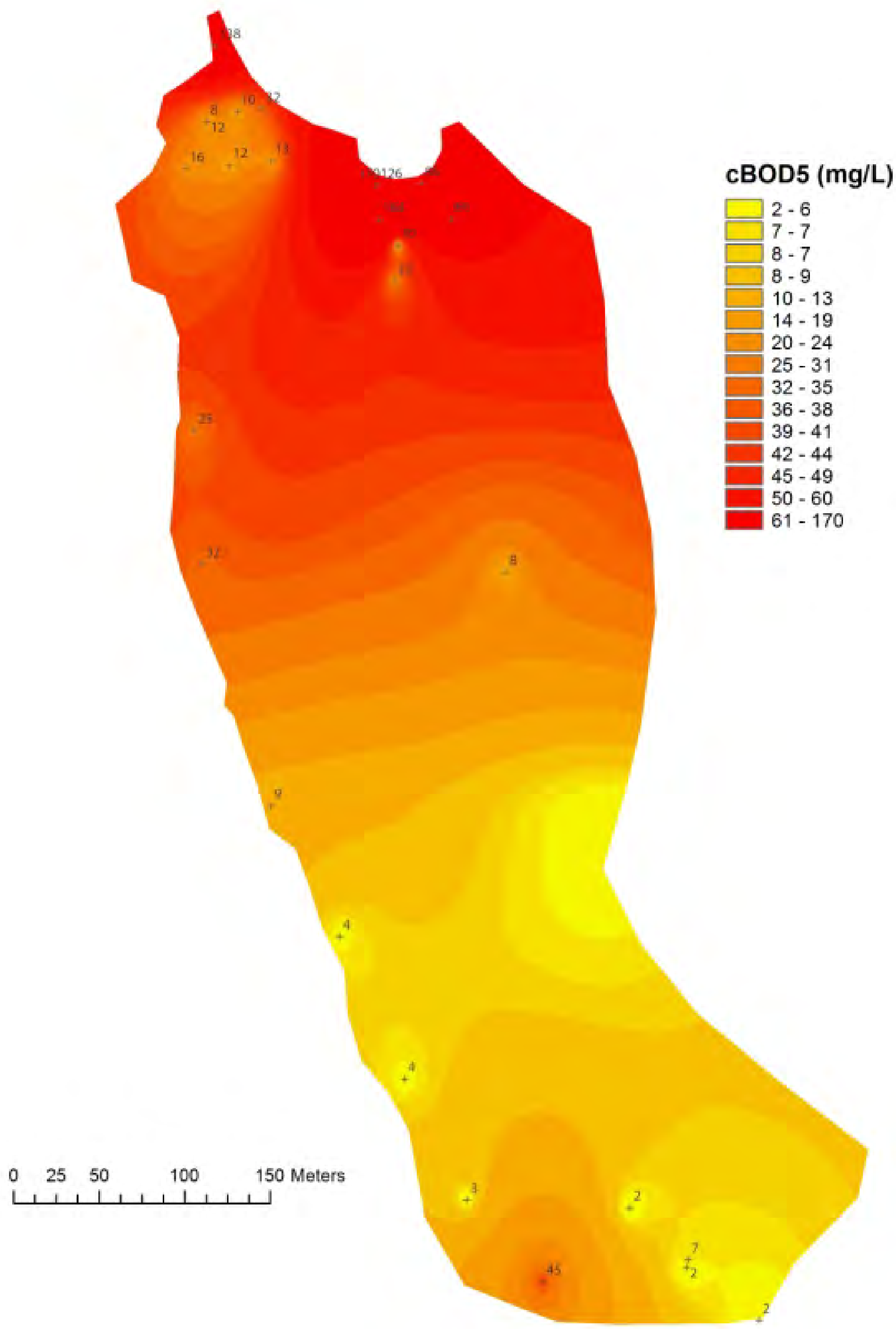


Figure C-30: Carbonaceous biochemical oxygen demand of effluent in the Gjoa Haven wetland. Note: flow of wastewater is from top to bottom.

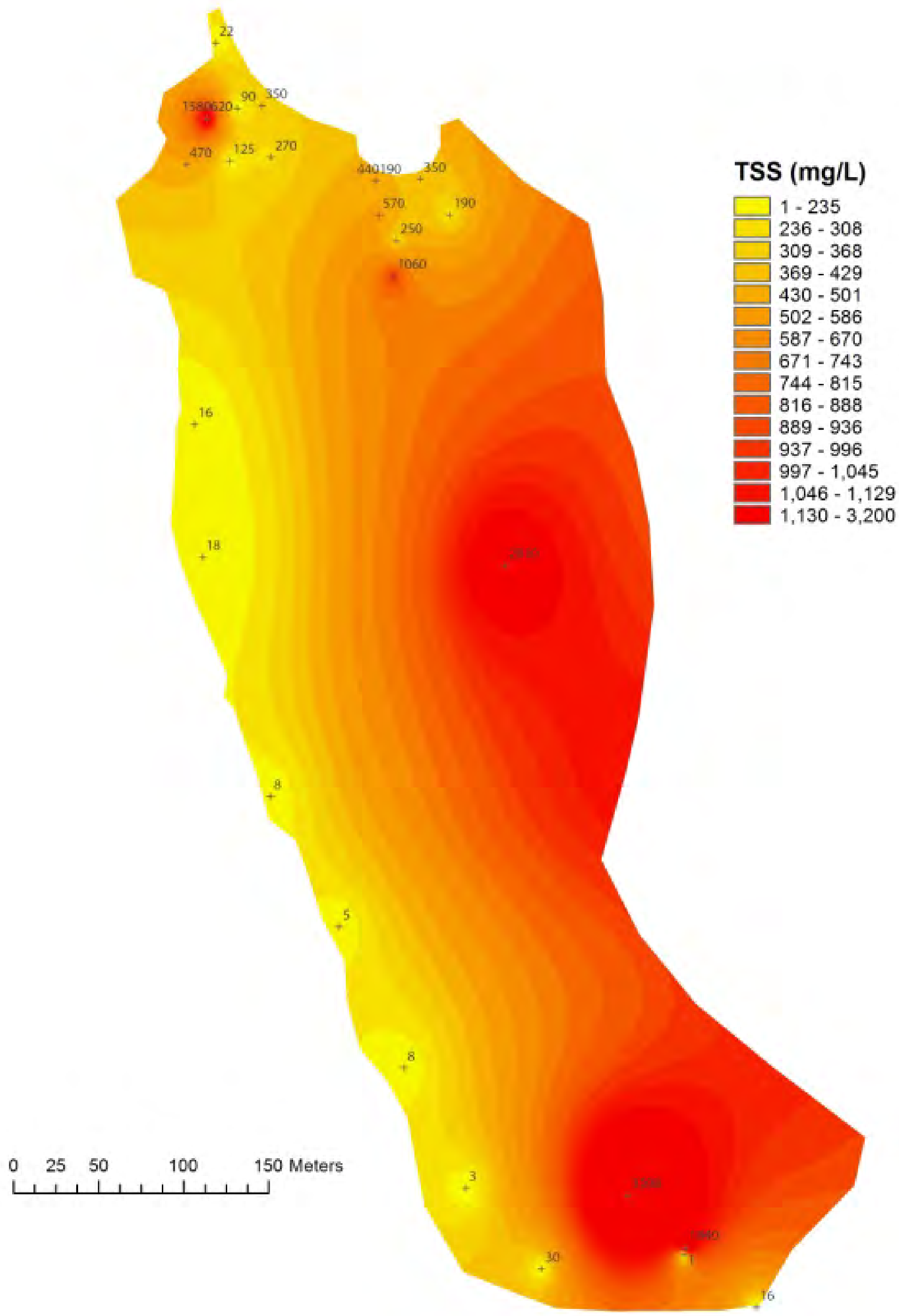


Figure C-31: Total suspended solids of the effluent in the Goja Haven wetland. Note: flow of wastewater is from top to bottom.

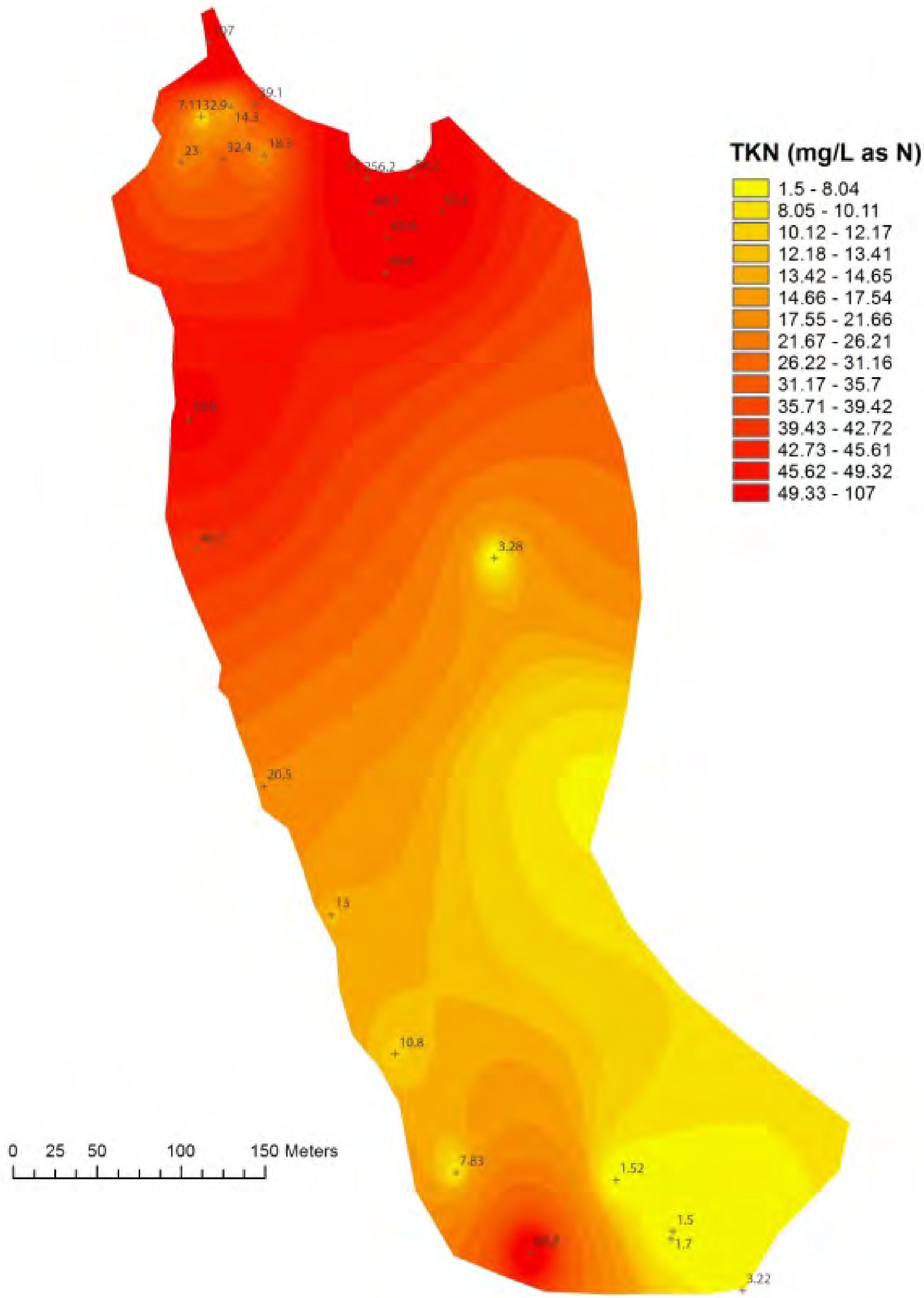


Figure C-32: Total Kjeldahl nitrogen of the effluent in the Gjoa Haven wetland. Note: flow of wastewater is from top to bottom.

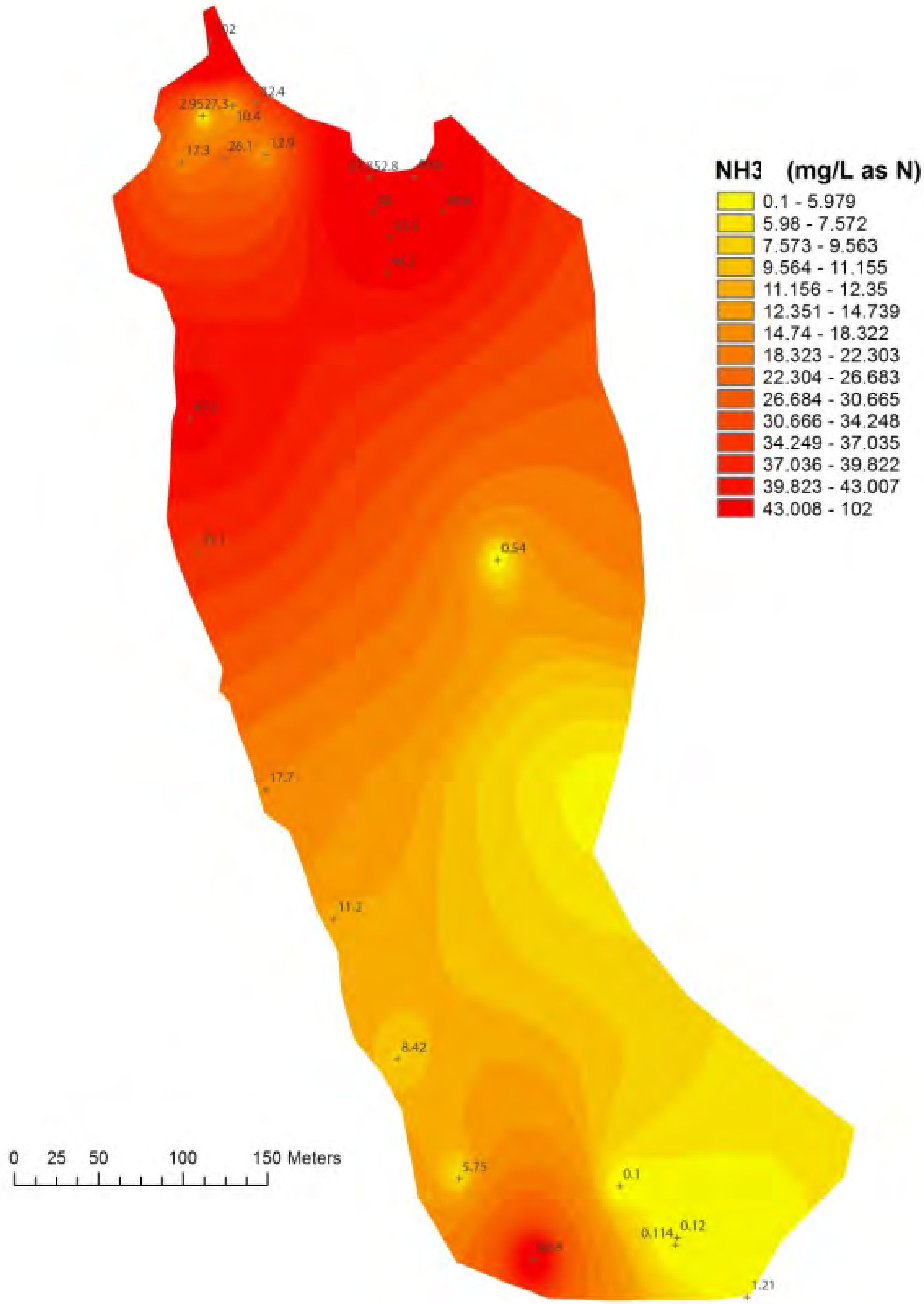


Figure C-33: Ammonia (NH_3 as N) of effluent in the Gjoa Haven wetland. Note: flow of wastewater is from top to bottom.

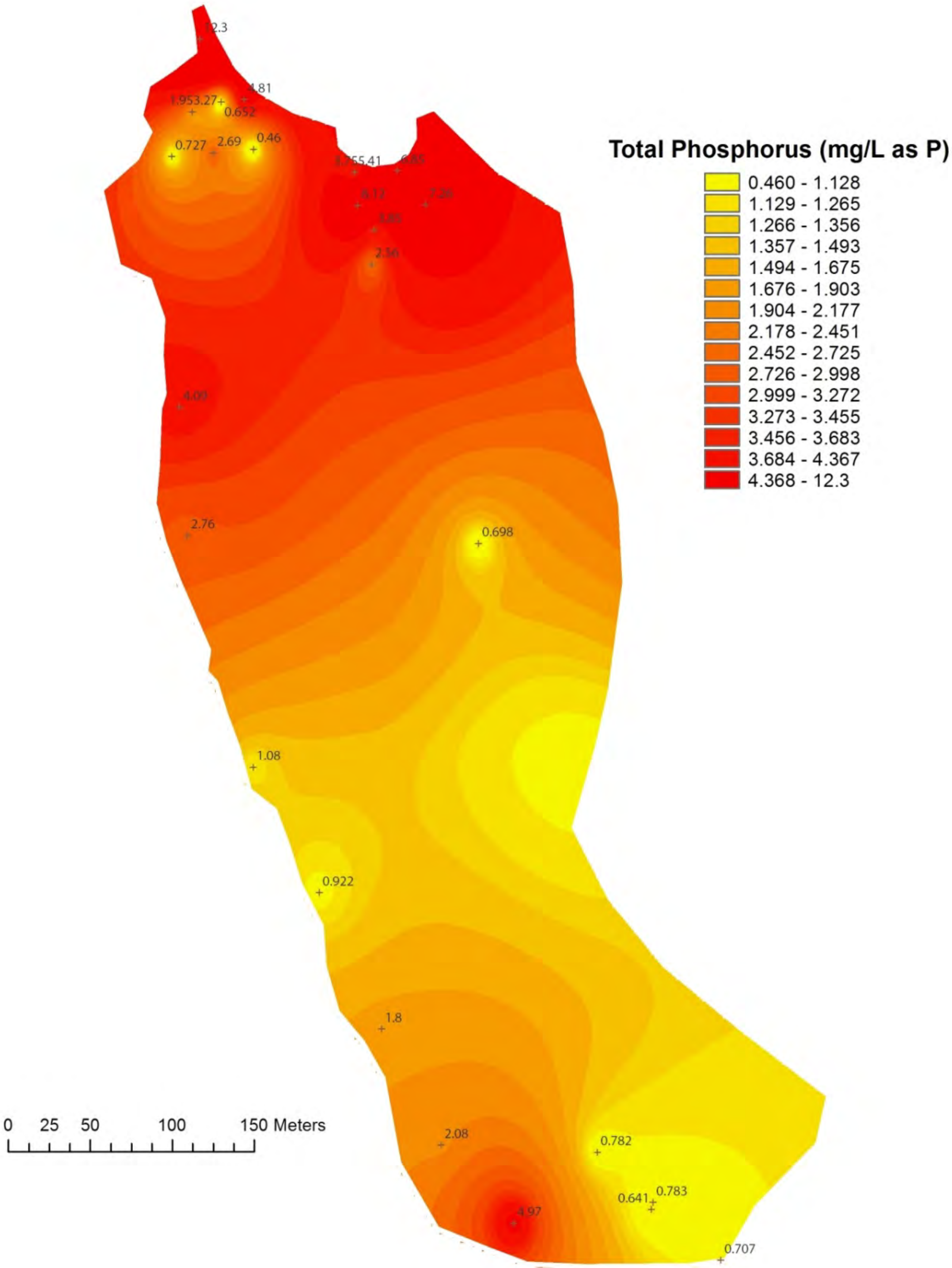


Figure C-34: Total phosphorus of the effluent in the Gjoa Haven wetland. Note: flow of wastewater is from top to bottom.

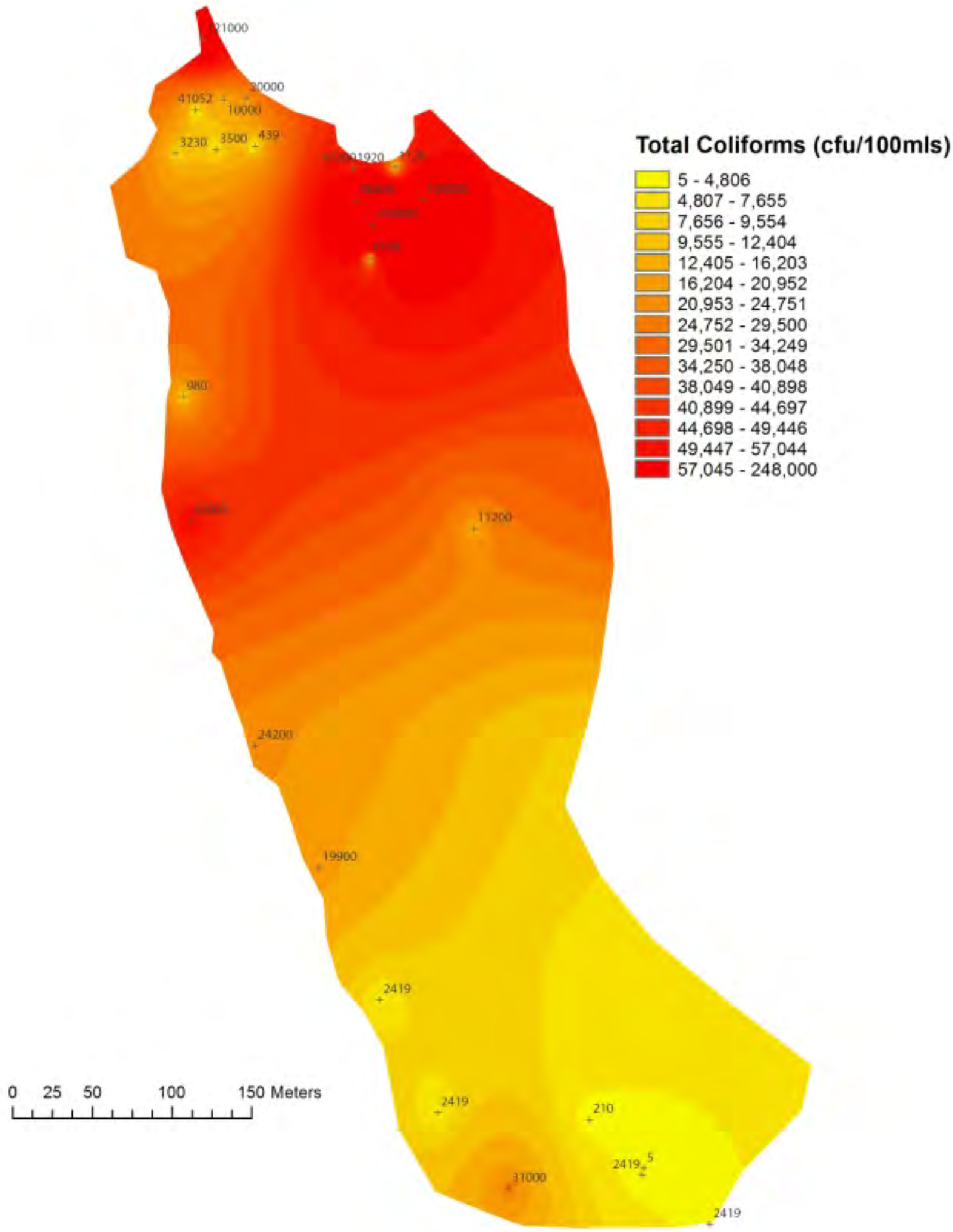


Figure C-35: Total coliform counts of effluent in the Gjoa Haven wetland. Note: flow of wastewater is from top to bottom.

Ulukhaktok, NT (Full survey – Sample date: July 29-August 3, 2010)

Interpolated data maps of water quality parameters

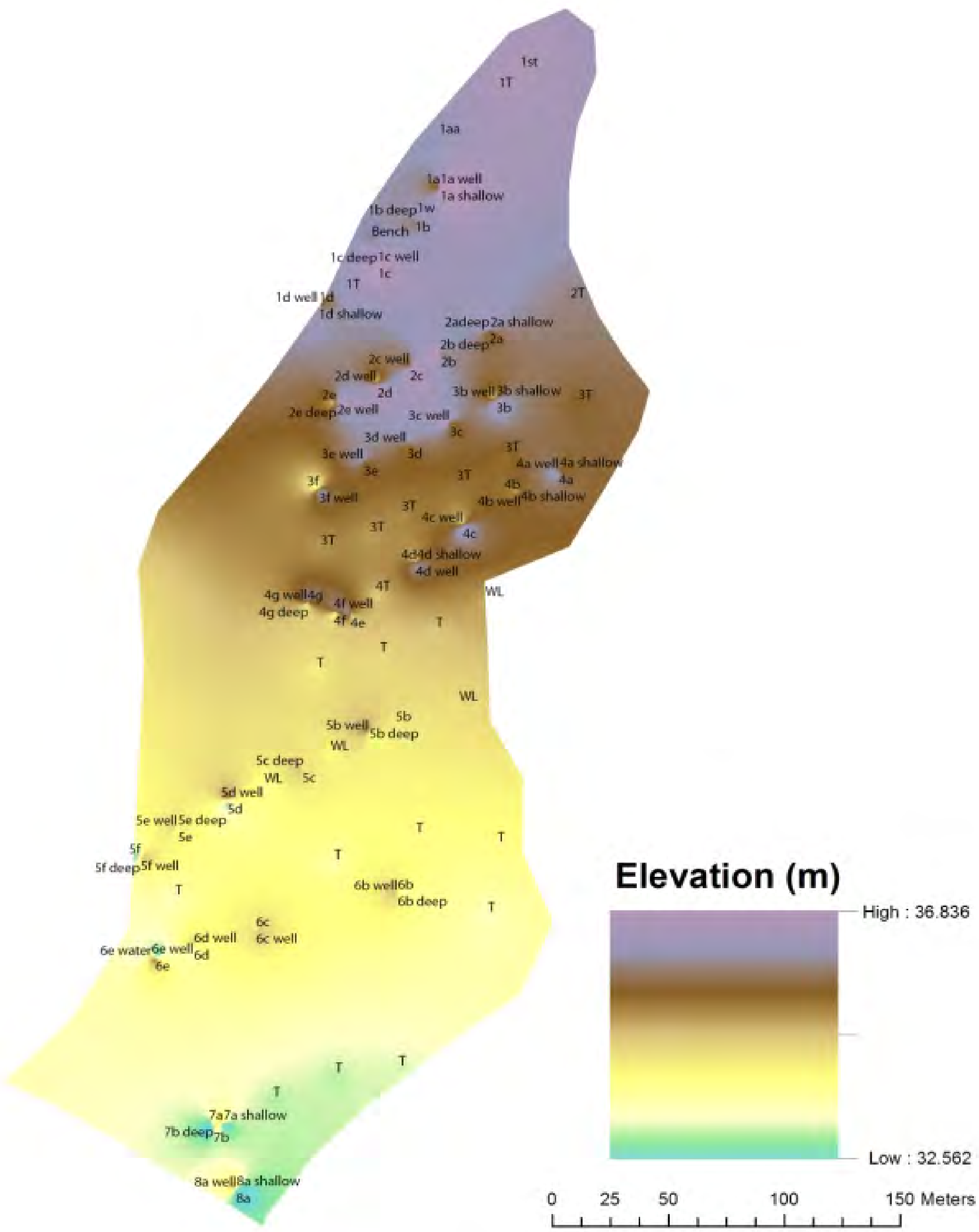


Figure C-36: An elevation map of the Ulukhaktok wetland. Note: the flow of wastewater is from top to bottom.

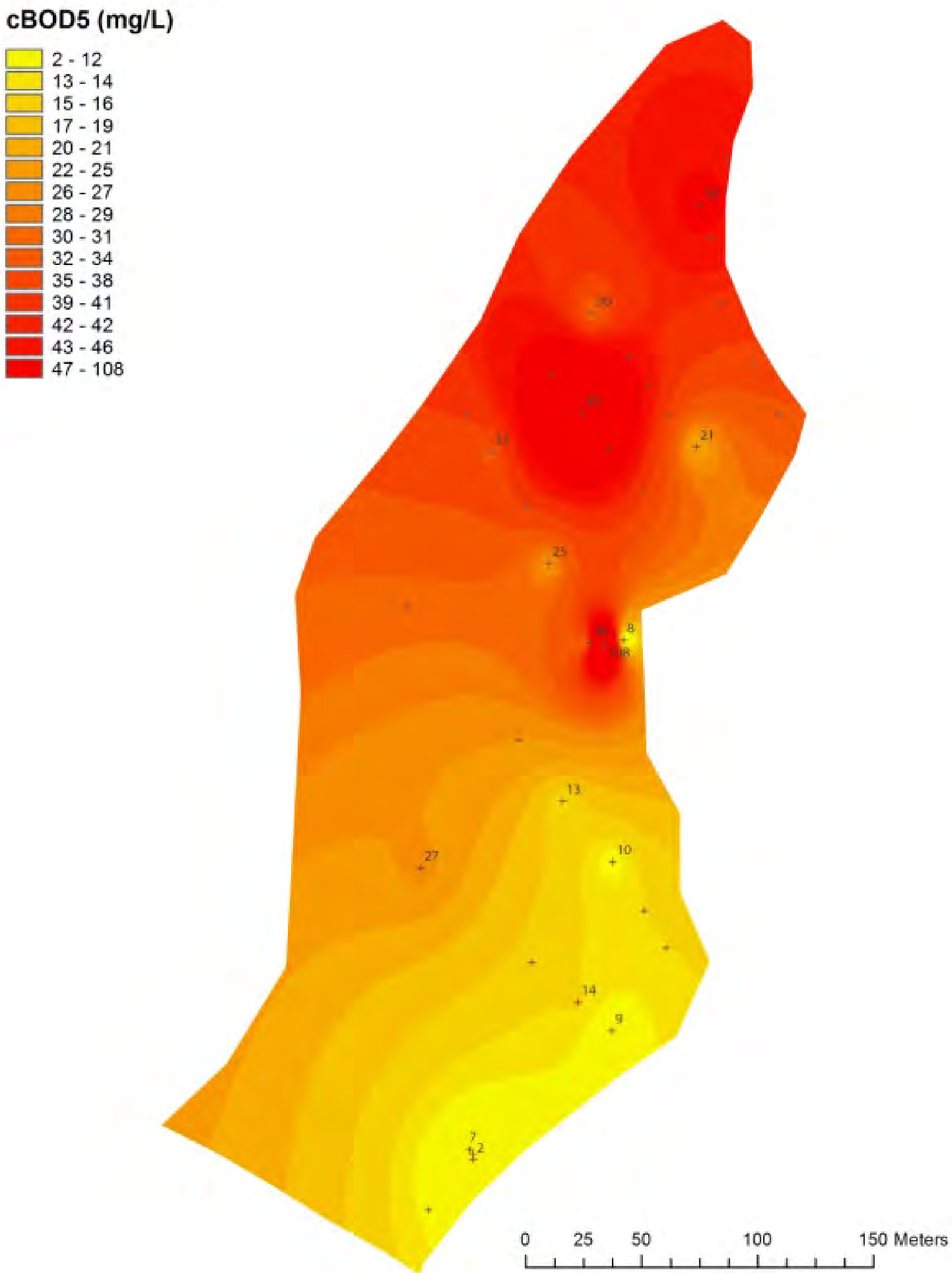


Figure C-37: Carbonaceous biochemical oxygen demand of effluent in the Ulukhaktok wetland. Note: the flow of wastewater is from top to bottom.

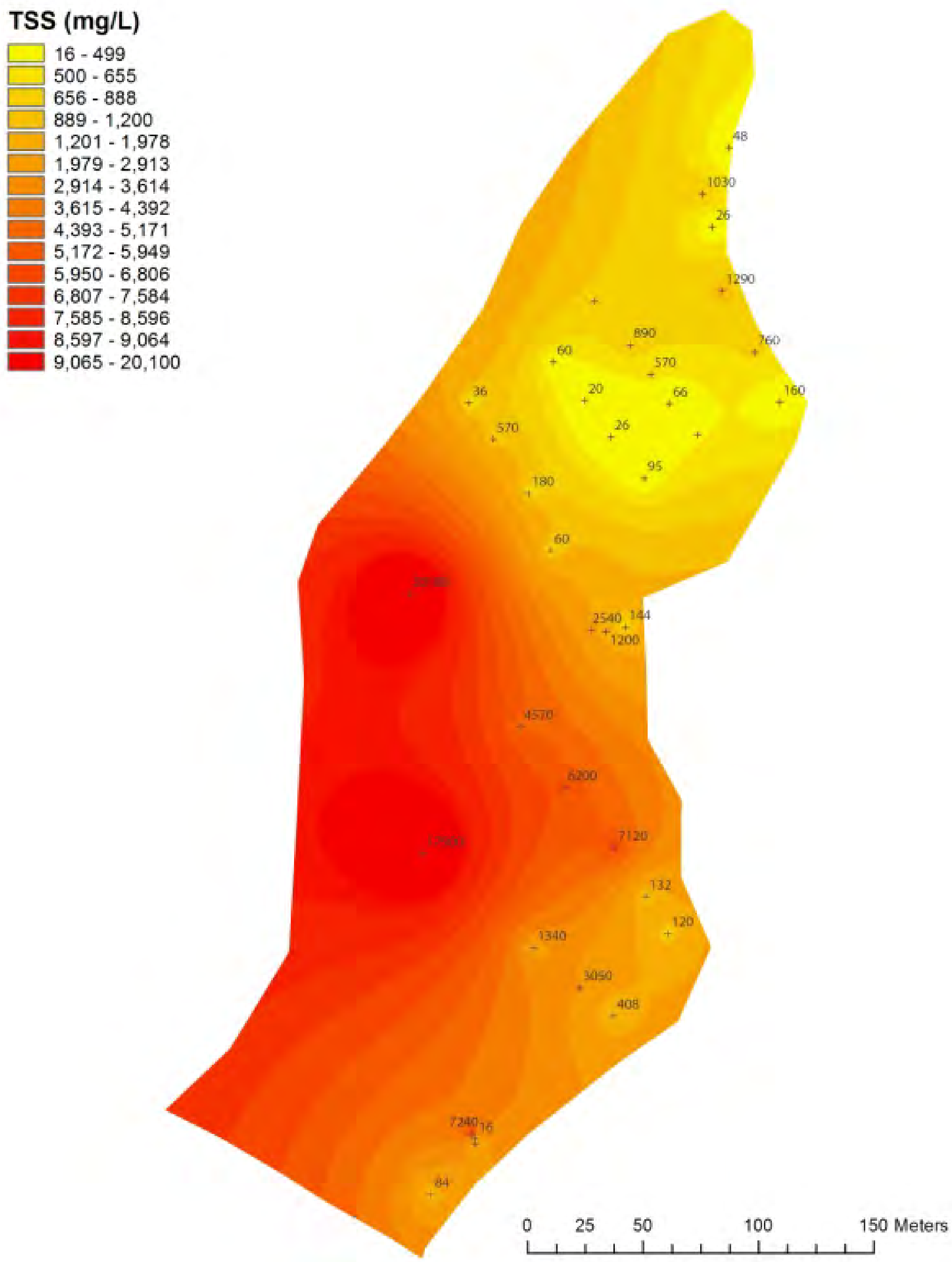


Figure C-39: Total suspended solids in the Ulukhaktok wetland. Note: the flow of wastewater is from top to bottom.

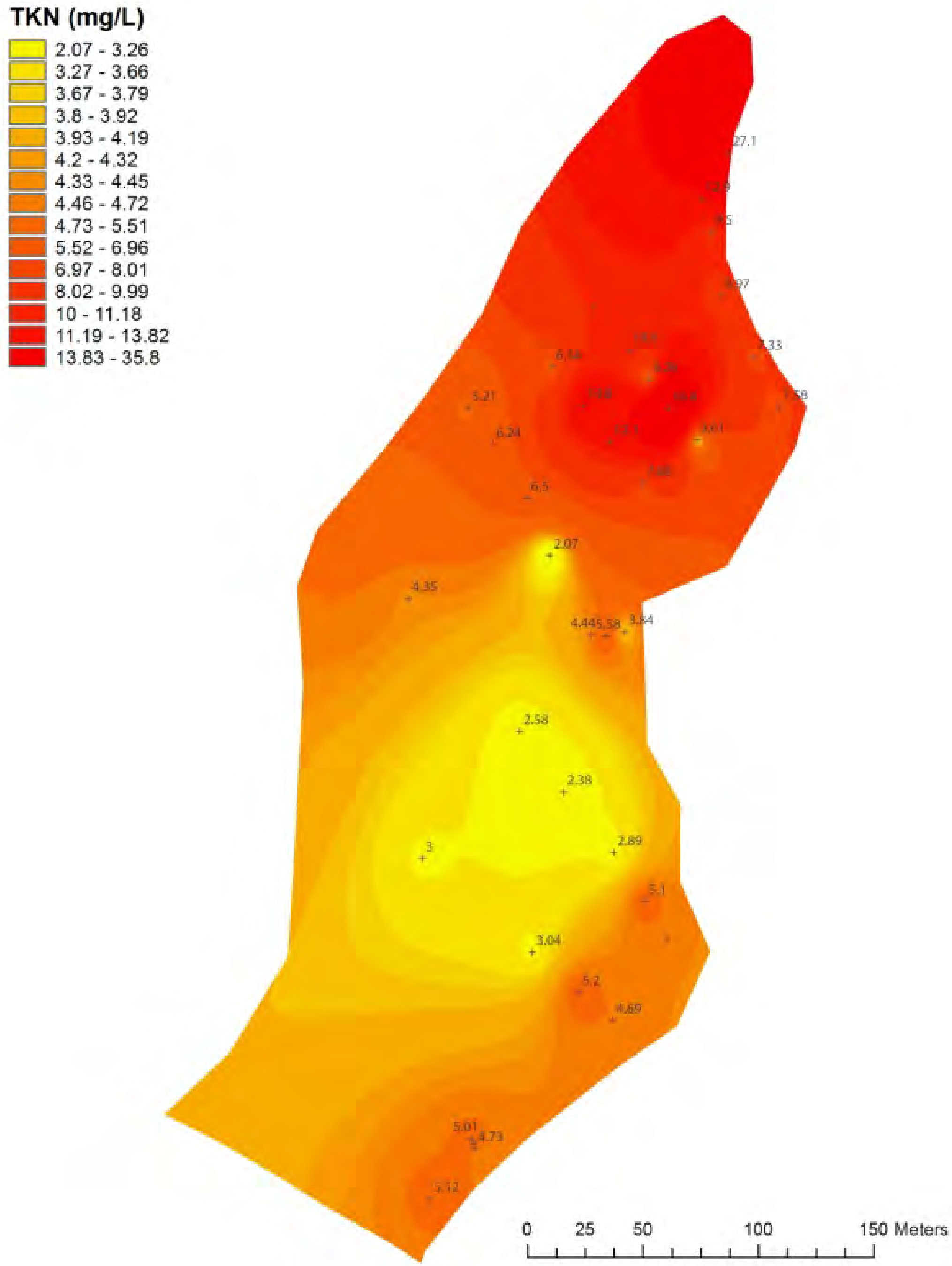


Figure C-39: Total Kjeldahl nitrogen of the effluent in the Ulukhaktok wetland. Note: the flow of wastewater is from top to bottom.

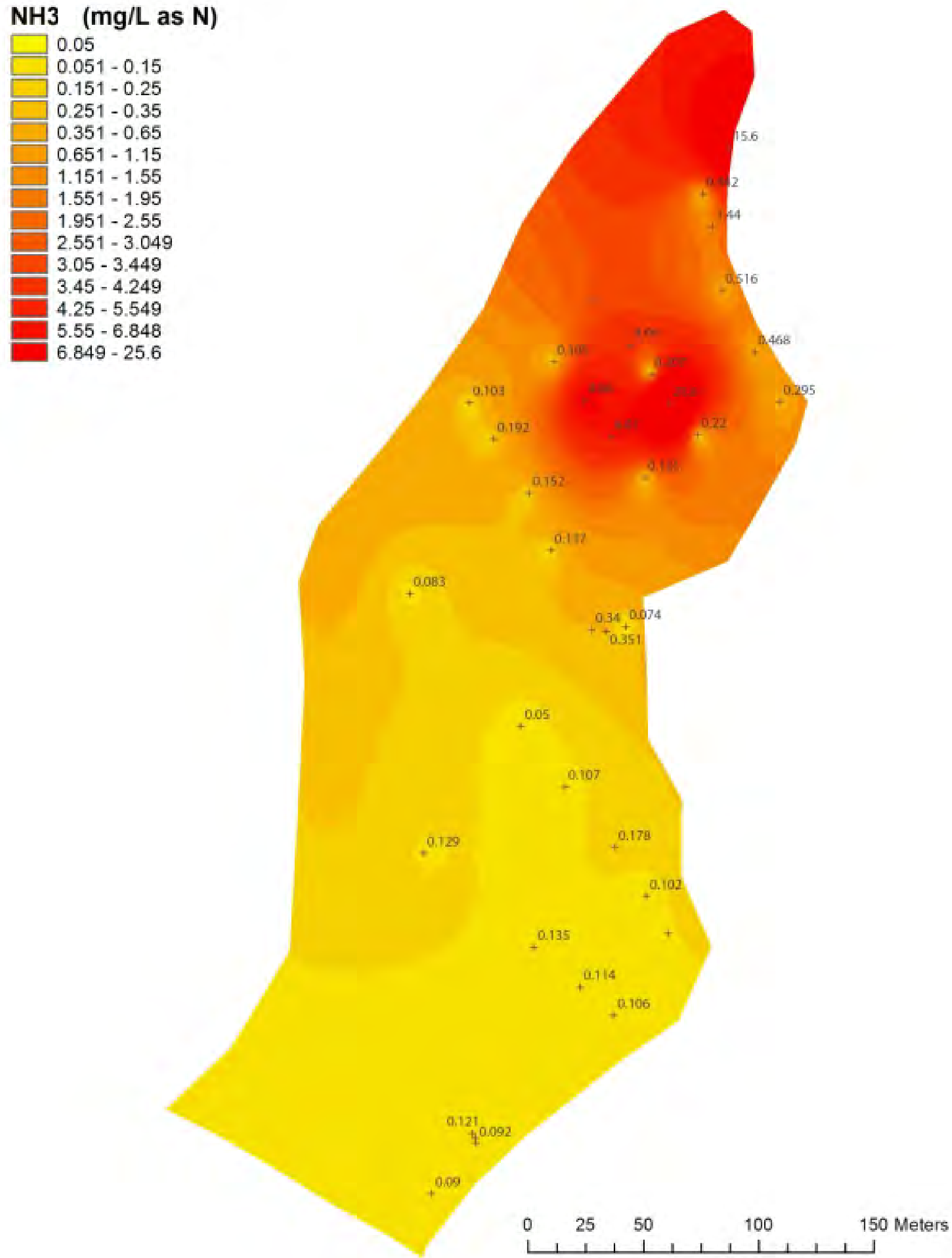


Figure C-40: Ammonia (NH_3 as N) of effluent in the Ulukhaktok wetland. Note: the flow of wastewater is from top to bottom.

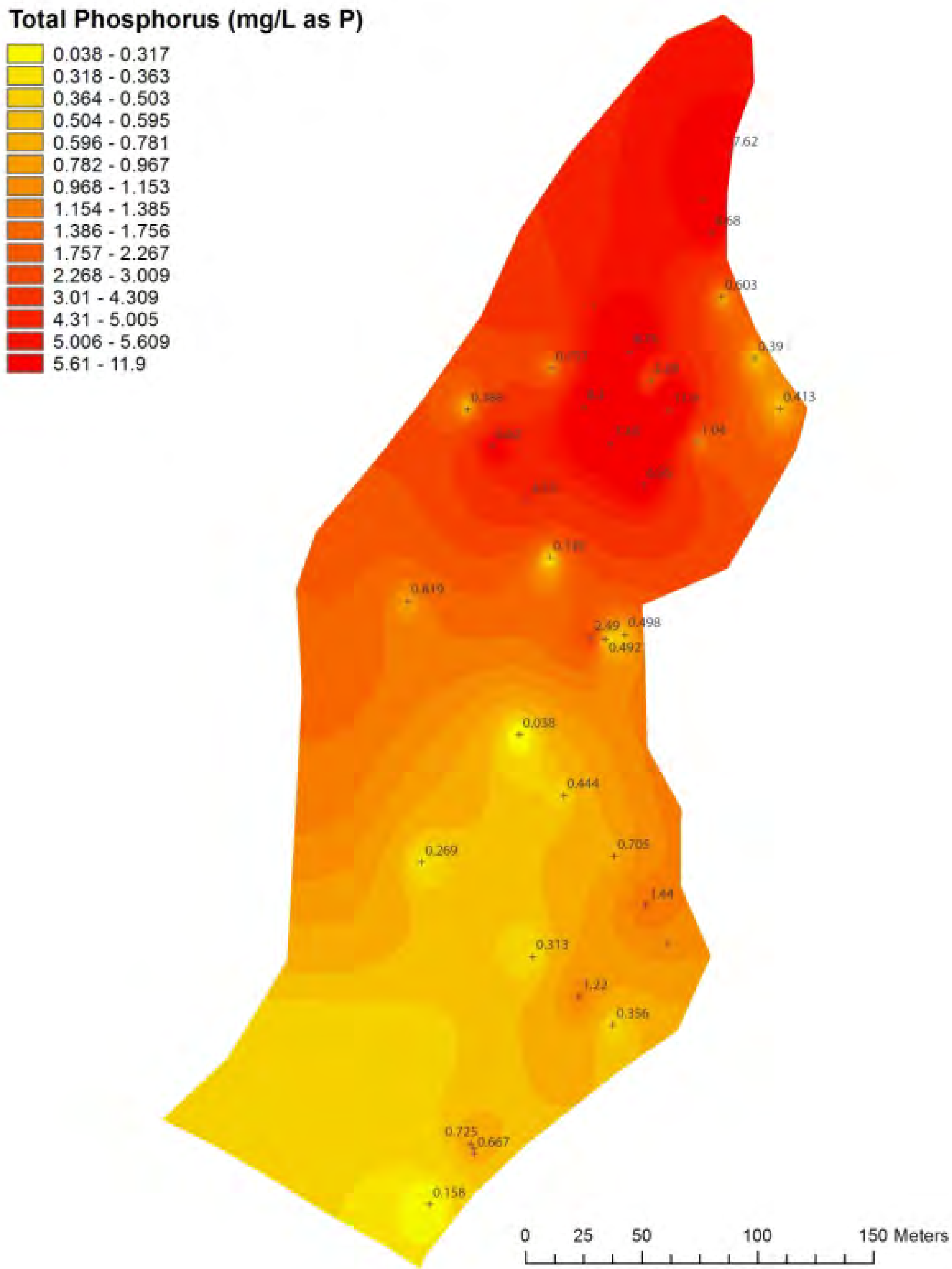


Figure C-41: Total phosphorus of the effluent in the Ulukhaktok wetland. Note: the flow of wastewater is from top to bottom.

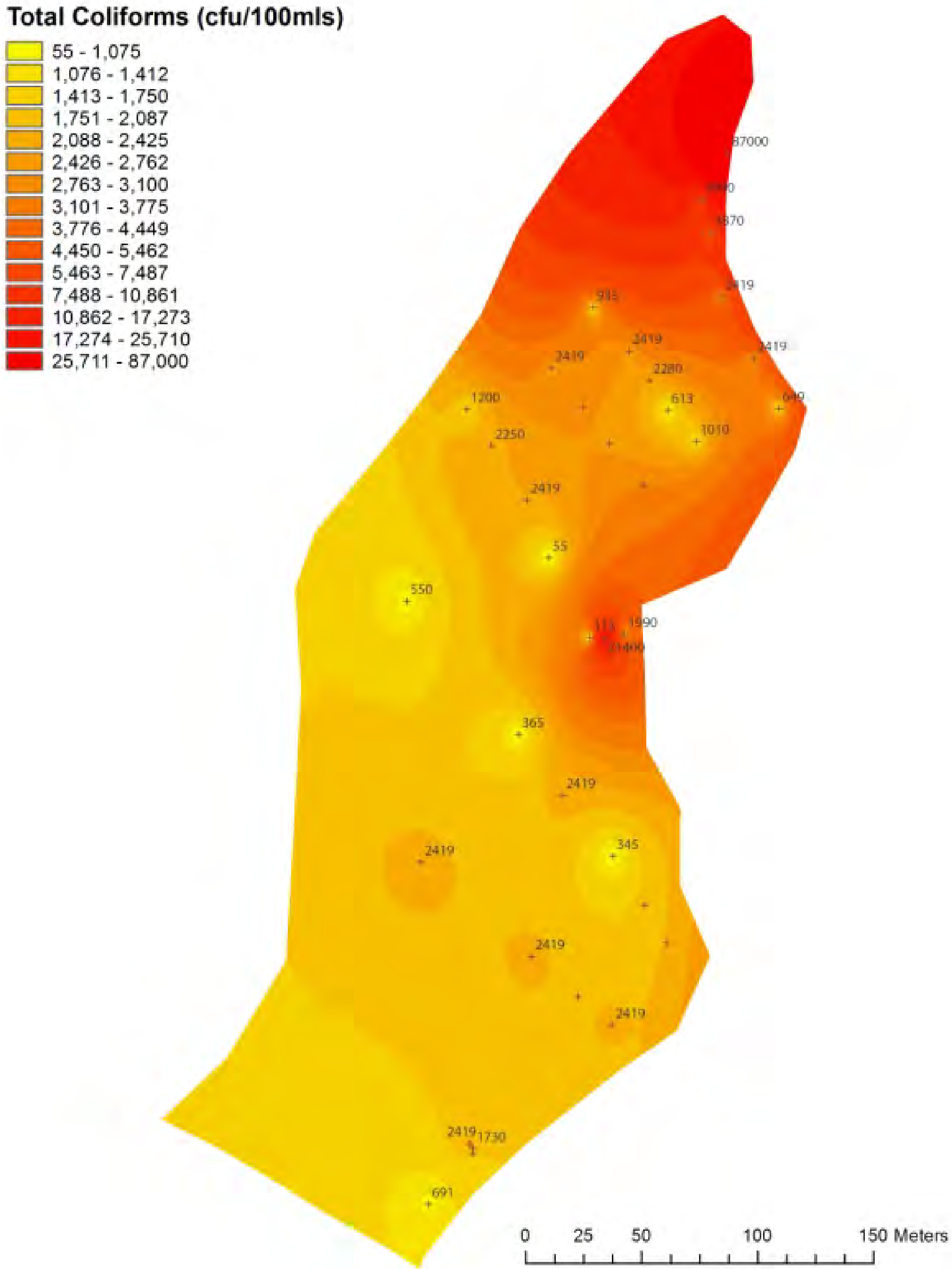


Figure C-42: Total coliform counts of effluent in the Ulukhaktok wetland. Note: the flow of wastewater is from top to bottom.

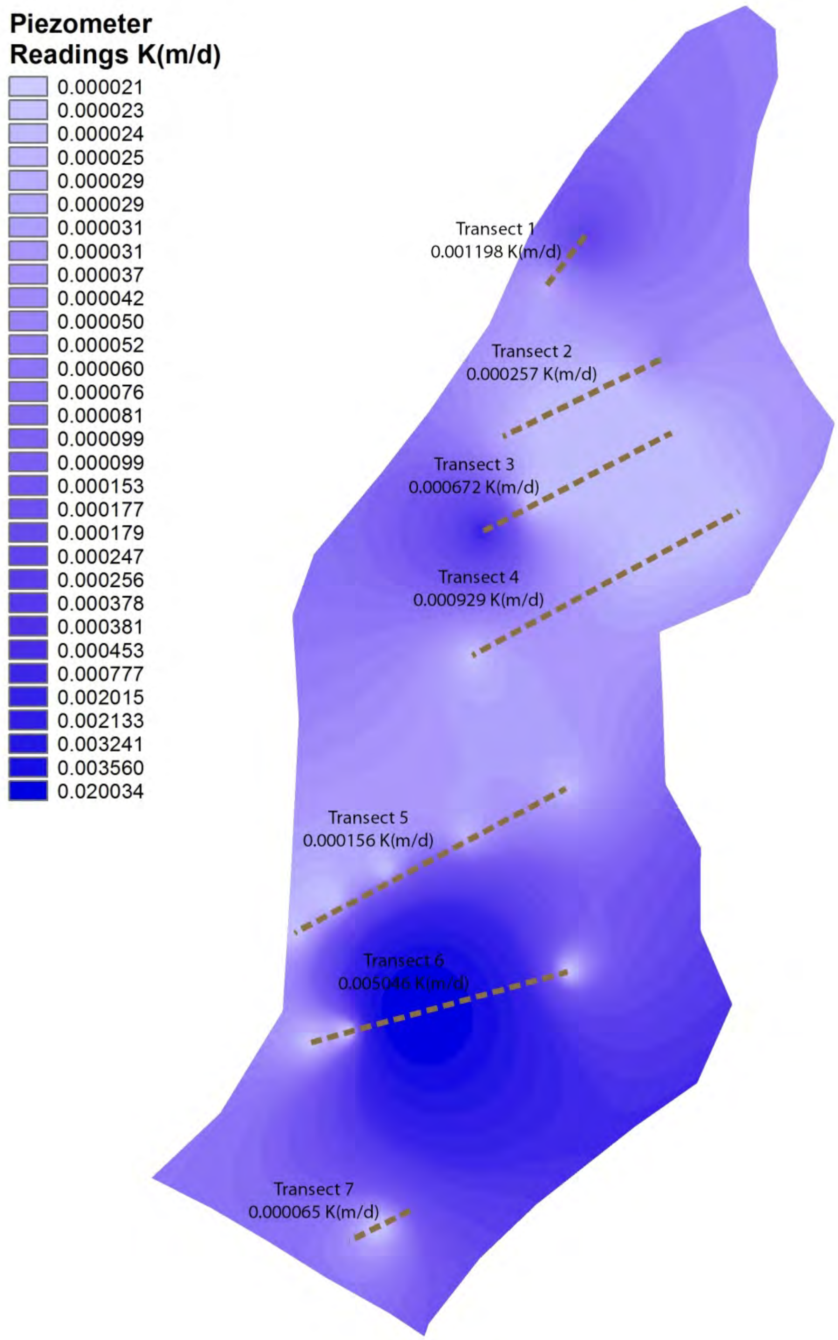


Figure C-43: Hydraulic conductivity of the Ulukhaktok wetland sediments expressed as K (m/d), which indicates the rate of water travel through the subsurface sediment. Note: the flow of wastewater is from top to bottom.

Taloyoak, NU (Full survey – Sample date: August 27 – Sept 1, 2011)

Interpolated data maps of water quality parameters

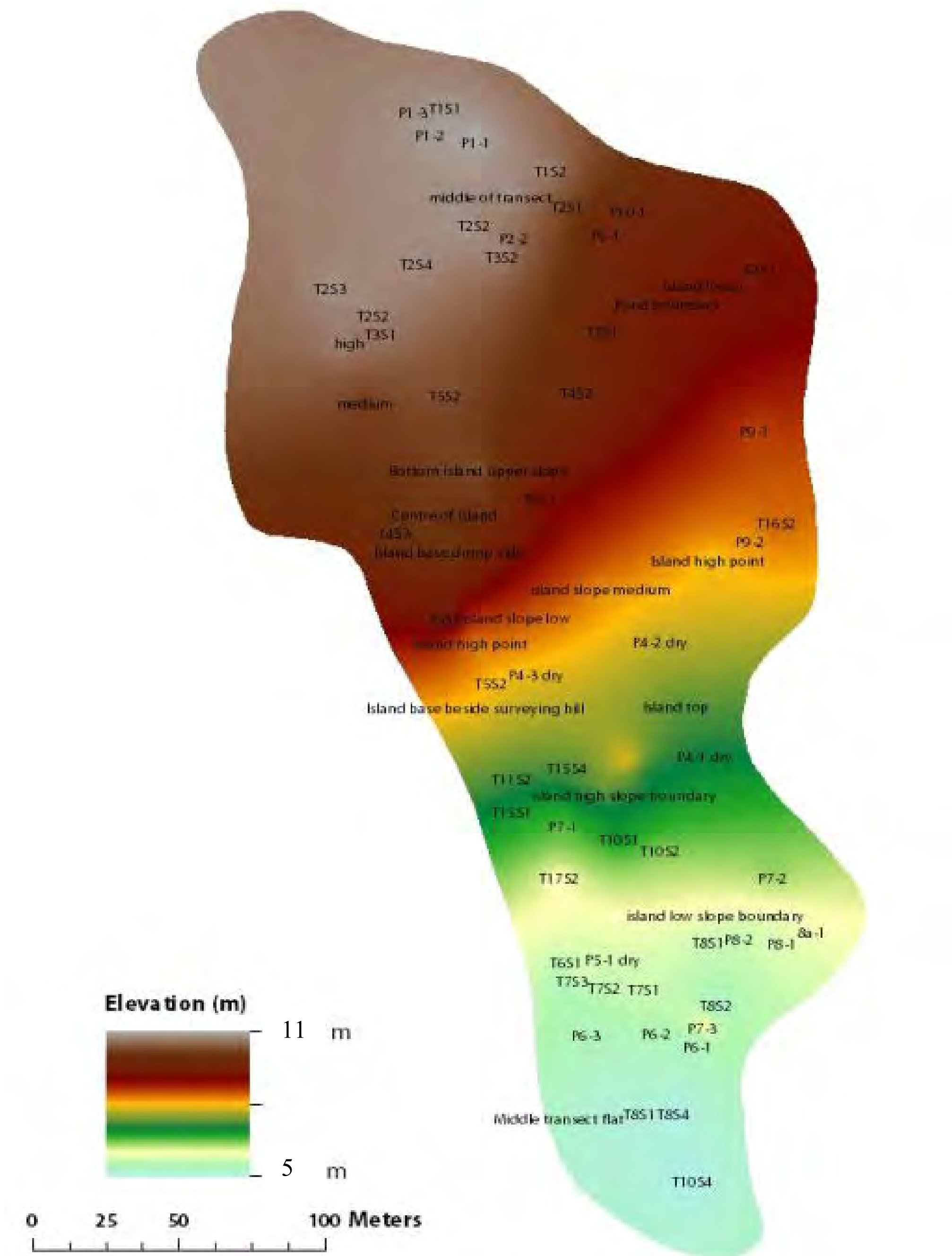


Figure C-44: An elevation map for the Taloyoak wetland. Note: the flow of water is from the top to bottom.

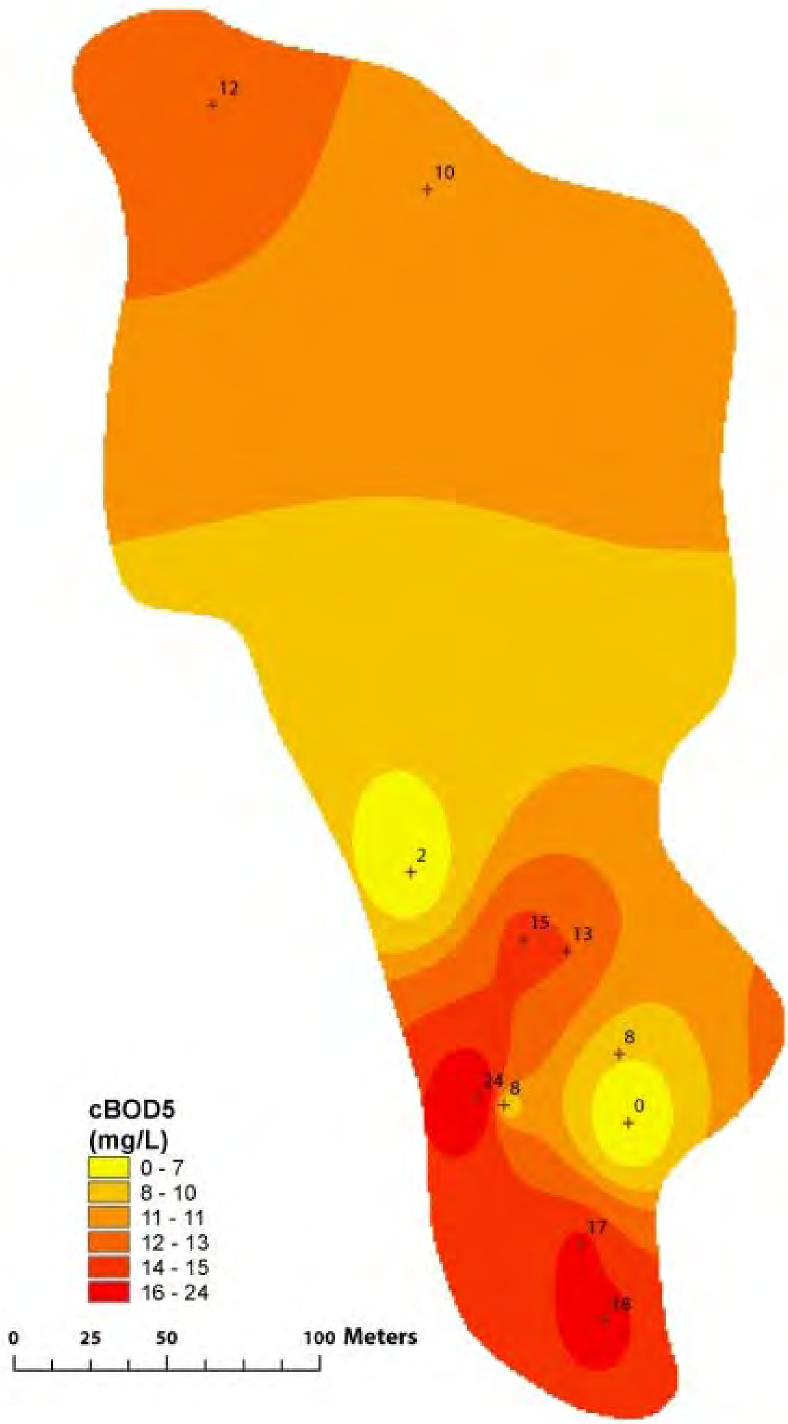


Figure C-45: Carbonaceous biochemical oxygen demand (5 day) of effluent in the Taloyoak wetland. Note: the flow of water is from the top to bottom.

Figure C-46: Total suspended solids of the effluent in the Taloyoak wetland. Note: the flow of water is from the top to bottom.

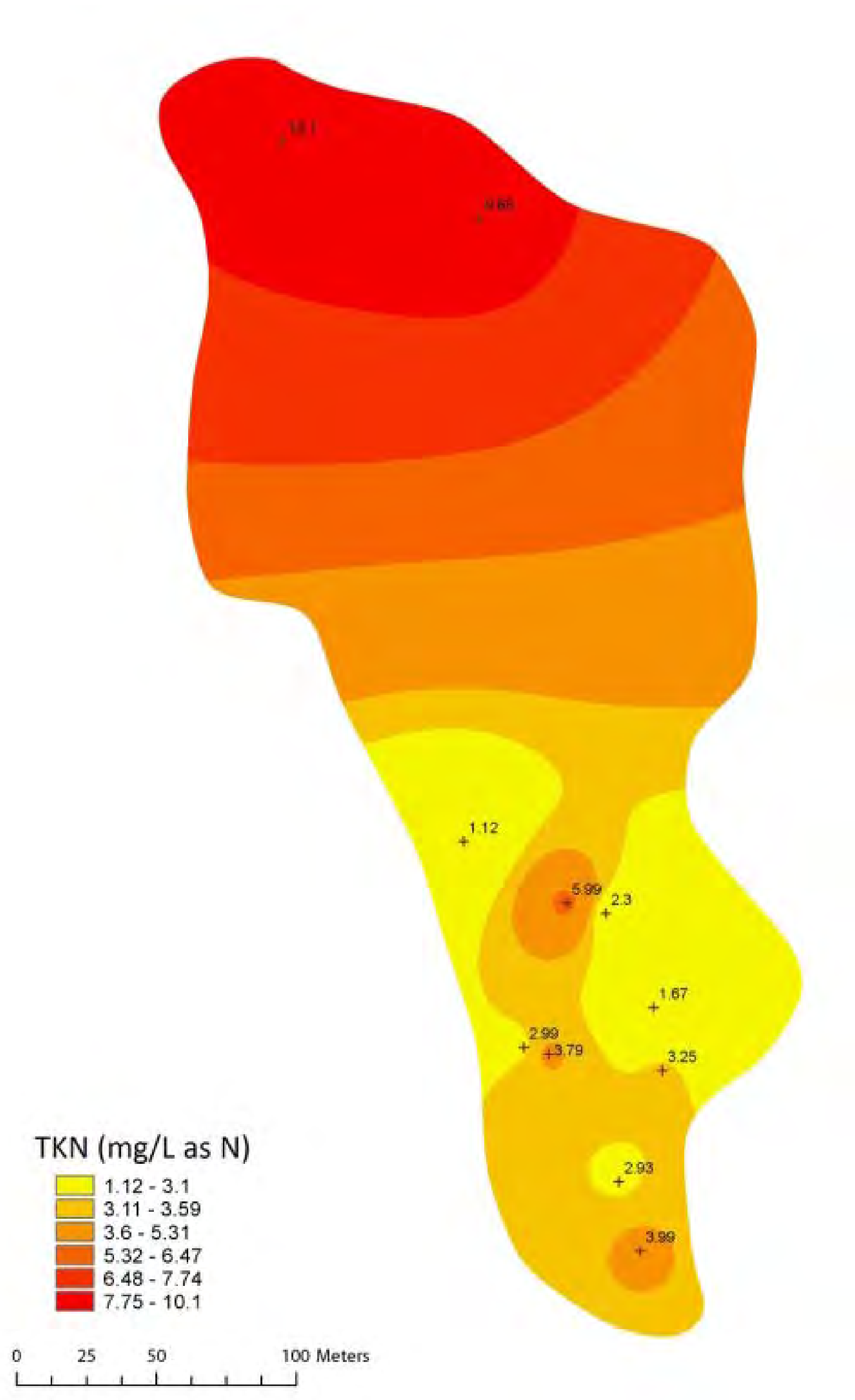


Figure C-47: Total Kjeldahl nitrogen of the effluent in the Taloyoak wetland. Note: the flow of water is from the top to bottom.

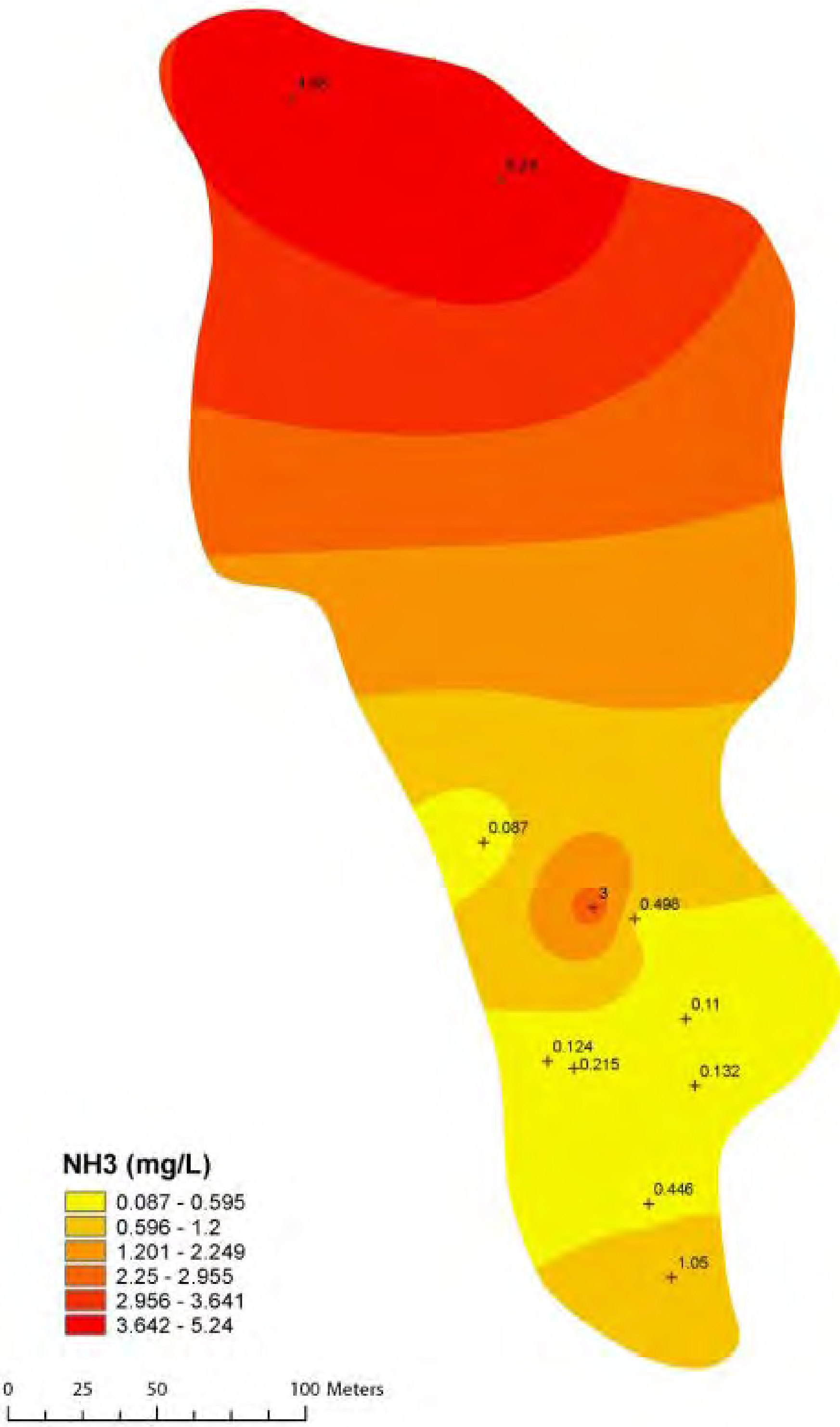


Figure C-48: Ammonia (NH_3 as N) of effluent in the Taloyoak wetland. Note: the flow of water is from the top to bottom.

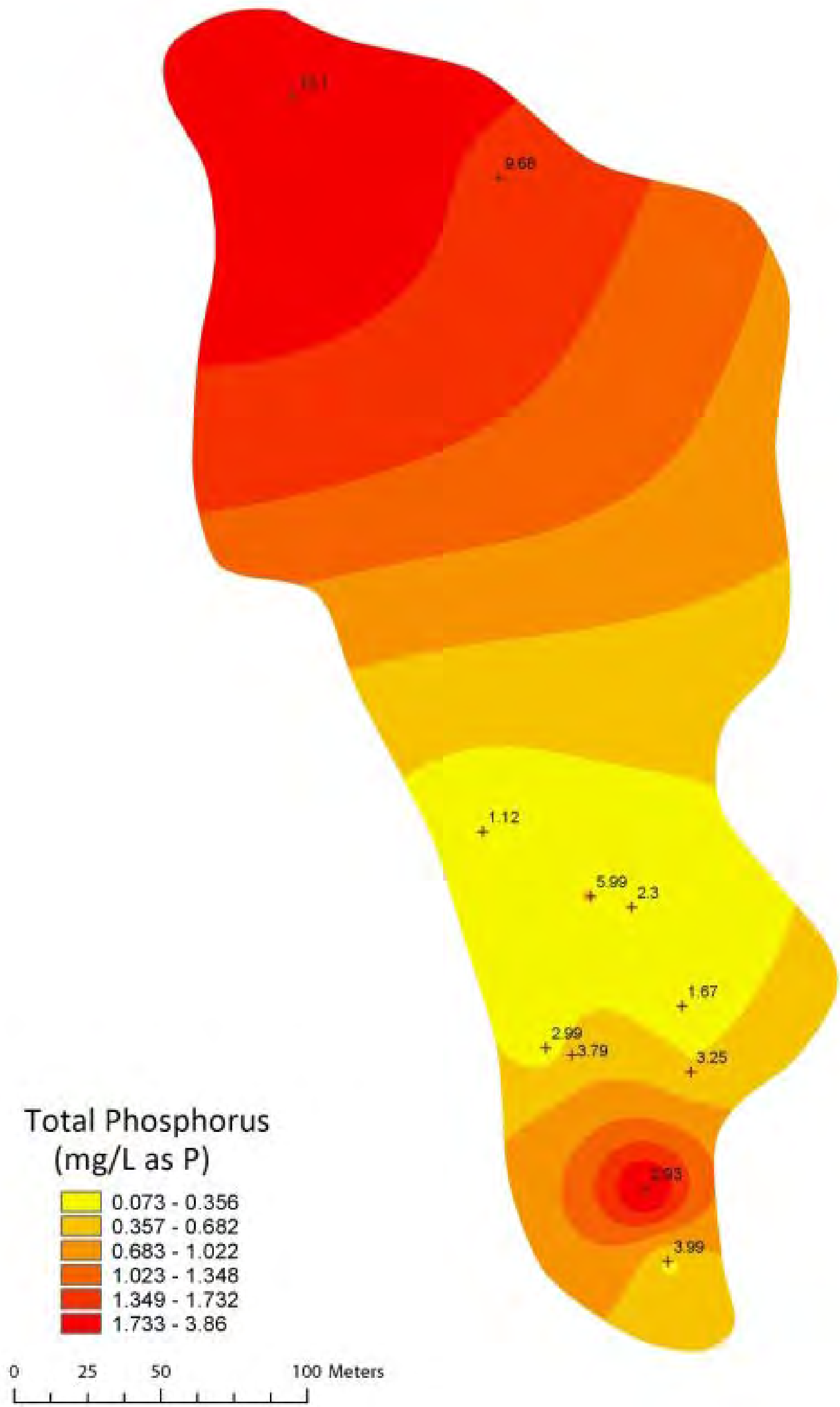


Figure C-49: Total phosphorus of the effluent in the Taloyoak wetland. Note: the flow of water is from the top to bottom.

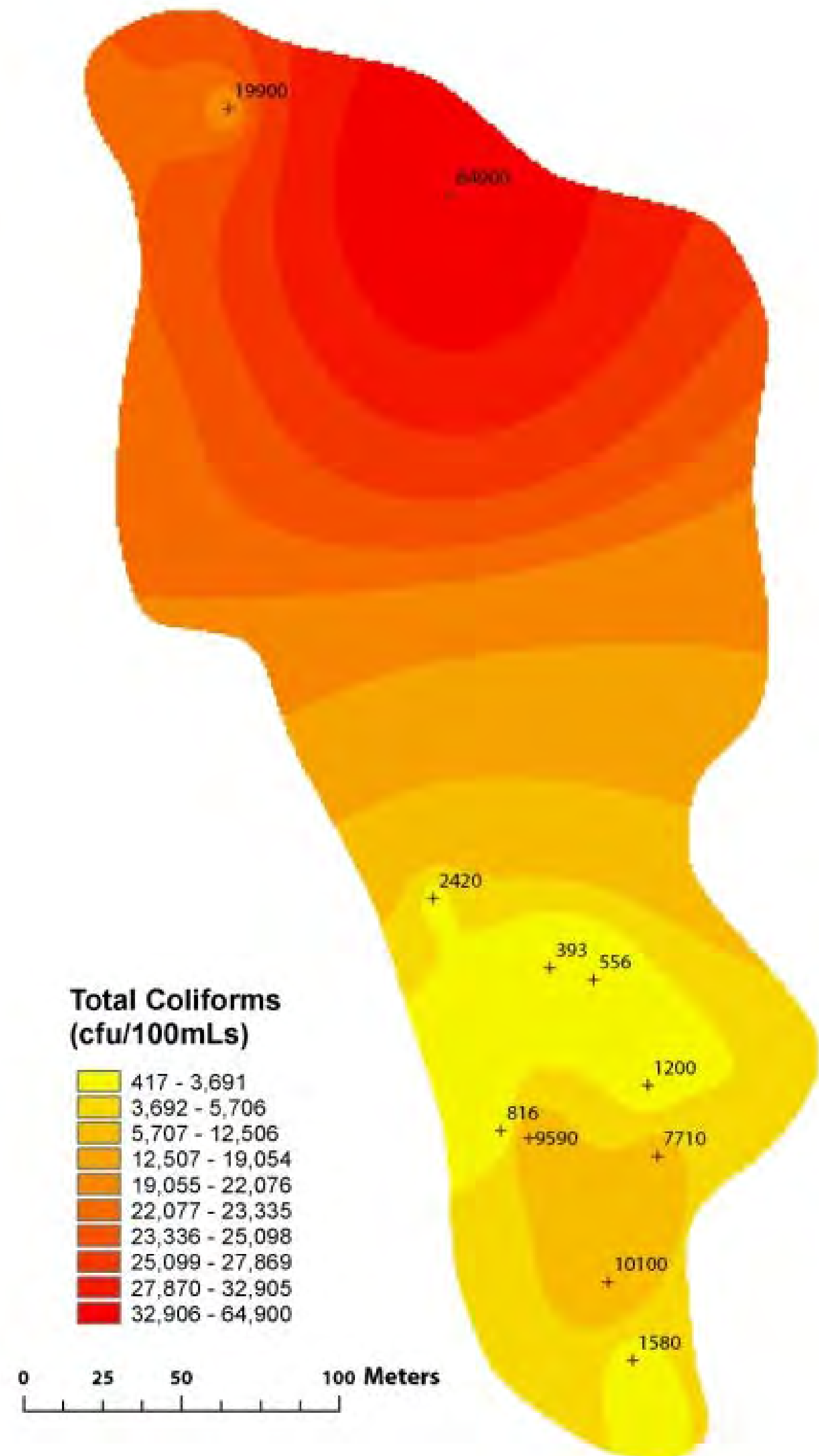


Figure C-50: Total coliform counts of the effluent in the Taloyoak wetland. Note: the flow of water is from the top to bottom.

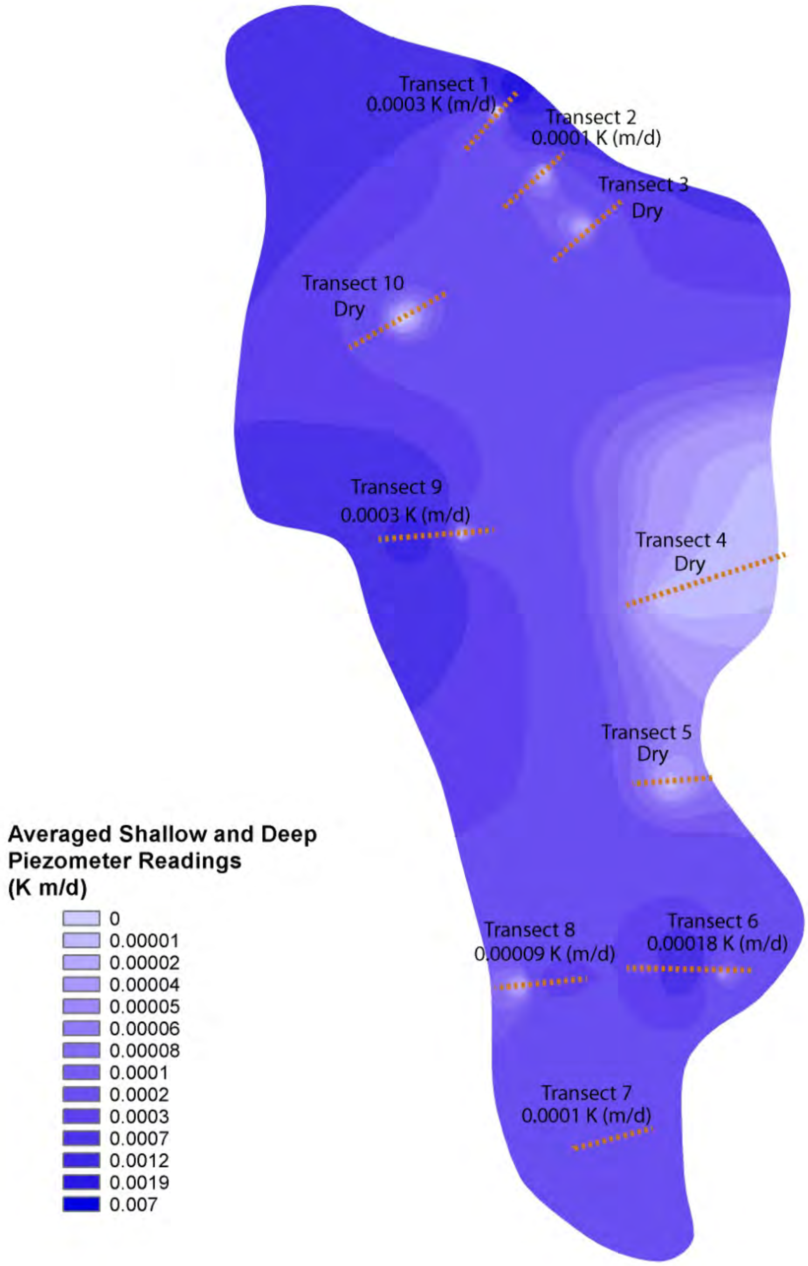


Figure C-51: Hydraulic conductivity of the Taloyoak wetland sediments expressed as K (m/d), which indicates the rate of water travel through the subsurface sediment. Note: the flow of water is from the top to bottom.

Appendix D: Raw water quality data for each of the seven sites studied for Environment Canada

The appended data are divided into the following sub appendices:

Appendix D-1: Raw data files for interpolated maps of Paulatuk

Appendix D-2: Raw data files for interpolated maps of Pond Inlet

Appendix D-3: Raw data files for Edzo (rapid survey, 2010)

Appendix D-4: Raw data files for interpolated maps for Edzo (full survey, 2011)

Appendix D-4 Raw data files for interpolated maps of Fort Providence (rapid survey, 2010)

Appendix D-6: Raw data files for interpolated maps of Gjoa Haven

Appendix D-7: Raw data files for interpolated maps of Ulukhaktok

Appendix D-8: Raw data files for interpolated maps of Talolyoak

Appendix D-1: Raw data file for Paulatuk

Paulatuk Chemical and Biochemical Parameters in Water, Sept 3, 2009 Raw Data

Sample Description	Ammonia (NH_3-N)	Nitrite (NO_2-N)	Nitrate ($N0_3$-N)	Total Kjeldahl Nitrogen (TKN-N)	Total Phosphorus (TP)	Phosphate as P (PO_4-P)
Units	*(mg/L as NH3-N)*	*(mg/L as NO2-N)*	*(mg/L as N03-N)*	*(mg/L as TKN-N)*	*(mg/L as P)*	*(mg/L as P)*
Laboratory of Origin	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*
Method Detection Limit	*0.02*	*0.01*	*0.02*	*0.04*	*0.063*	
Influent	3.19	0.05	0.17	13	2.42	1.35
T1S1	0.76	0.01	0.11	13.2	4.12	1.97
T1S2	1.1	0.01	0.02	9.71	0.75	0.091
T1S3	0.16	0.01	0.06	14	0.63	0.023
T1S4	4.24	0.01	0.74	16.3	3.9	2.51
T2S1	1.03	0.01	0.04	7.04	0.3	0.057
T2S2	0.18	0.01	0.05	4.58	0.13	0.002
T2S3	1.31	0.01	0.59	7.21	2.04	1.03
T2S4	0.31	0.01	0.05	10.5	0.32	0.002
T3S1	0.07	0.01	0.06	4.14	0.18	0.002
T3S2	0.05	0.01	0.05	2.44	0.1	0.002
T3S3	0.04	0.01	0.04	2.27	0.17	0.002
T3S4	1.31	0.01	0.11	14.2	7.12	0.138
T4S1	0.01	0.01	0.04	1.37	0.12	0.035
T4S2	0.17	0.01	0.05	4.85	0.78	0.105
T5S1	0.01	0.01	0.06	1.43	0.11	0.003
T5S2	0.21	0.01	0.14	4.8	0.91	0.334
T5S3	0.13	0.01	0.07	3.86	0.85	0.027
T6S1	0.01	0.01	0.05	1.55	0.13	0.002
T6S2	0.11	0.01	0.18	4.22	0.58	0.051
T6S3	1.07	0.01	0.01	9.6	1	0.005
T7S1	0.08	0.01	0.18	6.14	0.8	0.082
T7S2	0.17	0.01	0.01	6.65	0.45	0.006
T7S3	0.01	0.01	0.23	0.32	0.01	0.002
T8S1	0.24	0.01	0.05	11.8	0.68	0.002
T8S2	0.7	0.01	0.02	9.83	1.21	0.006
T8S3	0.13	0.01	0.03	4.15	0.28	0.002
T9S1	0.13	0.01	0.11	8.28	0.71	0.003
T9S2	0.36	0.01	0.04	5.23	0.72	0.002
T9S3	0.02	0.01	0.33	1.05	0.05	0.002
T10S1	0.05	0.01	0.3	2.88	0.28	0.002
T10S2	0.16	0.01	0.45	9.83	0.47	0.013
T10S3	0.14	0.01	0.1	6.08	0.48	0.002
T11S1	0.04	0.01	0.33	1.58	0.09	0.002
T11S2	0.01	0.01	0.37	1.42	0.04	0.002
T11S3	0.2	0.01	0.09	6.49	0.26	0.002
T12S1	0.01	0.01	0.38	0.56	0.01	0.002
T12S2	0.18	0.01	0.39	13.2	0.69	0.002
T12S3	0.02	0.01	0.34	1.43	0.06	0.003
T13S1	0.02	0.01	0.42	1.28	0.02	0.002
T13S2	1.87	0.01	0.27	42.8	0.91	0.002
Effluent	0.01	0.01	0.36	1.32	0.04	0.012
R1	0.01	0.01	0.17	0.27	0.01	0.002
Trip Blank Open	0.01	0.01	0.01	0.06	0.01	0.002
Trip Blank Closed	0.01	0.01	0.01	0.06	0.01	0.007

Paulatuk Chemical and Biochemical Parameters in Water, Sept 3, 2009 Raw Data Continued

Sample Description	Dissolved Organic Carbon (DOC)	Dissolved Oxygen (DO)	Chemical Oxygen Demand (COD)	Carbonaceous Biological Oxygen Demand - 5 Day (cBOD5)	Total Coliforms (TC)	E.coli (EC)	Fecal Coliform
Units	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(cfu/100mls)	(cfu/100mls)	(cfu/100mls)
Laboratory of Orig	Environment Canada	CAWT Fleming College	Environment Canada	Environment Canada	Environment Canada	Environment Canada	Environment Canada
Method Detection	0.40	n.a.	5	2	1	1	1
Influent	37.6	12.01	200	40	51700	2850	2300
T1S1	55.5	2.09	340	38	--	--	--
T1S2	78.1	0.70	280	14	40	2	4
T1S3	113	5.25	440	23	9210	6	2
T1S4	51.3	0.56	260	50	19900	830	840
T2S1	69.5	4.43	220	20	326	1	2
T2S2	49.4	3.40	110	7	225	1	4
T2S3	55.3	7.40	260	41	23600	1300	800
T2S4	94.1	3.22	330	12	>2420	6	4
T3S1	81.7	4.20	200	--	62	1	4
T3S2	53.2	8.74	53	4	613	1	1
T3S3	63.4	6.95	82	--	>2420	1	2
T3S4	72.6	4.35	330	32	>2420	74	56
T4S1	40.5	4.58	47	2	49	1	1
T4S2	51	5.37	180	17	1120	15	20
T5S1	36.1	3.90	41	2	38	1	5
T5S2	62.4	6.03	200	10	>2420	2	4
T5S3	55	6.79	200	11	961	7	10
T6S1	42.5	3.66	44	2	147	1	28
T6S2	56.2	7.04	78	7	1990	28	10
T6S3	44.8	3.90	150	12	74	1	4
T7S1	63.8	9.46	50	2	236	1	2
T7S2	39.1	6.75	120	6	649	1	2
T7S3	7.3	8.87	17	2	1	1	1
T8S1	57.4	8.26	360	6	22	1	10
T8S2	46.3	4.77	220	18	687	1	10
T8S3	15.2	10.61	147	2	2	1	1
T9S1	53.7	5.88	260	8	1	1	10
T9S2	52.7	8.84	120	6	12	1	100
T9S3	17.6	5.61	25	2	1	1	1
T10S1	13.4	10.44	100	2	3	1	2
T10S2	62.9	6.88	510	2	1	1	2
T10S3	29.8	8.82	170	2	6	1	1
T11S1	41.8	9.95	45	2	36	1	10
T11S2	52.2	6.73	40	2	46	1	1
T11S3	38.2	8.53	330	11	5	1	2
T12S1	19.8	8.89	18	2	4	1	1
T12S2	54.2	5.34	260	2	131	1	1
T12S3	26.7	7.24	38	2	4	1	10
T13S1	29.2	4.60	40	2	387	1	2
T13S2	40.4	7.36	78	2	>2420	1	1
Effluent	27.8	11.72	28	2	365	1	1
R1	4.4	16.67	5	2	125	9	2
Trip Blank Open	0.5	--	5	--	--	--	--
Trip Blank Closed	0.5	--	5	--	--	--	--

Paulatuk Physical Chemistry and Ionic Parameters in Water, Sept 3, 2009 Raw Data

Sample Description	*Temperature*	*Conductivity*	*pH*	**Total Alkalinity**	**Total Hardness ($CaCO_3$)**
Units	*(° C)*	**(µS)**		**(mg/L)**	**(mg/L)**
Laboratory of Origin	*CAWT Fleming College*	*CAWT Fleming College*	*CAWT Fleming College*	*Tiaga*	*Tiaga*
Method Detection Limit	*n.a.*	*n.a.*	*n.a.*	*0.4*	*0.7*
Influent	10.9	1227	8.81	380	864
T1S1	10.3	1264	6.93	472	809
T1S2	11.1	1149	6.85	490	751
T1S3	11.1	1314	6.35	586	866
T1S4	10.4	1276	7.70	391	771
T2S1	10.2	1223	6.99	489	768
T2S2	10.9	--	6.79	383	579
T2S3	10.9	1237	7.70	393	775
T2S4	9.5	1224	7.01	541	818
T3S1	9.7	1193	7.09	476	745
T3S2	10.3	1145	7.28	404	745
T3S3	10.5	1041	7.22	456	713
T3S4	10.9	1228	7.12	478	787
T4S1	10.6	1068	7.19	435	705
T4S2	11.0	1197	7.50	418	762
T5S1	12.5	1264	7.16	432	722
T5S2	13.0	1232	7.56	448	786
T5S3	13.6	1426	7.43	443	956
T6S1	13.9	1092	7.09	446	708
T6S2	13.5	1228	7.53	447	783
T6S3	13.7	1833	6.86	448	1310
T7S1	12.2	1275	7.59	460	810
T7S2	11.6	1167	7.58	384	882
T7S3	12.3	1168	7.30	277	864
T8S1	12.3	1083	7.53	412	722
T8S2	13.9	1182	7.15	398	706
T8S3	13.0	1024	7.54	307	785
T9S1	16.0	1151	6.88	419	728
T9S2	15.7	1065	7.24	372	733
T9S3	16.7	844	7.19	273	616
T10S1	15.9	984	8.06	332	649
T10S2	16.2	1186	7.21	453	760
T10S3	16.4	983	7.51	334	671
T11S1	15.7	996	7.73	347	663
T11S2	16.6	1030	7.25	382	656
T11S3	16.5	913	7.21	291	628
T12S1	15.9	1226	7.49	361	866
T12S2	16.3	1139	7.09	473	798
T12S3	16.1	1032	7.74	354	691
T13S1	15.8	1029	6.93	373	684
T13S2	16.9	1125	7.00	678	738
Effluent	15.8	1071	8.06	378	728
R1	16.7	--	8.40	--	275
Trip Blank Open	--	--	--	--	0.7
Trip Blank Closed	--	--	--	0.5	0.7

Paulatuk Physical Chemistry and Ionic Parameters in Water, Sept 3, 2009 Raw Data, Continued

Sample Description	Sulphate (SO_4^-)	Chloride (Cl^-)	Flouride (F^-)	Total Suspended Solids (TSS)	Turbidity
Units	(mg/L as P)	(mg/L as P04)	(mg/L as P)	(mg/L)	NTU
Laboratory of Orig	Tiaga	Tiaga	Tiaga	Tiaga	Tiaga
Method Detection	1	0.7	0.1	3	0.05
Influent	192	88.1	0.1	35	43.7
T1S1	95	89.6	0.1	560	87.2
T1S2	20	83.3	0.1	1450	262
T1S3	12	90.1	0.1	1120	250
T1S4	177	85.5	0.1	215	86.8
T2S1	50	92.6	0.3	741	136
T2S2	4	80.6	0.2	315	95.4
T2S3	157	84.7	0.1	140	66.3
T2S4	12	85.5	0.2	1270	230
T3S1	45	90.3	0.6	1180	108
T3S2	90	91.5	0.1	24	3.97
T3S3	2	76.3	0.1	130	38.6
T3S4	74	85.5	0.1	615	225
T4S1	40	77.4	0.1	36	7.29
T4S2	115	82.6	0.1	30	23.5
T5S1	54	78.8	0.1	6	12.5
T5S2	109	85.8	0.1	34	19.3
T5S3	221	93.2	0.1	96	56.8
T6S1	43	77.4	0.1	28	31.4
T6S2	105	86.9	0.1	4	19.5
T6S3	520	67.4	0.1	655	309
T7S1	116	85.6	0.1	1460	470
T7S2	245	24.8	0.1	880	201
T7S3	378	10.1	0.1	5	15.2
T8S1	89	64.4	0.1	1880	367
T8S2	110	87.8	0.1	1140	271
T8S3	256	15.3	0.1	700	537
T9S1	95	79.2	0.1	2900	1760
T9S2	146	49	0.1	850	270
T9S3	173	15.6	0.1	3	16.5
T10S1	115	62	0.1	1180	351
T10S2	82	80.8	0.1	1520	401
T10S3	142	46	0.1	468	100
T11S1	105	62.8	0.1	76	46.3
T11S2	73	71.5	0.1	14	7.54
T11S3	134	50	0.1	1450	446
T12S1	239	57.5	0.1	24	7.43
T12S2	49	72.7	0.7	2060	1110
T12S3	116	62.7	0.1	166	36.5
T13S1	84	73.6	0.1	36	11.5
T13S2	109	71.7	0.1	8320	1280
Effluent	130	61	0.1	3	0.36
R1	25	17.5	0.1	3	0.54
Trip Blank Open	1	0.7	0.1	3	0.08
Trip Blank Closed	1	0.7	0.1	3	0.08

Paulatuk Trace Elements in Water, Sept 3, 2009 Raw Data

Sample Description	Aluminum (Al)	Antimony (Sb)	Arsenic (As)	Barium (Ba)	Beryllium (Be)	Cadmium (Cd)	Calcium (Ca)	Calcium (Ca)
Units	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(mg/L)
Laboratory of Origin	Environment Canada	Environment Canada	Environment Canada	Environment Canada	Environment Canada	Environment Canada	Environment Canada	Tiaga
Method Detection Limit	0.067	0.024	0.200	0.039	0.029	0.067		0.100
Influent	4.79	0.858	9.48	26.4	<0.029	<0.067	65700	83.9
T1S1	--	--	--	--	--	--	--	77.1
T1S2	467	0.099	2.99	79.2	0.056	<0.067	47700	57.4
T1S3	--	--	--	--	--	--	--	65.6
T1S4	82.0	0.492	9.02	62.3	--	<0.067	63000	75.3
T2S1	964	0.041	3.71	135	0.037	<0.067	51900	54
T2S2	--	--	--	--	--	--	--	47.7
T2S3	--	--	--	--	--	--	--	70.9
T2S4	4810	0.063	4.01	149	0.232	0.411	90200	82.9
T3S1	--	--	--	--	--	--	--	94.6
T3S2	37.0	0.127	1.42	74.1	0.029	<0.067	55900	67
T3S3	11.1	<0.024	1.90	90.1	0.068	<0.067	53800	66.1
T3S4	--	--	--	--	--	--	--	66.9
T4S1	--	--	--	--	--	--	--	72
T4S2	--	--	--	--	--	--	--	66.9
T5S1	--	--	--	--	--	--	--	69.8
T5S2	--	--	--	--	--	--	--	68.6
T5S3	--	--	--	--	--	--	--	105
T6S1	16.0	0.045	1.98	66.3	0.036	0.180	59900	68.6
T6S2	1.93	0.142	4.07	23.1	--	0.116	64600	68.8
T6S3	--	--	--	--	--	--	--	213
T7S1	3870	0.246	7.21	69.2	0.213	0.173	87400	70.6
T7S2	--	--	--	--	--	--	--	140
T7S3	<0.067	<0.024	<0.200	34.7	<0.029	<0.067	17400	189
T8S1	--	--	--	--	--	--	--	70.7
T8S2	--	--	--	--	--	--	--	72.4
T8S3	--	--	--	--	--	--	--	152
T9S1	--	--	--	--	--	--	--	84.1
T9S2	9140	0.134	7.21	136	0.419	0.254	102000	84.7
T9S3	--	--	--	--	--	--	--	108
T10S1	--	--	--	--	--	--	--	91
T10S2	--	--	--	--	--	--	--	68.9
T10S3	--	--	--	--	--	--	--	88.8
T11S1	--	--	--	--	--	--	--	86.9
T11S2	--	--	--	--	--	--	--	80.7
T11S3	--	--	--	--	--	--	--	105
T12S1	29.0	<0.024	0.893	29.3	<0.029	0.165	136000	157
T12S2	3.35	<0.024	0.664	61.2	<0.029	<0.067	74900	91
T12S3	--	--	--	--	--	--	--	82.4
T13S1	28.8	<0.024	1.11	93.3	<0.029	<0.067	66600	76.5
T13S2	6.52	<0.024	1.130	29.9	<0.029	<0.067	70400	82.5
Effluent	207	<0.024	0.912	34.7	<0.029	<0.067	70100	80.6
R1	5.83	<0.024	<0.200	66.9	<0.029	<0.067	33900	36.4
Trip Blank Open	--	--	--	--	--	--	--	0.1
Trip Blank Closed	--	--	--	--	--	--	--	0.1

Paulatuk Trace Elements in Water, Sept 3, 2009 Raw Data, Continued

Sample Description	Chromium (Cr)	Cobalt (Co)	Copper (Cu)	Iron (Fe)	Lead (Pb)	Lithium (Li)	Magnesium (Mg)	Magnesium (Mg)
Units	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(ug/L)	(mg/L)
Laboratory of Origin	Environment Canada	Environment Canada	Environment Canada	Environment Canada	Environment Canada	Environment Canada	Environment Canada	Tiaga
Method Detection Limit	0.038	0.006	0.030	0.661	0.013	0.020	0.052	0.100
Influent	0.272	0.718	6.25	563	<0.013	8.86	101000	159
T1S1	--	--	--	--	--	--	--	150
T1S2	1.30	0.515	3.85	2420	0.323	8.96	94600	148
T1S3	--	--	--	--	--	--	--	170
T1S4	0.395	0.582	4.88	875	<0.013	9.12	91800	142
T2S1	1.84	1.80	7.23	15900	0.839	14.6	111000	154
T2S2	--	--	--	--	--	--	--	112
T2S3	--	--	--	--	--	--	--	145
T2S4	6.56	10.1	17.6	17300	4.66	23.0	114000	149
T3S1	--	--	--	--	--	--	--	124
T3S2	5.13	0.811	6.2	1840	<0.013	10.9	93100	140
T3S3	0.481	1.53	5.02	2690	<0.013	9.23	84600	133
T3S4	--	--	--	--	--	--	--	150
T4S1	--	--	--	--	--	--	--	128
T4S2	--	--	--	--	--	--	--	145
T5S1	--	--	--	--	--	--	--	133
T5S2	--	--	--	--	--	--	--	149
T5S3	--	--	--	--	--	--	--	169
T6S1	1.97	1.75	5.60	8480	<0.013	10.4	89500	130
T6S2	0.278	1.14	5.85	3470	<0.013	11.1	100000	149
T6S3	--	--	--	--	--	--	--	189
T7S1	5.81	4.28	23.8	9540	5.80	20.1	123000	154
T7S2	--	--	--	--	--	--	--	130
T7S3	0.059	0.481	1.82	2780	<0.013	6.11	63800	95.4
T8S1	--	--	--	--	--	--	--	132
T8S2	--	--	--	--	--	--	--	127
T8S3	--	--	--	--	--	--	--	98.4
T9S1	--	--	--	--	--	--	--	126
T9S2	13.3	10.1	22.3	23200	12.5	28.4	118000	127
T9S3	--	--	--	--	--	--	--	84.1
T10S1	--	--	--	--	--	--	--	102
T10S2	--	--	--	--	--	--	--	143
T10S3	--	--	--	--	--	--	--	109
T11S1	--	--	--	--	--	--	--	108
T11S2	--	--	--	--	--	--	--	110
T11S3	--	--	--	--	--	--	--	89.1
T12S1	0.348	0.553	5.10	2100	<0.013	14.1	73300	115
T12S2	0.220	0.245	5.18	1710	<0.013	8.95	71400	139
T12S3	--	--	--	--	--	--	--	118
T13S1	0.393	0.942	5.32	8630	<0.013	8.47	79000	120
T13S2	0.122	0.450	9.02	1200	<0.013	14.0	82300	129
Effluent	0.616	0.785	6.20	1440	<0.013	10.8	77700	128
R1	0.048	0.040	7.15	612	<0.013	6.01	28500	44.8
Trip Blank Open	--	--	--	--	--	--	--	0.1
Trip Blank Closed	--	--	--	--	--	--	--	0.1

Paulatuk Trace Elements in Water, Sept 3, 2009 Raw Data, Continued

Sample Description	Manganese (Mn)	Mercury (Hg)	Molybdenum (Mo)	Nickel (Ni)	Potassium (K)	Potassium (K)	Rubidium (Rb)	Silver (Ag)
Units	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(mg/L)*	*(mg/L)*	*(µg/L)*	*(µg/L)*
Laboratory of Origin	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Tiaga*	*Environment Canada*	*Environment Canada*
Method Detection Limit	*0.008*	*0.009*	*0.017*	*0.017*		*0.100*	*0.100*	*0.020*
Influent	180	<0.009	0.182	2.57	15000	13.7	64.7	<0.020
T1S1	--	--	--	--	--	9.5	67.2	--
T1S2	94.6	<0.009	0.057	2.18	7670	6.5	57.6	<0.020
T1S3	--	--	--	--	--	7.7	63	--
T1S4	325	<0.009	0.107	3.19	32500	13.1	59.3	<0.020
T2S1	278	<0.009	0.158	3.55	7610	6.8	63.7	<0.020
T2S2	--	--	--	--	--	0.7	48.2	--
T2S3	--	--	--	--	--	11.4	58.7	--
T2S4	1120	<0.009	0.302	13.8	5140	1.8	52.3	<0.020
T3S1	--	--	--	--	--	7.9	56.2	--
T3S2	343	<0.009	0.111	4.18	24.2	1.2	62.1	<0.020
T3S3	248	<0.009	0.077	3.08	1520	1.2	45.7	<0.020
T3S4	--	--	--	--	--	11.8	61.9	--
T4S1	--	--	--	--	--	1.8	47.7	--
T4S2	--	--	--	--	--	11.6	58.6	--
T5S1	--	--	--	--	--	2.1	51.6	--
T5S2	--	--	--	--	--	13.1	61.4	--
T5S3	--	--	--	--	--	10.5	58	--
T6S1	328	<0.009	0.101	4.47	3720	1.7	51.8	<0.020
T6S2	212	<0.009	0.068	3.21	9300	11.3	59.5	<0.020
T6S3	--	--	--	--	--	3.7	37.3	--
T7S1	125	<0.009	0.484	15.8	680	9.7	59.3	0.165
T7S2	--	--	--	--	--	2.3	12.5	--
T7S3	208	<0.009	0.046	2.79	1280	0.2	6.4	<0.020
T8S1	--	--	--	--	--	3	46.9	--
T8S2	--	--	--	--	--	6.1	57.4	--
T8S3	--	--	--	--	--	0.4	8.8	--
T9S1	--	--	--	--	--	5.4	55.8	--
T9S2	868	<0.009	0.656	20.4	9570	4.4	39.8	<0.020
T9S3	--	--	--	--	--	0.8	11.2	--
T10S1	--	--	--	--	--	1.5	41.7	--
T10S2	--	--	--	--	--	5.2	57.2	--
T10S3	--	--	--	--	--	1.8	34.2	--
T11S1	--	--	--	--	--	2.2	43.8	--
T11S2	--	--	--	--	--	2	45.8	--
T11S3	--	--	--	--	--	0.4	24	--
T12S1	35.7	<0.009	<0.008	3.61	3410	1	27.8	<0.020
T12S2	21.0	<0.009	0.019	2.40	3010	2.7	39.2	<0.020
T12S3	--	--	--	--	--	2.4	42.4	--
T13S1	1240	<0.009	0.249	3.61	2920	1.8	44.5	<0.020
T13S2	85.4	<0.009	0.030	4.09	9210	4.9	50.2	<0.020
Effluent	32.2	<0.009	0.052	3.84	7540	5.3	44.5	<0.020
R1	5.72	<0.009	0.135	1.10	3180	0.9	8.1	<0.020
Trip Blank Open	--	--	--	--	--	0.1	0.1	--
Trip Blank Closed	--	--	--	--	--	0.1	0.1	--

Paulatuk Trace Elements in Water, Sept 3, 2009 Raw Data, Continued

Sample Description	Sodium (Na)	Sodium (Na)	Strontium (Sr)	Thallium (Tl)	Titanium (Ti)	Vanadium (V)	Zinc (Zn)
Units	(ug/L)	(mg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)
Laboratory of Origin	Environment Canada	Tiaga	Environment Canada	Environment Canada	Environment Canada	Environment Canada	Environment Canada
Method Detection Limit	0.043	0.100	0.014	0.010	0.064	0.019	0.087
Influent	72100	64.7	78	<0.010	3.94	1.24	6.85
T1S1	--	67.2	--	--	--	--	--
T1S2	63400	57.6	38.5	<0.010	26.0	2.98	8.64
T1S3	--	63	--	--	--	--	--
T1S4	65800	59.3	80.6	<0.010	8.76	0.994	10.7
T2S1	71200	63.7	46	<0.010	27.2	3.16	14.6
T2S2	--	48.2	--	--	--	--	--
T2S3	--	58.7	--	--	--	--	--
T2S4	60100	52.3	84.3	<0.010	110	12.1	26
T3S1	--	56.2	--	--	--	--	--
T3S2	70000	62.1	59.6	<0.010	3.79	0.715	9.12
T3S3	51400	45.7	59.2	<0.010	33.2	0.682	3.88
T3S4	--	61.9	--	--	--	--	--
T4S1	--	47.7	--	--	--	--	--
T4S2	--	58.6	--	--	--	--	--
T5S1	--	51.6	--	--	--	--	--
T5S2	--	61.4	--	--	--	--	--
T5S3	--	58	--	--	--	--	--
T6S1	58200	51.8	58.8	<0.010	3.14	0.588	4.74
T6S2	64000	59.5	75.3	<0.010	3.52	0.614	5.37
T6S3	--	37.3	--	--	--	--	--
T7S1	67000	59.3	74.3	<0.010	82.1	9.77	17.3
T7S2	--	12.5	--	--	--	--	--
T7S3	9660	6.4	109	<0.010	1.63	0.348	6.66
T8S1	--	46.9	--	--	--	--	--
T8S2	--	57.4	--	--	--	--	--
T8S3	--	8.8	--	--	--	--	--
T9S1	--	55.8	--	--	--	--	--
T9S2	65400	39.8	130	<0.010	218	23.8	40.5
T9S3	--	11.2	--	--	--	--	--
T10S1	--	41.7	--	--	--	--	--
T10S2	--	57.2	--	--	--	--	--
T10S3	--	34.2	--	--	--	--	--
T11S1	--	43.8	--	--	--	--	--
T11S2	--	45.8	--	--	--	--	--
T11S3	--	24	--	--	--	--	--
T12S1	32900	27.8	247	<0.010	3.32	0.305	4.62
T12S2	39300	39.2	82.2	<0.010	3.1	0.341	2.84
T12S3	--	42.4	--	--	--	--	--
T13S1	52700	44.5	61.8	<0.010	3.38	0.556	2.61
T13S2	53300	50.2	71.4	<0.010	4.51	0.255	3.38
Effluent	48200	44.5	71.3	<0.010	8.51	0.735	4.18
R1	13300	8.1	56.8	<0.010	1.81	0.225	2.32
Trip Blank Open	--	0.1	--	--	--	--	--
Trip Blank Closed	--	0.1	--	--	--	--	--

Appendix D-2: Raw data files for Pond Inlet

Pond Inlet Chemical and Biochemical Parameters in Water, Sept 13, 2009 Raw Data

Sample Description	Ammonia (NH_3-N)	Total Kjeldahl Nitrogen (TKN-N)	Total Phosphorus (TP)	Chemical Oxygen Demand (COD)	Carbonaceous Biological Oxygen Demand - 5 Day (cBOD5)	Phenols
Units	(mg/L as NH3-N)	(mg/L as TKN-N)	(mg/L as P)	(mg/L)	(mg/L)	(mg/L)
Laboratory of Origin	Environment Canada	Environment Canada	Environment Canada	Environment Canada	Environment Canada	Environment Canada
Method Detection Limit	0.02	0.04	0.063	5	2	
PI10-Influent	75.4	95	7.67	377	70	1.98
PI9	74.6	92.7	7.31	377	74	0.925
PI8	69.3	89.2	6.76	347	83	0.626
PI7	63.9	85.6	6.07	331	69	0.727
PI6	53.9	70.3	5.41	295	53	0.591
PI5	54.6	72	5.52	294	56	0.914
PI4	51.8	67.4	4.92	282	60	0.763
PI3	47.8	61.2	4.32	275	63	0.053
PI2	38.5	52.3	3.11	260	54	0.303
PI1	37.5	51.2	2.95	255	53	0.435
PI1a-Effluent	31.6	48.6	2.55	242	50	0.067
Blank Open	0.044	0.034	<0.063	<5	--	0.011
Blank Un-Opened	0.047	0.089	<0.063	<5	--	0.008

Pond Inlet Physical Chemistry and Ionic Parameters in Water, Sept 13, 2009 Raw Data

Sample Description	*Conductivity*	*pH*	Total Alkalinity	Total Hardness ($CaCO_3$)	*Sulphate (SO_4^-)*	*Chloride (Cl^-)*	*Flouride (F^-)*	*Total Suspended Solids (TSS)*	*Volatile Suspended Solids (VSS)*
Units	**(µS)**		***(mg/L)***	***(mg/L)***	***(mg/L as P)***	***(mg/L as P04)***	***(mg/L as P)***	***(mg/L)***	***(mg/L)***
Laboratory of Origin	***Environment Canada***	***Environment Canada***	***Environment Canada***	***Environment Canada***	***Environment Canada***	***Environment Canada***	***Environment Canada***	***Environment Canada***	***Environment Canada***
Method Detection Limit	***n.a.***	***n.a.***	***0.555***	***0.781***	***0.04***	***0.03***	***0.05***	***5.18***	***6***
PI10-Influent	1110	7.79	434	64.7	4.63	64	4.46	70	50
PI9	1100	7.69	421	63.3	4.24	63	6.01	164	100
PI8	1070	7.78	418	66.7	4.62	62.6	5.47	94	50
PI7	1040	7.73	392	72.7	5.72	62.6	2.71	94	46
PI6	990	7.62	338	92.7	11.8	61.4	5.19	70	38
PI5	976	7.54	333	75.3	5.47	61.9	<0.05	56	40
PI4	943	7.55	315	76	5.36	69	4.84	50	38
PI3	923	7.61	302	72.7	6.12	62	5.18	56	40
PI2	862	7.55	241	74	5.7	62.1	3.9	42	34
PI1	847	7.57	237	72.7	5.51	62.1	3.47	48	36
PI1a-Effluent	828	7.51	204	87.3	6.95	60.8	<0.05	40	30
Blank Open	1	6.14	<0.555	0.67	<0.04	0.65	<0.05	2	1.33
Blank Un-Opened	1	5.92	0.02	<0.781	0.696	0.639	<0.05	1.33	0.67

Appendix D-3: Raw data files for Edzo (rapid survey September 15-16, 2010)

Edzo Chemical and Biochemical Parameters in Water, Sept 15-16, 2010 Raw Data

Sample Description	Ammonia (NH_3-N)	Total Kjeldahl Nitrogen (TKN-N)	Total Phosphorus (TP)	Dissolved Organic Carbon (DOC)	Total Organic Carbon (TOC)	Chemical Oxygen Demand (COD)	Carbonaceous Biological Oxygen Demand - 5 Day (cBOD5)	Total Coliforms (TC)	E.coli (EC)
Units	(mg/L as NH3-N)	(mg/L as TKN-N)	(mg/L as P)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(cfu/100mls)	(cfu/100mls)
Laboratory of Origin	Environment Canada	Environment Canada	Environment Canada	Environment Canada	Environment Canada	Environment Canada	Tiaga	Tiaga	Tiaga
Method Detection Limit	0.02	0.04	0.063	0.40	0.30	5	2	1	1
ES1	0.088	1.14	0.2	11.5	14.20	58.0	2	1960	6
ES2	0.093	1.33	0.353	9.8	11.40	56	2	>2420	2
ES3	1.28	3.13	0.38	10.8	12.00	41	7	3870	13
ES4	17.7	23.5	0.979	16.6	21.20	135.0	155	54800	3260
ES5	21.7	25.4	1.06	18.0	22.60	122.0	28	51700	19900
ES6	20.8	23.9	0.626	17.9	24.10	123.0	25	92100	32800
ES7	20.6	29.8	1.72	17.8	35.30	240.0	41	649000	77000
ES8	20.7	28.2	1.45	19.1	31.90	185.0	59	613000	141000
ES4a	0.459	1.94	0.187	<0.40	<0.30	45.0	5	--	--
ES3a	0.186	1.18	0.628	<0.40	<0.30	67.0	3	--	--

Edzo Physical Chemistry and Ionic Parameters in Water, Sept 15-16, 2010 Raw Data

Sample Description	*Conductivity*	**Total Alkalinity**	**Total Hardness ($CaCO_3$)**	*Sulphate (SO_4^-)*	*Chloride (Cl^-)*	*Flouride (F^-)*	*Total Suspended Solids (TSS)*
Units	(µS)	(mg/L)	(mg/L)	*(mg/L as P)*	*(mg/L as P04)*	*(mg/L as P)*	(mg/L)
Laboratory of Origin	*CAWT Fleming College*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*
Method Detection Limit	*n.a.*	*0.555*	*0.781*	*0.04*	*0.03*	*0.05*	*5.18*
ES1	530	127	208	85.1	52.7	0.074	6
ES2	494	115	198	89.6	42.2	0.519	11
ES3	484	87.3	179	86.6	34.7	0.071	95
ES4	615	171	165	109	30.9	0.551	208
ES5	592	192	154	82.6	26.7	0.065	40
ES6	595	197	172	81.5	26.9	0.065	20
ES7	600	198	179	82.7	26.9	0.075	40
ES8	596	182	171	99.9	27.0	0.062	90
ES4a	513	121	225	85.7	49.2	0.105	12
ES3a	523	118	213	91.2	48.2	0.598	74

Edzo Trace Elements in Water, Sept 15-16, 2010 Raw Data

Sample Description	Aluminum (Al)	Barium (Ba)	Calcium (Ca)	Copper (Cu)	Iron (Fe)	Lithium (Li)	Magnesium (Mg)
Units	***(µg/L)***	***(µg/L)***	***(µg/L)***	***(µg/L)***	***(µg/L)***	***(µg/L)***	***(µg/L)***
Laboratory of Origin	***Environment Canada***	***Environment Canada***	***Environment Canada***	***Environment Canada***	***Environment Canada***	***Environment Canada***	***Environment Canada***
Method Detection Limit	***2.874***	***0.143***	***2.672***	***0.172***	***0.387***	***0.007***	***0.105***
ES1	17.8	12.4	34600	<0.172	134	1.18	24500
ES2	1160	62.2	39100	22.9	6370	0.638	22400
ES3	65.9	34.5	33600	1.89	1160	0.931	17000
ES4	111	16.1	29700	12.0	132	0.565	17400
ES5	504	20.6	28700	30.5	206	0.452	15600
ES6	208	18.8	29200	26.4	119	0.648	15200
ES7	300	20.0	28800	29.2	133	0.734	14900
ES8	1460	27.8	29300	62.3	558	1.35	15300

Edzo Trace Elements in Water , Sept 15-16, 2010 Raw Data Continued

Sample Description	Manganese (Mn)	Nickel (Ni)	Potassium (K)	Rubidium (Rb)	Sodium (Na)	Strontium (Sr)	Titanium (Ti)	Zinc (Zn)
Units	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*
Laboratory of Origin	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*
Method Detection Limit	*0.087*	*0.082*	*0.115*	*0.100*	*7.286*	*0.055*	*0.598*	*0.059*
ES1	49.8	<0.082	6100	<0.100	44400	235	<0.598	<0.059
ES2	1720	0.237	8390	3.32	38700	262	13.4	18.5
ES3	1700	<0.082	11700	5.84	36600	231	<0.598	12.0
ES4	296	<0.082	9040	3.78	40000	214	<0.598	8.02
ES5	175	<0.082	9160	4.17	37800	204	<0.598	20.3
ES6	172	<0.082	9150	4.39	36700	209	<0.598	13.6
ES7	156	<0.082	9160	4.48	35700	210	<0.598	16.2
ES8	173	<0.082	10700	5.14	36400	218	6.78	45.5

AppendixD-4: Raw data files for Edzo (full survey September 3, 2011)

Edzo Chemical and Biochemical Parameters in Water, Sept 3, 2011 Raw Data

Sample Description	Ammonia (NH_3-N)	Nitrite (NO_2-N)	Nitrate ($N0_3$-N)	Total Kjeldahl Nitrogen (TKN-N)	Total Phosphorus (TP)	Dissolved Organic Carbon (DOC)	Dissolved Oxygen (DO)	Chemical Oxygen Demand (COD)	Carbonaceous Biological Oxygen Demand - 5 Day (cBOD5)	Total Coliforms (TC)	E.coli (EC)
Units	(mg/L as NH3-N)	(mg/L as NO2-N)	(mg/L as N03-N)	(mg/L as TKN-N)	(mg/L as P)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(cfu/100mls)	(cfu/100mls)
Laboratory of Origin	Environment Canada	Environment Canada	Environment Canada	Environment Canada	Environment Canada	Environment Canada	CAWT Fleming College	Environment Canada	Tiaga	Tiaga	Tiaga
Method Detection Limit	0.02	0.01	0.02	0.04	0.063	0.40	n.a.	5	2	1	1
Influent	16.1	<0.01	<0.02	20.5	1.03	43.5	5.03	119	26	57900	9090
T1S1	13.4	<0.01	<0.02	14.8	0.828	27.3	1.95	66.0	9	>242000	2420
T1S2	20.4	<0.01	<0.02	26.3	1.62	64.4	0.15	215	42	48800	4370
T1S3F	15.3	<0.01	<0.02	22.5	1.25	51.7	1.86	155	32	41100	6890
T1S4	6.47	<0.01	<0.02	8.05	0.679	24.1	0.31	64.0	15	>242000	2420
T2S1	5.60	<0.01	0.045	7.18	0.723	30.8	1.16	60.0	8	51700	6380
T2S2f	13.3	<0.01	0.02	15.9	1.05	31.0	2.28	82.0	16	6380	1550
T2S3	8.90	<0.01	0.027	11.1	0.795	29.4	0.30	69.0	15	72700	236
T3S1	9.60	<0.01	<0.02	10.6	0.512	33.3	2.20	66.0	4	1730	866
T3S2	2.75	<0.01	<0.02	4.21	0.288	24.1	1.90	58.0	9	68700	118
T3S3f	0.135	<0.01	1.2	1.1	0.122	14.3	5.71	33.0	2	1220	3
T3S4f	0.075	<0.01	0.087	1.27	0.067	31.3	8.55	77.0	2	2160	727
T4S1	1.16	<0.01	<0.02	2.55	0.491	22.0	1.06	67.0	6	3790	47
T4S2	0.191	<0.01	0.384	1.07	0.134	34.0	3.14	15.9	2	1200	1
T4S3	6.20	<0.01	<0.02	7.09	0.88	94.0	2.70	41.4	6	41100	3
T5S1bf	0.174	<0.01	0.425	1.11	0.114	19.0	4.38	57.0	2	1730	32
T5S1a	11.2	<0.01	<0.02	11.7	0.852	24.6	3.31	68.0	2	5380	1
T5S1	6.50	<0.01	<0.02	9.41	0.633	72.8	2.90	188	74	41100	5
T5S3	11.1	<0.01	0.103	12.3	0.726	26.7	1.34	57.0	4	81600	38
T5S4	0.017	<0.01	<0.02	2.68	0.985	31.3	2.33	105	3	3330	1
T5S5	13.4	<0.01	<0.02	15.9	1.53	45.2	1.82	165	5	>242000	435
T6S1	2.37	<0.01	0.023	7.01	1.38	50.4	3.26	215	5	16200	11
T6S2	2.83	<0.01	0.025	6.19	0.974	23.3	2.15	120	5	17300	19
T6S3	12.2	<0.01	<0.02	13.9	1.53	28.7	2.70	69.0	4	>242000	18
T6S4	6.16	<0.01	<0.02	8.64	1.06	26.0	0.63	97.0	3	86600	73
T7S1 (Pond)	17.9	<0.01	<0.02	20.3	1.11	31.8	2.26	85.0	5	1750	4
T7S2 (Pond)	2.79	<0.01	<0.02	4.62	0.346	25.7	0.72	83.0	4	6310	9
Effluent	0.305	<0.01	0.252	1.51	0.16	19.8	5.18	50.0	2	516	1
Reference	0.098	<0.01	0.036	0.858	<0.04	8.75	10.28	16.0	2	435	5
Blank Field	0.084	--	--	0.071	<0.04	0.769	--	<5.00	--	--	--
Blank	0.082	--	--	0.071	<0.04	0.724	--	5.00	--	--	--

Edzo Physical Chemistry and Ionic Parameters in Water, Sept 3, 2011 Raw Data

Sample Description	Temperature	Conductivity	pH	Total Alkalinity	Sulphate (SO_4^-)	Chloride (Cl^-)	Flouride (F^-)	Total Solids (TS)	Total Suspended Solids (TSS)	Volatile Suspended Solids (VSS)
Units	(° C)	(µS)		(mg/L)	(mg/L as P)	(mg/L as P04)	(mg/L as P)	(mg/L)	(mg/L)	(mg/L)
Laboratory of Origin	CAWT Fleming College	CAWT Fleming College	CAWT Fleming College	Environment Canada	Environment Canada	Environment Canada	Environment Canada	Environment Canada	Environment Canada	Environment Canada
Method Detection Limit	n.a.	n.a.	n.a.	0.555	0.04	0.03	0.05	15.6	5.18	6
Influent	18.1	693	7.24	193	108	31.8	0.241	27.1	433	27.1
T1S1	18.5	703	7.07	213	86.1	36.1	0.278	60.2	480	33.7
T1S2	19.2	729	7.22	237	65.3	33.1	0.200	159	579	77.8
T1S3F	18.9	690	7.09	236	108	32.0	0.233	282	715	272
T1S4	17.6	624	6.98	169	86.5	37.0	0.179	180	585	107
T2S1	18.0	703	6.99	193	110	38.0	0.367	58.2	539	55.7
T2S2f	18.5	661	7.20	196	92.5	32.1	0.251	20.3	404	14.5
T2S3	18.7	649	7.00	212	52	42.5	0.214	<15.6	384	<6
T3S1	22.8	1052	6.94	283	106	103	0.194	251	978	126
T3S2	17.3	919	6.63	20.8	40.7	50.3	0.089	23.5	333	20.6
T3S3f	19.7	617	7.09	143	94.7	50.2	0.277	90.6	503	86.8
T3S4f	18.0	298	6.98	192	112	105	0.249	112	789	38.5
T4S1	17.3	898	6.94	179	105	113	0.215	67.1	741	27.4
T4S2	18.4	615	7.09	139	96.9	50.6	0.247	41.2	455	38.2
T4S3	17.3	530	6.82	194	41.4	49.9	0.233	1190	1630	149
T5S1bf	18.4	717	7.18	135	118	71.4	0.182	<15.6	518	<6
T5S1a	18.3	929	6.86	266	47.6	106	0.265	141	701	10.2
T5S1	17.1	828	6.65	294	10.4	79.2	0.268	1390	1830	68.1
T5S3	18.8	726	6.99	280	15.8	50.8	0.261	1360	1450	89.4
T5S4	18.1	526	6.70	178	18.9	46.2	0.312	1760	1990	124
T5S5	18.8	909	6.95	357	9.73	74.6	0.183	293	855	29.9
T6S1	16.2	634	7.12	190	50.4	61.3	0.297	138	565	19.8
T6S2	17.9	635	7.10	168	71.9	52.3	0.224	2860	3230	192
T6S3	16.7	923	7.00	332	8.26	86.9	0.271	1150	1450	51.3
T6S4	17.6	632	7.04	152	85.6	50.1	0.232	255	1410	25.5
T7S1 (Pond)	19.1	974	7.05	387	5.58	80.3	0.310	830	694	21.9
T7S2 (Pond)	18.5	905	6.88	298	35.5	82.1	0.241	2060	2530	143
Effluent	18.1	705	7.13	144	116	70.3	0.195	32.1	536	13.1
Reference	19.7	815	8.38	104	98.7	131	0.797	<15.6	486	<6

Edzo Trace Metals in Water, Sept 3, 2011 Raw Data

Sample Description	Aluminum (Al)	Antimony (Sb)	Arsenic (As)	Barium (Ba)	Beryllium (Be)	Cadmium (Cd)	Calcium (Ca)	Cesium (Cs)
Units	**(µg/L)**	**(µg/L)**	**(µg/L)**	**(µg/L)**	**(µg/L)**	**(µg/L)**	**(µg/L)**	**(µg/L)**
Laboratory of Origin	***Environment Canada***	***Environment Canada***	***Environment Canada***	***Environment Canada***	***Environment Canada***	***Environment Canada***	***Environment Canada***	***Environment Canada***
Method Detection Limit	***2.874***	***0.005***	***0.118***	***0.143***	***0.008***	***0.026***	***2.672***	***0.002***
Influent	153	<0.005	0.195	20.9	<0.008	<0.026	34200	0.926
T1S1	2670	<0.005	1.36	55.5	0.095	0.077	55700	0.993
T1S2	7390	0.439	1.60	110	0.169	0.278	67900	1.12
T1S3F	4480	0.127	1.03	87.3	0.056	0.105	50000	0.237
T1S4	1390	<0.005	0.413	21.8	0.066	0.049	45900	0.317
T2S1	513	<0.005	0.877	27.4	<0.008	<0.026	45100	0.209
T2S2f	172	<0.005	0.291	18.8	<0.008	<0.026	36700	0.267
T2S3	454	<0.005	0.670	23.2	0.012	<0.026	31400	0.197
T3S1	3090	<0.005	2.06	74.9	0.063	0.293	91700	0.464
T3S2	5950	<0.005	1.16	80.7	0.139	0.098	75100	0.626
T3S3f	<2.874	<0.005	0.144	32.2	<0.008	<0.026	53100	0.119
T3S4f	28.5	<0.005	0.413	5.89	<0.008	<0.026	12200	<0.002
T4S1	4680	<0.005	0.783	70.5	0.172	0.119	80500	0.475
T4S2	<2.874	<0.005	<0.118	18.4	<0.008	<0.026	50900	<0.002
T4S3	6370	<0.005	3.82	75.6	0.261	0.157	36800	0.552
T5S1bf	171	<0.005	0.539	25.4	0.008	<0.026	59900	<0.002
T5S1a	9650	<0.005	4.00	134	0.425	0.179	78200	1.83
T5S1	14900	<0.005	5.21	185	0.594	0.271	71300	3.00
T5S3	5700	<0.005	2.87	128	0.260	0.109	53800	2.18
T5S4	6020	<0.005	3.72	84.1	0.248	0.148	40700	2.16
T5S5	8910	<0.005	5.49	129	0.392	0.264	77200	3.32
T6S1	4150	<0.005	3.90	64.7	0.184	0.145	52900	1.67
T6S2	14500	<0.005	2.42	132	0.632	0.252	50400	2.76
T6S3	3870	<0.005	1.83	82.3	0.162	0.060	66400	2.32
T6S4	20600	<0.005	3.63	171	0.788	0.287	52900	3.69
T7S1 (Pond)	5590	<0.005	5.07	123	0.262	0.322	72100	2.91
T7S2 (Pond)	6650	<0.005	7.05	114	0.273	0.174	95700	3.01
Effluent	26.4	<0.005	0.296	17.9	<0.008	<0.026	59100	1.32
Reference	<2.874	<0.005	0.937	27.1	<0.008	<0.026	44700	1.26

Edzo Trace Metals in Water, Sept 3, 2011 Raw Data Continued

Sample Description	Chromium (Cr)	Cobalt (Co)	Copper (Cu)	Iron (Fe)	Lead (Pb)	Lithium (Li)	Magnesium (Mg)	Manganese (Mn)
Units	***(µg/L)***	***(µg/L)***	***(µg/L)***	***(µg/L)***	***(µg/L)***	***(µg/L)***	***(µg/L)***	***(µg/L)***
Laboratory of Origin	***Environment Canada***	***Environment Canada***	***Environment Canada***	***Environment Canada***	***Environment Canada***	***Environment Canada***	***Environment Canada***	***Environment Canada***
Method Detection Limit	***0.110***	***0.006***	***0.172***	***0.387***	***0.006***	***0.007***	***0.105***	***0.087***
Influent	0.236	0.161	11.3	440	<0.006	6.86	11700	212
T1S1	2.99	1.21	43.7	3020	1.45	7.24	21300	1060
T1S2	6.12	4.65	170	5630	5.67	11.4	22900	260
T1S3F	2.34	1.58	102	2490	1.66	10.1	16400	340
T1S4	2.71	1.25	44.6	1350	1.06	7.51	16700	315
T2S1	0.867	3.03	24.5	3440	1.14	3.62	20800	523
T2S2f	0.266	0.391	8.50	409	<0.006	6.04	12600	192
T2S3	0.938	0.452	5.95	1240	0.416	7.03	13500	504
T3S1	8.43	1.70	167	7270	7.63	10.6	50400	1800
T3S2	6.57	1.69	32.0	7640	2.65	16.6	37100	764
T3S3f	0.123	0.403	0.471	476	<0.006	9.70	23200	117
T3S4f	0.235	0.034	1.34	372	<0.006	0.197	15600	<0.087
T4S1	7.02	2.05	43.8	5000	3.12	21.1	37700	646
T4S2	0.347	0.388	1.27	594	<0.006	9.70	23200	214
T4S3	10.2	2.70	21.1	7620	2.39	10.6	27500	485
T5S1bf	0.655	0.652	4.70	982	<0.006	11.9	27100	288
T5S1a	19.5	6.08	87.3	14200	4.59	21.5	37000	1620
T5S1	29.0	7.15	27.7	18200	5.26	23.3	37200	627
T5S3	12.8	2.96	55.4	9100	2.59	13.7	26600	1180
T5S4	12.9	2.97	22.7	24400	3.31	16.4	18400	2090
T5S5	20.5	5.49	17.6	10300	3.43	24.2	39900	780
T6S1	8.25	2.29	28.3	6990	3.64	13.2	28000	659
T6S2	24.8	6.57	29.6	14100	6.03	25.8	25200	629
T6S3	7.63	1.83	15.6	6410	1.59	12.6	34400	303
T6S4	39.6	12.4	42.9	20000	7.40	32.5	30700	719
T7S1 (Pond)	10.2	2.98	6.95	20700	2.76	16.4	35700	1280
T7S2 (Pond)	12.1	3.92	17.9	28600	3.34	26.9	31700	4100
Effluent	0.440	0.323	1.19	504	<0.006	11.1	28400	52.7
Reference	0.186	0.047	0.761	335	<0.006	9.70	33800	17.2

Edzo Trace Metals in Water, Sept 3, 2011 Raw Data Continued

Sample Description	Mercury (Hg)	Molybdenum (Mo)	Nickel (Ni)	Potassium (K)	Rubidium (Rb)	Selenium (Se)	Silver (Ag)
Units	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*
Laboratory of Origin	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*
Method Detection Limit	*0.003*	*0.005*	*0.082*	*0.115*	*0.100*	*0.021*	*0.005*
Influent	<0.003	0.531	1.14	8060	8.38	0.049	<0.005
T1S1	<0.003	2.29	4.38	10500	11.1	0.106	<0.005
T1S2	<0.003	82.6	10.4	12300	15.4	0.618	<0.005
T1S3F	<0.003	15.5	3.87	11400	11.6	0.369	<0.005
T1S4	<0.003	5.80	4.27	8420	7.94	0.070	<0.005
T2S1	<0.003	0.323	11.4	6170	3.51	0.085	<0.005
T2S2f	<0.003	0.994	1.05	8430	7.57	0.070	<0.005
T2S3	<0.003	1.09	2.30	6280	5.86	0.065	<0.005
T3S1	0.008	0.865	7.91	9220	8.37	0.149	4.87
T3S2	<0.003	0.626	5.26	8620	15.9	0.239	<0.005
T3S3f	<0.003	0.517	1.46	7700	5.41	<0.021	<0.005
T3S4f	<0.003	<0.005	0.56	372	0.153	<0.021	<0.005
T4S1	<0.003	<0.005	6.01	4760	9.56	0.132	<0.005
T4S2	<0.003	<0.005	1.45	6860	4.60	<0.021	<0.005
T4S3	<0.003	<0.005	7.01	7990	13.1	0.072	<0.005
T5S1bf	<0.003	<0.005	2.38	4760	8.40	<0.021	<0.005
T5S1a	0.007	<0.005	14.8	13800	28.9	0.097	<0.005
T5S1	<0.003	<0.005	23.6	16400	33.4	0.157	<0.005
T5S3	<0.003	<0.005	8.27	12600	21.4	0.125	<0.005
T5S4	<0.003	<0.005	7.92	5060	16.3	0.083	<0.005
T5S5	<0.003	1.18	14.4	12600	32.8	0.137	<0.005
T6S1	<0.003	<0.005	7.61	6510	12.3	0.135	<0.005
T6S2	<0.003	<0.005	16.1	11600	34.8	0.144	<0.005
T6S3	<0.003	<0.005	5.40	11500	12.1	0.050	<0.005
T6S4	<0.003	1.14	26.9	14500	50.4	0.155	<0.005
T7S1 (Pond)	<0.003	<0.005	7.58	14300	14.4	0.217	<0.005
T7S2 (Pond)	<0.003	<0.005	10.3	6490	16.2	0.103	<0.005
Effluent	<0.003	<0.005	2.09	4550	4.22	<0.021	<0.005
Reference	<0.003	1.43	0.821	4560	3.08	<0.021	<0.005

Edzo Trace Metals in Water, Sept 3, 2011 Raw Data Continued

Sample Description	Sodium (Na)	Strontium (Sr)	Thallium (Tl)	Titanium (Ti)	Uranium (U)	Vanadium (V)	Zinc (Zn)
Units	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)
Laboratory of Origin	Environment Canada	Environment Canada	Environment Canada	Environment Canada	Environment Canada	Environment Canada	Environment Canada
Method Detection Limit	7.286	0.055	0.007	0.598	0.005	0.006	0.059
Influent	32700	202	<0.007	2.58	1.39	0.19	17.9
T1S1	40600	273	<0.007	44.1	2.39	3.73	39.4
T1S2	39500	318	<0.007	95.9	3.39	6.28	199
T1S3F	40300	290	<0.007	35.1	0.430	1.92	243
T1S4	41400	231	<0.007	31.1	0.138	2.18	18.9
T2S1	34800	183	<0.007	16.3	0.253	1.09	14.9
T2S2f	34500	191	<0.007	3.92	<0.005	0.147	17.4
T2S3	28400	141	<0.007	23.3	0.082	1.33	8.66
T3S1	47000	314	<0.007	83.8	0.518	6.00	87.3
T3S2	49100	387	<0.007	149	0.375	6.73	35.8
T3S3f	43700	260	<0.007	1.75	<0.005	0.131	4.41
T3S4f	15400	33.5	<0.007	1.87	<0.005	0.23	4.75
T4S1	58000	375	<0.007	150	0.323	7.06	64.6
T4S2	42900	245	<0.007	1.74	<0.005	0.057	5.73
T4S3	34200	149	<0.007	198	0.530	13.1	19.8
T5S1bf	41800	300	<0.007	9.75	0.019	0.660	8.97
T5S1a	40200	341	<0.007	435	0.809	23.7	35.9
T5S1	49400	309	<0.007	591	1.05	34.7	35.7
T5S3	44700	291	<0.007	270	0.388	13.7	22.9
T5S4	37200	160	<0.007	267	0.484	16.2	23.5
T5S5	45500	409	<0.007	425	1.17	26.1	32.0
T6S1	45200	228	<0.007	162	0.651	11.3	18.0
T6S2	37200	240	0.017	522	1.23	29.2	43.3
T6S3	51900	278	<0.007	163	0.201	9.08	13.1
T6S4	38200	242	0.098	762	1.39	42.5	55.8
T7S1 (Pond)	52800	303	0.052	227	0.643	13.4	19.5
T7S2 (Pond)	49600	372	<0.007	280	0.885	16.3	21.9
Effluent	46400	276	<0.007	2.87	<0.005	0.275	6.38
Reference	57900	269	<0.007	0.938	1.39	0.203	3.79

Appendix D-5: Raw data files for Fort Providence (rapid survey September 12-14, 2010)

Fort Providence Chemical and Biochemical Parameters in Water, Sept 12-14 2010 Raw Data

Sample Description	Ammonia (NH_3-N)	Total Kjeldahl Nitrogen (TKN-N)	Total Phosphorus (TP)	Dissolved Organic Carbon (DOC)	Total Organic Carbon (TOC)	Chemical Oxygen Demand (COD)	Carbonaceous Biological Oxygen Demand - 5 Day (cBOD5)	Total Coliforms (TC)	E.coli (EC)
Units	**(mg/L as NH3-N)**	**(mg/L as TKN-N)**	**(mg/L as P)**	**(mg/L)**	**(mg/L)**	**(mg/L)**	**(mg/L)**	**(cfu/100mls)**	**(cfu/100mls)**
Laboratory of Origin	**Environment Canada**	**Environment Canada**	**Environment Canada**	**Environment Canada**	**Environment Canada**	**Environment Canada**	**Tiaga**	**Tiaga**	**Tiaga**
Method Detection Limit	**0.02**	**0.04**	**0.063**	**0.40**	**0.30**	**5**	**2**	**1**	**1**
FP1	26.5	44.9	111	31.7	81.6	296	57	242000	2480
FP2	27.2	44.3	11.0	0.138	81.7	284	39	>2419.2	2420
FP3	16.4	27.8	7.55	28.4	68.9	214	26	242000	1730
FP4	24.2	44.0	10.9	31.1	89.2	328	44	248000	1670
FP5	25.0	43.8	10.3	28.5	60.9	310	38	130000	2010
FP6	22.7	43.7	10.2	37.7	70.2	370	67	155000	1780
FP7	30.0	51.1	11.6	26.2	29.6	362	60	261000	1990
FP8	28.5	49.4	11.3	33.9	82.0	360	61	112000	2010
FP9	18.5	36.9	8.94	27.6	55.7	312	32	81600	990
FPCulv1	0.118	2.51	0.360	25.3	31.4	95	<2	1720	5.2
FPCulv2	0.158	2.80	0.269	34.4	42.3	121	<2	3870	2

Fort Providence Physical Chemistry and Ionic Parameters in Water, Sept 12-14 2010 Raw Data

Sample Description	*Conductivity*	Total Alkalinity	Total Hardness ($CaCO_3$)	*Sulphate (SO_4^-)*	*Chloride (Cl^-)*	*Flouride (F^-)*	*Total Suspended Solids (TSS)*
Units	(µS)	(mg/L)	(mg/L)	(mg/L as P)	(mg/L as P04)	(mg/L as P)	(mg/L)
Laboratory of Origin	CAWT Fleming College	Environment Canada	Environment Canada	Environment Canada	Environment Canada	Environment Canada	Environment Canada
Method Detection Limit	n.a.	0.555	0.781	0.04	0.03	0.05	5.18
FP1	1060	376	258	66.0	90.6	0.079	160
FP2	1070	380	273	69.9	90.8	0.065	130
FP3	1100	302	300	144	97.9	0.558	90.0
FP4	1030	365	252	62.9	90.2	0.645	230
FP5	991	348	239	58.2	89.5	0.624	64.1
FP6	994	348	243	64.1	90.7	0.052	270
FP7	1020	365	244	56.2	89.0	0.689	200
FP8	1030	369	239	50.7	88.2	0.603	170
FP9	928	315	244	62.3	89.6	0.736	220
FPCulv1	842	180	418	198	65.0	0.064	12.0
FPCulv2	862	300	322	159	37.5	<0.05	18.0

Fort Providence Trace Elements in Water, Sept 12-14 2010 Raw Data

Sample Description	Aluminum (Al)	Calcium (Ca)	Copper (Cu)	Iron (Fe)	Lithium (Li)	Magnesium (Mg)	Manganese (Mn)
Units	***(µg/L)***	***(µg/L)***	***(µg/L)***	***(µg/L)***	***(µg/L)***	***(µg/L)***	***(µg/L)***
Laboratory of Origin	***Environment Canada***	***Environment Canada***	***Environment Canada***	***Environment Canada***	***Environment Canada***	***Environment Canada***	***Environment Canada***
Method Detection Limit	***2.874***	***2.672***	***0.172***	***0.387***	***0.007***	***0.105***	***0.087***
FP1	95.6	45400	4.34	298	5.66	29900	278
FP5	102	41800	2.60	302	5.45	26900	432
FP8	227	42000	4.26	439	5.09	25600	209
FPCulv1	88.8	74900	<0.172	370	2.15	41300	326
FPCulv2	256	77200	<0.172	4160	3.18	46800	194

Fort Providence Trace Elements in Water , Sept 12-14 2010 Raw Data Continued

Sample Description	Nickel (Ni)	Potassium (K)	Rubidium (Rb)	Sodium (Na)	Strontium (Sr)	Titanium (Ti)	Zinc (Zn)
Units	***(µg/L)***	***(µg/L)***	***(µg/L)***	***(µg/L)***	***(µg/L)***	***(µg/L)***	***(µg/L)***
Laboratory of Origin	***Environment Canada***	***Environment Canada***	***Environment Canada***	***Environment Canada***	***Environment Canada***	***Environment Canada***	***Environment Canada***
Method Detection Limit	***0.082***	***0.115***	***0.100***	***7.286***	***0.055***	***0.598***	***0.059***
FP1	0.912	31700	18.1	101000	296	<0.598	19.9
FP5	0.769	29000	17.1	101000	268	<0.598	12.9
FP8	1.31	28900	17.6	97700	273	<0.598	13.2
FPCulv1	<0.082	18200	<0.100	26500	395	<0.598	2020
FPCulv2	0.125	10500	<0.100	35600	381	2.07	47.2

Appendix D-6: Raw data files for Gjoa Haven

Gjoa Haven Chemical and Biochemical Parameters in Water, Aug 4-7, 2010 Raw Data

Sample Description	Ammonia (NH_3-N)	Total Kjeldahl Nitrogen (TKN-N)	Total Phosphorus (TP)	Dissolved Organic Carbon (DOC)	Total Organic Carbon (TOC)	Chemical Oxygen Demand (COD)	Carbonaceous Biological Oxygen Demand - 5 Day (cBOD5)	Total Coliforms (TC)	E.coli (EC)
Units	(mg/L as NH3-N)	(mg/L as TKN-N)	(mg/L as P)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(cfu/100mls)	(cfu/100mls)
Laboratory of Origin	Environment Canada	Environment Canada	Environment Canada	Environment Canada	Environment Canada	Environment Canada	Tiaga	Tiaga	Tiaga
Method Detection Limit	0.028	0.109	0.033	0.253	0.253	5	2	1	1
Lagoon 1	87.9	98.6	10.1	2.67	101	312	187	8160000	816000
Lagoon 2	64.8	74.9	8.73	42.6	59.6	191	38	6300	1000
1a	32.4	39.1	4.81	57.9	69.7	226	32	20000	37
1b	67.8	71.2	3.75	89.6	101	330	170	47300	3100
1c	52.8	56.2	5.41	35.3	104	352	126	1920	134
1d	49.6	54.2	6.85	77.0	96.8	298	86	1120	45
2a	10.4	14.3	0.652	34.5	46.9	156	10	10000	10000
2b	12.9	18.5	0.460	43.0	56.5	182	13	439	20
2c	56.0	60.3	8.12	55.1	65.2	224	164	98400	1000
2d	49.8	56.5	7.26	59.5	61.3	308	84	104000	1200
3a	2.95	7.11	1.95	30.9	41.5	142	12	52	5
3b	26.1	32.4	2.69	36.6	56.6	176	12	3500	1
3c	53.5	63.6	3.85	84.5	105	320	10	248000	1000
4a	27.3	32.9	3.27	31.9	36.3	123	8	410	20
4b	17.3	23.0	0.727	34.0	46.2	134	16	3230	100
4c	44.2	50.4	2.56	46.5	65.0	208	23	6100	192
5cs	--	--	--	--	--	--	14	5480	488
5d	0.54	3.28	0.698	19.0	21.6	75	8	11200	1
6c	4.12	6.19	1.67	13.2	15.1	46	12	>2420	30
6d	0.100	1.52	0.782	11.7	12.6	38	2	210	30
7c	0.120	1.50	0.783	10.9	12.4	38	7	5	1
7ds	0.114	1.70	0.641	13.4	14.9	43	2	>2420	86
8a	1.21	3.22	0.707	10.8	13.8	48	2	>2420	10
1sw	5.75	7.83	2.08	13.0	15.2	52	3	>2420	33
2sw	8.42	10.8	1.80	16.1	15.4	60	4	>2420	88
3sw	11.2	13.0	0.922	14.1	17.2	56	4	19900	80
4sw	17.7	20.5	1.08	19.8	22.9	72	9	24200	308
5sw	35.1	40.7	2.76	26.0	34.5	115	32	62900	200
6sw	47.3	53.9	4.09	32.9	35.6	141	25	980	100
7sw	62.8	68.8	4.97	42.9	54.8	171	45	31000	10000
8sw	102	107	12.3	34.3	96.2	299	138	121000	>2420

Gjoa Haven Physical Chemistry and Ionic Parameters in Water, Aug 4-7, 2010 Raw Data

Sample Description	Total Alkalinity	Total Hardness ($CaCO_3$)	*Sulphate (SO_4^-)*	*Chloride (Cl^-)*	*Total Solids (TS)*	*Total Suspended Solids (TSS)*	*Volatile Suspended Solids (VSS)*
Units	***(mg/L)***	***(mg/L)***	***(mg/L as P)***	***(mg/L as P04)***	***(mg/L)***	***(mg/L)***	***(mg/L)***
Laboratory of Origin	***Environment Canada***	***Environment Canada***	***Environment Canada***	***Environment Canada***	***Environment Canada***	***Environment Canada***	***Environment Canada***
Method Detection Limit	***0.555***	***0.781***	***0.04***	***0.03***	***15.6***	***5.18***	***6***
Lagoon 1	528	213	10.9	160	880	40	20
Lagoon 2	538	237	1.42	193	1170	112	104
1a	482	460	1.32	172	934	350	150
1b	610	404	3.52	178	980	440	210
1c	558	342	0.456	201	1070	190	110
1d	482	276	0.878	224	1060	350	170
2a	370	292	28.8	121	774	90	50
2b	376	254	0.969	197	884	270	110
2c	532	276	1.64	194	926	570	200
2d	498	276	1.97	201	984	190	120
3a	374	628	0.643	172	792	1580	380
3b	392	280	2.5	196	880	125	70
3c	540	370	0.758	186	936	250	110
4a	400	580	11.7	177	802	620	70
4b	372	362	7.78	177	798	470	120
4c	502	422	4.71	197	904	1060	270
5cs	392	--	7.68	125	764	32	20
5d	356	362	7.75	156	722	2010	320
6c	250	215	11.0	74.4	502	8	6
6d	262	428	17.9	91.4	690	3200	<6
7c	198	269	22.4	79.2	530	1940	233
7ds	222	194	15.7	74.7	568	<5.18	<6
8a	240	275	13.6	71.0	572	16	16
1sw	260	214	10.8	76.4	542	<5.18	<6
2sw	280	215	10.1	85.0	588	8	5.33
3sw	298	240	9.63	91.5	618	5.33	5.33
4sw	352	224	4.74	110	742	8	5.33
5sw	434	239	3.71	142	712	18	16
6sw	492	242	5.35	162	790	16	10
7sw	528	255	1.78	174	848	30	28
8sw	602	210	4.05	172	996	22	22

Gjoa Haven Trace Metals in Water, Aug 4-7, 2010 Raw Data

Sample Description	Aluminum (Al)	Antimony (Sb)	Arsenic (As)	Barium (Ba)	Beryllium (Be)	Cadmium (Cd)	Calcium (Ca)	Cesium (Cs)
Units	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*
Laboratory of Origin	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*
Method Detection Limit	*2.874*	*0.005*	*0.118*	*0.143*	*0.008*	*0.026*	*2.672*	*0.002*
Lagoon 1	213	<0.005	<0.118	0.481	<0.008	<0.026	23300	0.136
Lagoon 2	--	--	--	--	--	--	--	--
1a	287	<0.005	15.1	28.1	<0.008	<0.026	56000	0.069
1b	274	<0.005	18.3	29.4	<0.008	<0.026	57200	0.073
1c	223	<0.005	16.3	29.2	<0.008	<0.026	51000	0.085
1d	200	<0.005	14.1	25.4	<0.008	<0.026	41800	0.088
2a	--	--	--	--	--	--	--	--
2b	658	<0.005	3.95	37.0	<0.008	<0.026	50400	0.089
2c	--	--	--	--	--	--	--	--
2d	167	<0.005	5.91	16.7	<0.008	<0.026	37300	0.239
3a	109	<0.005	11.3	37.3	<0.008	<0.026	77000	0.095
3b	191	<0.005	14.4	25.1	<0.008	<0.026	47200	0.073
3c	174	<0.005	14.7	16.4	<0.008	<0.026	50400	0.085
4a	232	<0.005	7.73	27.0	<0.008	<0.026	81000	0.086
4b	135	<0.005	11.8	43.7	<0.008	<0.026	53600	0.073
4c	464	<0.005	16.7	28.0	<0.008	<0.026	69800	0.099
5cs	40.1	<0.005	9.34	8.84	<0.008	<0.026	36000	0.074
5d	281	<0.005	0.199	21.8	<0.008	<0.026	57400	0.063
6c	16.1	<0.005	0.856	8.53	<0.008	<0.026	37000	0.050
6d	150	<0.005	<0.118	18.4	<0.008	<0.026	56300	0.046
7c	285	<0.005	<0.118	23.9	<0.008	<0.026	37500	0.051
7ds	21.1	<0.005	<0.118	12.4	<0.008	<0.026	32700	0.034
8a	21.4	<0.005	<0.118	13.2	<0.008	<0.026	38200	0.029
1sw	21.9	<0.005	1.85	8.14	<0.008	<0.026	35600	0.029
2sw	25.9	<0.005	2.78	7.74	<0.008	<0.026	35600	0.027
3sw	--	--	--	--	--	--	--	--
4sw	33.9	<0.005	8.14	6.49	<0.008	<0.026	36900	0.027
5sw	--	--	--	--	--	--	--	--
6sw	47.9	<0.005	14.8	5.54	<0.008	<0.026	16700	0.047
7sw	--	--	--	--	--	--	--	--
8sw	65.6	<0.005	17.6	8.12	<0.008	<0.026	25600	0.065

Gjoa Haven Trace Metals in Water, Aug 4-7, 2010 Raw Data Continued

Sample Description	Chromium (Cr)	Cobalt (Co)	Copper (Cu)	Iron (Fe)	Lead (Pb)	Lithium (Li)	Magnesium (Mg)	Manganese (Mn)
Units	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*
Laboratory of Origin	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*
Method Detection Limit	*0.110*	*0.006*	*0.172*	*0.387*	*0.006*	*0.007*	*0.105*	*0.087*
Lagoon 1	<0.110	<0.006	40	381	<0.006	1.14	23300	65.6
Lagoon 2	--	--	--	--	--	--	--	--
1a	<0.110	3.67	15.7	2530	1.95	2.12	43400	1010
1b	<0.110	4.60	20.7	1460	1.42	1.78	33200	876
1c	<0.110	1.53	18.4	3400	2.28	0.031	38200	1010
1d	<0.110	1.61	6.80	2270	2.21	0.026	27900	1270
2a	--	--	--	--	--	--	--	--
2b	<0.110	3.05	15.2	1040	<0.006	2.52	34500	942
2c	--	--	--	--	--	--	--	--
2d	<0.110	0.696	22.60	1160	<0.006	0.971	31500	548
3a	<0.110	4.95	4.8	4560	<0.006	0.843	54100	1810
3b	<0.110	1.22	16.0	380	<0.006	1.77	34500	321
3c	<0.110	0.673	16.6	1010	0.777	0.208	40400	893
4a	<0.110	2.22	38.9	6440	<0.006	1.13	54700	718
4b	<0.110	2.13	15.4	528	<0.006	1.25	45400	200
4c	<0.110	1.51	9.20	1930	0.365	<0.007	53100	1040
5cs	9.09	0.585	1.58	3990	<0.006	0.014	33000	281
5d	<0.110	5.20	4.80	376	<0.006	<0.007	46700	612
6c	<0.110	<0.006	1.79	1190	<0.006	<0.007	30500	141
6d	<0.110	<0.006	8.23	264	<0.006	<0.007	53700	57.1
7c	<0.110	0.847	14.5	990	<0.006	<0.007	36700	224
7ds	4.27	<0.006	7.09	51.8	<0.006	<0.007	34200	<0.087
8a	<0.110	<0.006	4.10	818	<0.006	<0.007	31200	95.8
1sw	<0.110	<0.006	2.53	1550	<0.006	<0.007	30000	153
2sw	<0.110	<0.006	2.55	2010	<0.006	<0.007	31800	187
3sw	--	--	--	--	--	--	--	--
4sw	<0.110	0.186	1.29	3350	<0.006	<0.007	33300	243
5sw	--	--	--	--	--	--	--	--
6sw	2.41	0.337	2.69	4060	<0.006	0.952	41300	233
7sw	--	--	--	--	--	--	--	--
8sw	<0.110	1.52	11.6	2240	<0.006	1.63	24700	240

Gjoa Haven Trace Metals in Water, Aug 4-7, 2010 Raw Data Continued

Sample Description	Mercury (Hg)	Molybdenum (Mo)	Nickel (Ni)	Potassium (K)	Rubidium (Rb)	Selenium (Se)	Silver (Ag)	Sodium (Na)
Units	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*
Laboratory of Origin	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*
Method Detection Limit	*0.003*	*0.005*	*0.082*	*0.115*	*0.100*	*0.021*	*0.005*	*7.286*
Lagoon 1	<0.003	<0.005	3.12	36000	23.5	<0.021	<0.005	131000
Lagoon 2	--	--	--	--	--	--	--	--
1a	<0.003	3.80	10.2	40800	14.0	4.98	<0.005	17800
1b	<0.003	2.10	15.1	38100	16.5	<0.021	<0.005	16100
1c	<0.003	0.663	8.52	45200	13.5	<0.021	<0.005	172000
1d	<0.003	2.08	7.25	46100	14.4	<0.021	<0.005	185000
2a	--	--	--	--	--	--	--	--
2b	<0.003	<0.005	5.83	17500	2.01	0.119	<0.005	179000
2c	--	--	--	--	--	--	--	--
2d	<0.003	<0.005	5.52	44900	24.2	<0.021	<0.005	170000
3a	<0.003	<0.005	11.9	12000	0.461	0.649	<0.005	127000
3b	<0.003	1.87	5.30	34600	18.6	<0.021	<0.005	178000
3c	<0.003	0.055	6.14	50000	19.6	1.89	<0.005	152000
4a	<0.003	<0.005	8.37	32200	7.18	7.05	<0.005	170000
4b	<0.003	1.69	9.30	25200	9.27	7.02	<0.005	147000
4c	<0.003	3.43	7.70	44700	9.67	6.33	<0.005	170000
5cs	<0.003	<0.005	8.05	22400	7.28	1.46	<0.005	98100
5d	<0.003	1.59	14.4	11800	<0.100	<0.021	<0.005	109000
6c	<0.003	<0.005	3.94	9710	0.079	4.06	<0.005	57500
6d	<0.003	<0.005	4.89	3630	<0.100	1.88	<0.005	63300
7c	<0.003	<0.005	6.29	1810	<0.100	8.37	<0.005	59200
7ds	<0.003	<0.005	5.32	3390	<0.100	4.39	<0.005	58700
8a	<0.003	<0.005	4.69	6140	<0.100	0.341	<0.005	55500
1sw	<0.003	<0.005	4.39	9980	0.433	1.10	<0.005	57900
2sw	<0.003	<0.005	4.93	12000	1.23	<0.021	<0.005	65900
3sw	--	--	--	--	--	--	--	--
4sw	<0.003	<0.005	5.42	19000	4.43	0.710	<0.005	88500
5sw	--	--	--	--	--	--	--	--
6sw	<0.003	<0.005	7.42	32200	16.5	0.561	<0.005	171000
7sw	--	--	--	--	--	--	--	--
8sw	<0.003	<0.005	6.26	43600	32.8	3.00	<0.005	148000

Gjoa Haven Trace Metals in Water, Aug 4-7, 2010 Raw Data Continued

Sample Description	**Strontium (Sr)**	**Thallium (Tl)**	**Titanium (Ti)**	**Uranium (U)**	**Vanadium (V)**	**Zinc (Zn)**
Units	***(µg/L)***	***(µg/L)***	***(µg/L)***	***(µg/L)***	***(µg/L)***	***(µg/L)***
Laboratory of Origin	***Environment Canada***	***Environment Canada***	***Environment Canada***	***Environment Canada***	***Environment Canada***	***Environment Canada***
Method Detection Limit	***0.055***	***0.007***	***0.598***	***0.005***	***0.006***	***0.059***
Lagoon 1	39.8	<0.007	<0.598	<0.005	<0.006	45.4
Lagoon 2	--	--	--	--	--	--
1a	94.5	<0.007	9.61	<0.005	0.331	132
1b	70.9	<0.007	5.89	<0.005	3.00	118
1c	73.4	<0.007	3.69	<0.005	1.86	120
1d	63.1	<0.007	3.08	<0.005	1.12	63.8
2a	--	--	--	--	--	--
2b	101	<0.007	7.76	<0.005	2.84	219
2c	--	--	--	--	--	--
2d	58.6	<0.007	0.922	<0.005	<0.006	34.1
3a	73.7	<0.007	<0.598	<0.005	1.11	149
3b	67.8	<0.007	0.490	<0.005	<0.006	38.0
3c	61.2	<0.007	3.31	<0.005	2.06	30.2
4a	61.2	<0.007	0.247	<0.005	4.75	87.8
4b	65.8	<0.007	2.20	<0.005	3.24	75.1
4c	60.6	<0.007	3.51	<0.005	5.43	93.9
5cs	33.3	<0.007	<0.598	<0.005	3.21	0.351
5d	63.9	<0.007	1.77	<0.005	1.60	20.8
6c	32.5	<0.007	<0.598	<0.005	<0.006	2.81
6d	49.7	<0.007	<0.598	<0.005	<0.006	48.8
7c	32.1	<0.007	10.8	<0.005	<0.006	52.6
7ds	31.8	<0.007	<0.598	<0.005	<0.006	<0.059
8a	33.0	<0.007	<0.598	<0.005	<0.006	2.68
1sw	31.5	<0.007	<0.598	<0.005	<0.006	4.18
2sw	32.6	<0.007	<0.598	<0.005	<0.006	4.77
3sw	--	--	--	--	--	--
4sw	32.7	<0.007	<0.598	<0.005	1.92	9.44
5sw	--	--	--	--	--	--
6sw	33.3	<0.007	0.213	<0.005	5.44	1.92
7sw	--	--	--	--	--	--
8sw	40.4	<0.007	0.413	<0.005	3.68	12.6

AppendixD-7: Raw data files for Ulukhaktok

Ulukhaktok Chemical and Biochemical Parameters in Water, July 29 - Aug 3, 2010
Raw Data

Sample Description	Ammonia (NH_3-N)	Total Kjeldahl Nitrogen (TKN-N)	Total Phosphorus (TP)	Dissolved Organic Carbon (DOC)	Total Organic Carbon (TOC)
Units	(mg/L as NH3-N)	(mg/L as TKN-N)	(mg/L as P)	(mg/L)	(mg/L)
Laboratory of Origin	Environment Canada	Environment Canada	Environment Canada	Environment Canada	Environment Canada
Method Detection Limit	0.028	0.109	0.033	0.253	0.253
Lagoon	9.61	25.2	8.19	62	86.5
1a	0.442	12.9	--	143	161
1aas	15.6	27.1	7.62	52.5	64.1
1bs	1.44	9.5	6.68	73.2	78.4
1c	0.516	8.97	0.603	104	120
1d	0.468	7.33	0.390	98.9	118
1e	0.295	7.58	0.413	73.1	82.2
2a	--	--	--	--	--
2b	--	--	--	--	--
2bs	4.06	10.5	9.75	47.1	54.4
2c	0.207	6.26	2.39	<0.253	<0.253
2cs	--	--	--	--	--
2d	--	--	--	--	--
2ds	25.6	35.8	11.9	83.2	84.4
2e	0.22	3.61	1.04	<0.253	<0.253
3bs	0.105	6.54	0.757	64.3	69.5
3cs	8.66	14.8	8.3	50.3	55.1
3d	--	--	--	--	--
3ds	6.01	12.1	7.34	51.6	54.8
3es	0.135	7.68	6.95	59.5	70.5
4a	--	--	--	--	--
4as	0.103	5.21	0.388	64	75.1
4b	--	--	--	--	--
4bs	0.192	6.24	6.62	47.3	62.8
4c	0.152	6.5	4.53	<0.253	<0.253
4cs	--	--	--	--	--
4d	0.137	2.07	0.139	<0.253	<0.253
4ds	--	--	--	--	--
4e	0.34	4.44	2.49	46	54.1
4f	0.351	5.58	0.492	<0.253	<0.253
4fs	--	--	--	--	--
4gs	0.074	3.84	0.498	35	42.1
5a	0.083	4.35	0.819	44.8	55.7
5as	--	--	--	--	--
5b	--	--	--	--	--
5bs	0.05	2.58	0.038	28.9	33.8
5c	0.107	2.38	0.444	22.4	23.6
5d	0.178	2.89	0.705	32.3	40.7
5e	0.102	5.1	1.44	<0.253	<0.253
5es	--	--	--	--	--
5fs	--	--	--	--	--
6b	0.129	3	0.269	46.3	56.6
6c	0.135	3.04	0.313	<0.253	<0.253
6d	0.114	5.2	1.22	<0.253	<0.253
6ds	--	--	--	--	--
6e	0.106	4.69	0.356	<0.253	<0.253
6es	--	--	--	--	--
7a	0.121	5.01	0.725	<0.253	<0.253
7as	--	--	--	--	--
7cs	0.092	4.73	0.667	<0.253	<0.253
8a	--	--	--	--	--
8as	0.090	5.12	0.158	<0.253	<0.253

Ulukhaktok Chemical and Biochemical Parameters in Water, July 29 - Aug 3, 2010
Raw Data Continued

Sample Description	Chemical Oxygen Demand (COD)	Carbonaceous Biological Oxygen Demand - 5 Day (cBOD5)	Total Coliforms (TC)	E.coli (EC)
Units	(mg/L)	(mg/L)	(cfu/100mls)	(cfu/100mls)
Laboratory of Origin	Environment Canada	Tiaga	Tiaga	Tiaga
Method Detection Limit	5	2	1	1
Lagoon	208	94	242000	9210
1A	--	50	2990	478
1AAS	190	<2	87000	387
1BS	290	<2	3870	2
1C	330	<2	>2420	1
1D	330	<2	>2420	1730
1E	290	<2	649	17
2A	--	30	935	251
2B	--	<2	>2420	30
2BS	176	--	--	--
2C	249	<2	2280	2
2CS	--	--	--	--
2D	--	<2	613	17
2DS	290	110	<1	<1
2E	117	21	1010	18
3BS	230	<2	>2420	1
3CS	181	93	<1	<1
3D	--	--	--	--
3Ds	184	--	--	--
3ES	215	--	--	--
4A	--	<2	1200	1
4AS	170	5	13000	5
4B	--	33	2250	2250
4BS	186	<2	8660	1
4C	211	<2	>2420	1
4CS	--	--	--	--
4D	68	25	55	46
4DS	--	--	--	--
4E	140	39	113	83
4F	199	108	21400	6220
4FS	--	--	--	--
4GS	131	8	1990	1
5A	158	<2	550	1
5AS	--	<2	>2420	1
5B	--	<2	365	1
5BS	99	14	<1	<1
5C	83	13	>2420	1
5D	113	10	345	1
5E	164	--	--	--
5ES	--	<2	921	1
5FS	--	11	263	3
6B	114	27	>2420	1
6C	125	<2	>2420	1
6D	208	14	<1	<1
6DS	--	<2	164	1
6E	159	--	--	--
6ES	--	9	>2420	1
7A	181	7	>2420	1
7AS	--	<2	1730	1
7CS	178	2	<1	<1
8A	--	7	<1	<1
8AS	181	<2	691	1

Ulukhaktok Physical Chemistry and Ionic Parameters in Water, July 29 - Aug 3, 2010 Raw Data

Sample Description	Conductivity	Total Alkalinity	Total Hardness ($CaCO_3$)	Sulphate (SO_4^-)	Chloride (Cl^-)	Flouride (F^-)	Total Suspended Solids (TSS)	Volatile Suspended Solids (VSS)
Units	(µS)	(mg/L)	(mg/L)	(mg/L as P)	(mg/L as P04)	(mg/L as P)	(mg/L)	(mg/L)
Laboratory of Origin	Environment Canada	Environment Canada	Environment Canada	Environment Canada	Environment Canada	Environment Canada	Environment Canada	Environment Canada
Method Detection Limit	n.a.	0.555	0.781	0.04	0.03	0.05	5.18	6
Lagoon	1720	389	378	55.9	269	0.127	140	140
1a	2230	940	1240	0.653	308	0.296	1030	370
1aas	1790	466	435	30.1	276	0.189	48	36
1bs	2080	652	684	10.3	319	0.223	26.7	20
1c	2240	1100	1290	7.18	233	0.262	1290	380
1d	1760	700	860	0.49	227	0.330	760	210
1e	2110	654	738	35.0	327	0.468	160	68
2a	--	--	--	--	--	--	--	--
2b	--	--	--	--	--	--	--	--
2bs	1800	548	524	6.52	285	0.187	890	680
2c	--	--	1100	--	--	--	--	--
2cs	2020	492	--	0.485	323	0.147	570	120
2d	1990	588	--	8.91	300	0.185	67	40
2ds	--	--	658	--	--	--	--	--
2e	--	--	1700	--	--	--	--	--
3bs	1960	634	788	<0.04	277	0.155	60	45
3cs	1790	492	492	8.98	282	0.19	20	20
3d	1800	514	--	8.73	281	0.183	27	27
3ds	--	--	550	--	--	--	--	--
3es	2010	568	720	1.54	329	0.203	95	70
4a	--	--	--	--	--	--	--	--
4as	1850	564	580	0.163	290	0.172	36	12
4b	1770	534	--	0.883	287	0.171	570	410
4bs	--	--	506	--	--	--	--	--
4c	--	--	820	--	--	--	--	--
4cs	1380	560	--	5.11	177	0.145	180	80
4d	--	--	1510	--	--	--	--	--
4ds	1860	478	--	0.494	288	0.227	60	47
4e	1810	654	606	0.84	278	0.200	2540	200
4f	--	--	830	--	--	--	--	--
4fs	1950	660	--	1.16	292	0.269	1200	300
4gs	1740	552	612	0.235	266	0.223	144	36
5a	1700	1160	700	4.84	252	0.223	20100	1360
5as	--	--	--	--	--	--	--	--
5b	--	--	--	--	--	--	--	--
5bs	1450	676	462	3.23	247	0.144	4570	250
5c	1350	520	994	<0.04	191	0.094	6200	1080
5d	1200	585	938	19	138	0.176	7120	980
5e	--	--	640	--	--	--	--	--
5es	1890	582	--	0.628	297	0.183	132	8
5fs	1960	600	--	0.439	311	0.177	120	60
6b	1560	1640	2740	24.9	257	0.205	17500	1120
6c	1310	392	715	5.82	199	0.212	1340	680
6d	1900	504	1040	0.706	345	0.204	3050	127
6ds	--	--	--	--	--	--	--	--
6e	--	--	586	--	--	--	--	--
6es	1950	636	--	28.2	305	0.246	408	36
7a	1800	724	1090	16.3	303	0.303	7240	680
7as	1900	510	--	5.31	321	0.216	16	12
7cs	--	--	610	--	--	--	--	--
8a	--	--	--	--	--	--	--	--
8as	1920	536	558	8.1	329	0.235	84	76

Ulukhaktok Trace Elements in Water, July 29 - Aug 3, 2010 Raw Data

Sample Description	**Aluminum (Al)**	**Antimony (Sb)**	**Arsenic (As)**	**Barium (Ba)**	**Beryllium (Be)**	**Cadmium (Cd)**	**Calcium (Ca)**
Units	***(µg/L)***	***(µg/L)***	***(µg/L)***	***(µg/L)***	***(µg/L)***	***(µg/L)***	***(µg/L)***
Laboratory of Origin	***Environment Canada***	***Environment Canada***	***Environment Canada***	***Environment Canada***	***Environment Canada***	***Environment Canada***	***Environment Canada***
Method Detection Limit	***2.874***	***0.005***	***0.118***	***0.143***	***0.008***	***0.026***	***2.672***
Lagoon	48	<0.005	0.442	<0.143	<0.008	<0.026	69400
1a	--	--	--	--	--	--	--
1aas	29.3	<0.005	2.69	29.5	<0.008	<0.026	86200
1bs	--	--	--	--	--	--	--
1c	--	--	--	--	--	--	--
1d	--	--	--	--	--	--	--
1e	--	--	--	--	--	--	--
2a	--	--	--	--	--	--	--
2b	--	--	--	--	--	--	--
2bs	469	<0.005	6.64	1320	<0.008	<0.026	140000
2c	--	--	--	--	--	--	--
2cs	--	--	--	--	--	--	--
2d	--	--	--	--	--	--	--
2ds	2350	<0.005	11.3	242	<0.008	<0.026	277000
2e	--	--	--	--	--	--	--
3bs	19.7	<0.005	5.78	122	<0.008	<0.026	150000
3cs	29.2	<0.005	2.64	197	<0.008	<0.026	96600
3d	--	--	--	--	--	--	--
3ds	--	--	--	--	--	--	--
3es	10.6	<0.005	5.91	61.3	<0.008	<0.026	149000
4a	--	--	--	--	--	--	--
4as	1820	<0.005	2.76	120	<0.008	<0.026	234000
4b	--	--	--	--	--	--	--
4bs	544	<0.005	1.82	133	<0.008	<0.026	115000
4c	--	--	--	--	--	--	--
4cs	5.94	<0.005	2.53	6.61	<0.008	<0.026	83400
4d	--	--	--	--	--	--	--
4ds	--	--	--	--	--	--	--
4e	--	--	--	--	--	--	--
4f	--	--	--	--	--	--	--
4fs	21.9	<0.005	0.694	31	<0.008	<0.026	126000
4gs	130	<0.005	0.346	45.9	<0.008	<0.026	112000
5a	--	--	--	--	--	--	--
5as	--	--	--	--	--	--	--
5b	--	--	--	--	--	--	--
5bs	6.62	<0.005	<0.118	60.2	<0.008	<0.026	95100
5c	--	--	--	--	--	--	--
5d	--	--	--	--	--	--	--
5e	--	--	--	--	--	--	--
5es	--	--	--	--	--	--	--
5fs	--	--	--	--	--	--	--
6b	--	--	--	--	--	--	--
6c	--	--	--	--	--	--	--
6d	--	--	--	--	--	--	--
6ds	--	--	--	--	--	--	--
6e	--	--	--	--	--	--	--
6es	14.3	<0.005	0.729	62.6	<0.008	<0.026	123000
7a	--	--	--	--	--	--	--
7as	7.27	<0.005	2.02	65.4	<0.008	<0.026	103000
7cs	--	--	--	--	--	--	--
8a	--	--	--	--	--	--	--
8as	17.9	<0.005	2.71	77.7	<0.008	<0.026	123000

Ulukhaktok Trace Elements in Water, July 29 - Aug 3, 2010 Raw Data Continued

Sample Description	Cesium (Cs)	Chromium (Cr)	Cobalt (Co)	Copper (Cu)	Iron (Fe)	Lead (Pb)	Lithium (Li)	Magnesium (Mg)
Units	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*
Laboratory of Origin	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*
Method Detection Limit	*0.002*	*0.110*	*0.006*	*0.172*	*0.387*	*0.006*	*0.007*	*0.105*
Lagoon	0.056	0.67	<0.006	9.55	49.9	<0.006	13.7	77300
1a	--	--	--	--	--	--	--	--
1aas	<0.002	<0.110	1.08	2.62	634	<0.006	11.3	71300
1bs	--	--	--	--	--	--	--	--
1c	--	--	--	--	--	--	--	--
1d	--	--	--	--	--	--	--	--
1e	--	--	--	--	--	--	--	--
2a	--	--	--	--	--	--	--	--
2b	--	--	--	--	--	--	--	--
2bs	0.007	<0.110	6.09	28.5	25600	<0.006	10.6	80900
2c	--	--	--	--	--	--	--	--
2cs	--	--	--	--	--	--	--	--
2d	--	--	--	--	--	--	--	--
2ds	0.242	2.52	11.2	4.02	17000	<0.006	17	177000
2e	--	--	--	--	--	--	--	--
3bs	<0.002	3.46	4.92	0.278	7450	<0.006	10.3	82200
3cs	<0.002	7.19	1.61	1.02	9940	<0.006	11.4	72800
3d	--	--	--	--	--	--	--	--
3ds	--	--	--	--	--	--	--	--
3es	<0.002	0.448	3.74	1.38	2040	<0.006	11.7	94300
4a	--	--	--	--	--	--	--	--
4as	0.048	3.32	5.59	13.2	5350	0.568	13.8	152000
4b	--	--	--	--	--	--	--	--
4bs	0.043	<0.110	1.4	3.06	10300	<0.006	12.9	85300
4c	--	--	--	--	--	--	--	--
4cs	<0.002	<0.110	2.38	<0.172	366	<0.006	9.83	70600
4d	--	--	--	--	--	--	--	--
4ds	--	--	--	--	--	--	--	--
4e	--	--	--	--	--	--	--	--
4f	--	--	--	--	--	--	--	--
4fs	0.014	<0.110	<0.006	0.669	655	<0.006	13.1	94500
4gs	0.022	<0.110	<0.006	0.051	605	<0.006	13.1	90700
5a	--	--	--	--	--	--	--	--
5as	--	--	--	--	--	--	--	--
5b	--	--	--	--	--	--	--	--
5bs	0.013	<0.110	<0.006	0.429	80.8	<0.006	13.1	66000
5c	--	--	--	--	--	--	--	--
5d	--	--	--	--	--	--	--	--
5e	--	--	--	--	--	--	--	--
5es	--	--	--	--	--	--	--	--
5fs	--	--	--	--	--	--	--	--
6b	--	--	--	--	--	--	--	--
6c	--	--	--	--	--	--	--	--
6d	--	--	--	--	--	--	--	--
6ds	--	--	--	--	--	--	--	--
6e	--	--	--	--	--	--	--	--
6es	0.016	<0.110	<0.006	<0.172	108	<0.006	12.8	94800
7a	--	--	--	--	--	--	--	--
7as	0.018	<0.110	<0.006	0.37	91.4	<0.006	14.5	101000
7cs	--	--	--	--	--	--	--	--
8a	--	--	--	--	--	--	--	--
8as	0.03	<0.110	<0.006	0.98	169	<0.006	16.1	119000

Ulukhaktok Trace Elements in Water, July 29 - Aug 3, 2010 Raw Data Continued

Sample Description	Manganese (Mn)	Mercury (Hg)	Molybdenum (Mo)	Nickel (Ni)	Potassium (K)	Rubidium (Rb)	Selenium (Se)	Silver (Ag)
Units	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*
Laboratory of Origin	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*
Method Detection Limit	*0.087*	*0.003*	*0.005*	*0.082*	*0.115*	*0.100*	*0.021*	*0.005*
Lagoon	39	<0.003	<0.005	3.75	50900	29.3	<0.021	<0.005
1a	--	--	--	--	--	--	--	--
1aas	445	<0.003	<0.005	5.53	43600	20.1	<0.021	<0.005
1bs	--	--	--	--	--	--	--	--
1c	--	--	--	--	--	--	--	--
1d	--	--	--	--	--	--	--	--
1e	--	--	--	--	--	--	--	--
2a	--	--	--	--	--	--	--	--
2b	--	--	--	--	--	--	--	--
2bs	2880	<0.003	<0.005	14.4	45600	22	<0.021	<0.005
2c	--	--	--	--	--	--	--	--
2cs	--	--	--	--	--	--	--	--
2d	--	--	--	--	--	--	--	--
2ds	1590	<0.003	<0.005	15	29400	12.8	1.11	<0.005
2e	--	--	--	--	--	--	--	--
3bs	1070	<0.003	<0.005	8.37	1410	<0.100	<0.021	<0.005
3cs	1110	<0.003	<0.005	5.38	37800	17.4	1.32	<0.005
3d	--	--	--	--	--	--	--	--
3ds	--	--	--	--	--	--	--	--
3es	611	<0.003	<0.005	11.5	7950	<0.100	2.5	<0.005
4a	--	--	--	--	--	--	--	--
4as	692	<0.003	<0.005	11.9	8200	1.49	5.32	<0.005
4b	--	--	--	--	--	--	--	--
4bs	682	<0.003	<0.005	5.38	22000	8.88	0.36	<0.005
4c	--	--	--	--	--	--	--	--
4cs	603	<0.003	<0.005	6.06	12100	4.83	5.12	<0.005
4d	--	--	--	--	--	--	--	--
4ds	--	--	--	--	--	--	--	--
4e	--	--	--	--	--	--	--	--
4f	--	--	--	--	--	--	--	--
4fs	117	<0.003	<0.005	5.55	2430	<0.100	1.63	<0.005
4gs	145	<0.003	<0.005	5.2	1920	<0.100	<0.021	<0.005
5a	--	--	--	--	--	--	--	--
5as	--	--	--	--	--	--	--	--
5b	--	--	--	--	--	--	--	--
5bs	71.9	<0.003	<0.005	4.53	6700	<0.100	2.85	<0.005
5c	--	--	--	--	--	--	--	--
5d	--	--	--	--	--	--	--	--
5e	--	--	--	--	--	--	--	--
5es	--	--	--	--	--	--	--	--
5fs	--	--	--	--	--	--	--	--
6b	--	--	--	--	--	--	--	--
6c	--	--	--	--	--	--	--	--
6d	--	--	--	--	--	--	--	--
6ds	--	--	--	--	--	--	--	--
6e	--	--	--	--	--	--	--	--
6es	8.22	<0.003	<0.005	5.68	1580	<0.100	1.89	<0.005
7a	--	--	--	--	--	--	--	--
7as	4.88	<0.003	<0.005	5.66	2840	<0.100	<0.021	<0.005
7cs	--	--	--	--	--	--	--	--
8a	--	--	--	--	--	--	--	--
8as	25	<0.003	<0.005	5.71	3780	<0.100	1.09	<0.005

Ulukhaktok Trace Elements in Water, July 29 - Aug 3, 2010 Raw Data Continued

Sample Description	Sodium (Na)	Strontium (Sr)	Thallium (Tl)	Titanium (Ti)	Uranium (U)	Vanadium (V)	Zinc (Zn)
Units	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*
Laboratory of Origin	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*
Method Detection Limit	*7.286*	*0.055*	*0.007*	*0.598*	*0.005*	*0.006*	*0.059*
Lagoon	249000	79.7	<0.007	<0.598	<0.005	<0.006	12.9
1a	--	--	--	--	--	--	--
1aas	239000	95.8	<0.007	<0.598	<0.005	<0.006	4.92
1bs	--	--	--	--	--	--	--
1c	--	--	--	--	--	--	--
1d	--	--	--	--	--	--	--
1e	--	--	--	--	--	--	--
2a	--	--	--	--	--	--	--
2b	--	--	--	--	--	--	--
2bs	215000	325	<0.007	<0.598	<0.005	8.54	70.4
2c	--	--	--	--	--	--	--
2cs	--	--	--	--	--	--	--
2d	--	--	--	--	--	--	--
2ds	266000	331	<0.007	48.9	<0.005	6.96	61.9
2e	--	--	--	--	--	--	--
3bs	158000	217	<0.007	<0.598	<0.005	<0.006	5.32
3cs	229000	138	<0.007	<0.598	<0.005	<0.006	8.27
3d	--	--	--	--	--	--	--
3ds	--	--	--	--	--	--	--
3es	270000	176	<0.007	<0.598	<0.005	<0.006	3.5
4a	--	--	--	--	--	--	--
4as	217000	203	<0.007	13.2	<0.005	13.1	43.6
4b	--	--	--	--	--	--	--
4bs	226000	151	<0.007	8.75	<0.005	1.07	9.58
4c	--	--	--	--	--	--	--
4cs	203000	111	<0.007	<0.598	<0.005	<0.006	0.641
4d	--	--	--	--	--	--	--
4ds	--	--	--	--	--	--	--
4e	--	--	--	--	--	--	--
4f	--	--	--	--	--	--	--
4fs	276000	140	<0.007	<0.598	<0.005	<0.006	5.03
4gs	205000	154	<0.007	0.283	<0.005	<0.006	2.58
5a	--	--	--	--	--	--	--
5as	--	--	--	--	--	--	--
5b	--	--	--	--	--	--	--
5bs	146000	134	<0.007	<0.598	<0.005	<0.006	0.878
5c	--	--	--	--	--	--	--
5d	--	--	--	--	--	--	--
5e	--	--	--	--	--	--	--
5es	--	--	--	--	--	--	--
5fs	--	--	--	--	--	--	--
6b	--	--	--	--	--	--	--
6c	--	--	--	--	--	--	--
6d	--	--	--	--	--	--	--
6ds	--	--	--	--	--	--	--
6e	--	--	--	--	--	--	--
6es	230000	153	<0.007	<0.598	<0.005	<0.006	1.91
7a	--	--	--	--	--	--	--
7as	247000	140	<0.007	<0.598	<0.005	<0.006	2.55
7cs	--	--	--	--	--	--	--
8a	--	--	--	--	--	--	--
8as	278000	155	<0.007	<0.598	<0.005	<0.006	2.73

Appendix D-8: Raw data files for Taloyoak

Taloyoak Chemical and Biochemical Parameters in Water, Aug 29, 2011 Raw Data

Sample Description	Ammonia (NH_3-N)	Nitrite (NO_2-N)	Nitrate ($N0_3$-N)	Total Kjeldahl Nitrogen (TKN-N)	Total Phosphorus (TP)	Dissolved Organic Carbon (DOC)	Dissolved Oxygen (DO)	Chemical Oxygen Demand (COD)	Carbonaceous Biological Oxygen Demand - 5 Day (cBOD5)	Total Coliforms (TC)	E.coli (EC)
Units	*(mg/L as NH3-N)*	*(mg/L as NO2-N)*	*(mg/L as N03-N)*	*(mg/L as TKN-N)*	*(mg/L as P)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(cfu/100mls)*	*(cfu/100mls)*
Laboratory of Origin	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*CAWT Fleming College*	*Environment Canada*	*Tiaga*	*Tiaga*	*Tiaga*
Method Detection Limit	*0.02*	*0.01*	*0.02*	*0.04*	*0.063*	*0.40*	*n.a.*	*5*	*2*	*1*	*1*
Influent	4.58	<0.01	1.14	10.1	3.86	39.4	11.1	120	12	19900	1300
Ref 1	0.084	<0.01	<0.02	1.49	<0.063	20.9	11.8	52	2	20	1
Pond 1	0.522	<0.01	<0.02	46.2	6.34	296	10.1	1010	215	119	20
Pond 2	0.126	<0.01	<0.02	1.34	0.14	16.3	11.8	45	14	816	308
T1S1	--	--	--	--	--	--	--	--	54	6910	31
T1S2	5.24	<0.01	0.041	9.68	1.38	32.1	5.08	85	10	64900	387
T7S2	0.215	<0.01	<0.02	3.79	0.51	34.8	7.04	94	8	9590	3
T7S3	0.124	<0.01	<0.02	2.99	0.162	25.4	3.68	75	24	816	7
T8S1	0.110	<0.01	<0.02	1.67	0.151	20.7	4.20	49	8	1200	1
T8S2	0.132	<0.01	<0.02	3.25	0.388	26.0	4.27	120	--	7710	1
T8S3Flow	0.090	<0.01	<0.02	1.14	<0.063	13.2	9.80	44	2	1050	9
T8S4	0.446	<0.01	0.034	2.93	2.50	21.6	4.47	70	17	101000	66
T9S1Flow	0.089	<0.01	<0.02	1.13	<0.063	13.9	9.63	21	2	>2420	26
T10S1	3.00	<0.01	<0.02	5.99	0.366	37.2	4.74	97	15	393	10
T10S2	0.498	<0.01	<0.02	2.3	0.121	22.0	6.95	56	13	556	10
T10S3Flow	0.087	<0.01	<0.02	1.11	<0.063	14.2	11.5	33	2	>2420	26
T10S4	1.05	<0.01	<0.02	3.99	0.300	34.7	1.10	139	18	1580	10
T11S1	0.688	<0.01	<0.02	4.41	0.502	38.4	10.3	268	54	--	--
T11S2Flow	0.087	<0.01	<0.02	1.12	0.073	13.4	12.6	34	2	>2420	>2420
T12S1Flow	0.147	<0.01	0.101	1.43	0.156	15.3	10.1	43	2	2420	23
T13S1Flow	0.120	<0.01	<0.02	1.48	0.246	15.2	14.8	37	2	>2420	19
T14S1Flow	0.104	<0.01	<0.02	1.38	0.226	16.8	14.8	33	2	1550	12
Effluent	0.127	<0.01	<0.02	1.46	0.324	19.4	12.6	38	3	4610	24
Blank Nutrients	0.075	--	--	<0.04	<0.063	--	--	<5	--	--	--
Field Blank Nutrients	0.077	--	--	<0.04	<0.063	--	--	<5	--	--	--

Taloyoak Physical Chemistry and Ionic Parameters in Water, Aug 29, 2011 Raw Data

Sample Description	Temperature	Conductivity	pH	Total Alkalinity	Sulphate (SO_4^-)	Chloride (Cl^-)	Flouride (F^-)	Total Solids (TS)	Total Suspended Solids (TSS)	Volatile Suspended Solids (VSS)
Units	(° C)	(µS)		(mg/L)	(mg/L as P)	(mg/L as P04)	(mg/L as P)	(mg/L)	(mg/L)	(mg/L)
Laboratory of Origin	CAWT Fleming College	CAWT Fleming College	CAWT Fleming College	Environment Canada	Environment Canada	Environment Canada	Environment Canada	Environment Canada	Environment Canada	Environment Canada
Method Detection Limit	n.a.	n.a.	n.a.	0.555	0.04	0.03	0.05	15.6	5.18	6
Influent	10.7	667	8.17	272	41.3	81.5	0.100	547	11.9	<6
Ref 1	10.0	700	8.56	163	197	68.6	0.132	658	5.29	<6
Pond 1	10.2	781	8.58	242	103	130	0.326	1550	612	447
Pond 2	9.40	634	8.45	217	120	66.4	0.157	616	14.8	7.41
T1S1	--	--	--	--	--	--	--	--	--	--
T1S2	9.60	784	7.10	306	85.1	90.0	0.085	647	21.0	14.5
T7S2	9.90	1057	7.13	--	108	195	0.288	--	--	--
T7S3	8.40	1251	6.96	453	132	202	0.351	1290	112	34.6
T8S1	9.00	704	6.91	370	70.1	54.0	0.314	905	342	45.9
T8S2	8.70	678	6.85	158	211	65.1	0.241	2930	2220	124
T8S3Flow	9.20	1197	7.65	281	247	209	0.287	1150	11.6	<6
T8S4	8.70	1266	7.04	289	354	188	0.276	2460	1100	82.7
T9S1Flow	9.40	1210	7.72	286	247	211	0.220	1110	10.1	<6
T10S1	9.70	2019	7.11	506	41.3	534	0.394	1580	57.7	6.13
T10S2	9.40	899	7.06	334	110	117	0.462	1360	562	17.1
T10S3Flow	10.0	1227	7.96	282	248	211	0.297	1130	6.82	<6
T10S4	9.30	1205	7.23	402	31.2	249	0.598	2160	1410	48.2
T11S1	9.70	1510	7.38	269	539	212	0.284	4590	2750	90.5
T11S2Flow	9.90	1219	8.30	297	254	211	0.284	1170	<5.18	<6
T12S1Flow	9.70	1260	7.80	273	264	229	0.300	1210	<5.18	<6
T13S1Flow	9.80	1291	8.44	285	267	237	0.311	1230	<5.18	<6
T14S1Flow	9.70	1290	8.60	279	269	237	0.300	1210	17.8	<6
Effluent	10.2	1336	8.36	287	266	243	0.317	1220	13.0	<6

Taloyoak Trace Metals in Water, Aug 29, 2011 Raw Data

Sample Description	Aluminum (Al)	Antimony (Sb)	Arsenic (As)	Barium (Ba)	Beryllium (Be)	Cadmium (Cd)	Calcium (Ca)	Cesium (Cs)
Units	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)
Laboratory of Origin	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*
Method Detection Limit	*2.874*	*0.005*	*0.118*	*0.143*	*0.008*	*0.026*	*2.672*	*0.002*
Influent	67.1	<0.005	0.763	2.57	<0.008	<0.026	47600	<0.002
Ref 1	<2.874	<0.005	1.2	9.67	<0.008	<0.026	39600	<0.002
Pond 1	638	0.152	3.14	16.1	<0.008	<0.026	61200	<0.002
Pond 2	15.4	<0.005	0.127	19.6	<0.008	<0.026	65500	<0.002
T1S1	--	--	--	--	--	--	--	--
T1S2	169	<0.005	0.978	20.7	<0.008	<0.026	74200	<0.002
T7S2	563	<0.005	0.574	36.3	<0.008	<0.026	139000	<0.002
T7S3	790	<0.005	3.260	46.5	<0.008	<0.026	146000	<0.002
T8S1	1460	<0.005	0.792	44.1	<0.008	<0.026	105000	<0.002
T8S2	3800	<0.005	3.71	65.2	0.245	0.108	111000	<0.002
T8S3Flow	36.9	<0.005	0.285	31.8	<0.008	<0.026	118000	<0.002
T8S4	1890	<0.005	1.15	56.4	0.014	<0.026	167000	<0.002
T9S1Flow	14.7	<0.005	0.264	31.9	<0.008	<0.026	113000	<0.002
T10S1	2850	<0.005	2.31	47.1	0.095	0.076	126000	<0.002
T10S2	1210	<0.005	0.963	38.8	0.009	<0.026	88300	<0.002
T10S3Flow	6.43	<0.005	0.234	33.0	<0.008	<0.026	118000	<0.002
T10S4	9070	<0.005	5.63	109	0.383	0.479	134000	0.733
T11S1	--	--	--	--	--	--	--	--
T11S2Flow	4.56	<0.005	0.344	33.1	<0.008	<0.026	114000	<0.002
T12S1Flow	24.6	<0.005	0.363	28.8	<0.008	<0.026	123000	<0.002
T13S1Flow	20	<0.005	0.375	24.7	<0.008	<0.026	114000	<0.002
T14S1Flow	3.34	<0.005	0.286	24.5	<0.008	<0.026	123000	<0.002
Effluent	47.1	<0.005	0.598	27.3	<0.008	<0.026	120000	<0.002

Taloyoak Trace Metals in Water, Aug 29, 2011 Raw Data Continued

Sample Description	Chromium (Cr)	Cobalt (Co)	Copper (Cu)	Iron (Fe)	Lead (Pb)	Lithium (Li)	Magnesium (Mg)	Manganese (Mn)
Units	***(µg/L)***	***(µg/L)***	***(µg/L)***	***(µg/L)***	***(µg/L)***	***(µg/L)***	***(µg/L)***	***(µg/L)***
Laboratory of Origin	***Environment Canada***	***Environment Canada***	***Environment Canada***	***Environment Canada***	***Environment Canada***	***Environment Canada***	***Environment Canada***	***Environment Canada***
Method Detection Limit	***0.110***	***0.006***	***0.172***	***0.387***	***0.006***	***0.007***	***0.105***	***0.087***
Influent	<0.11	0.154	8.70	136	0.064	5.50	21000	29.0
Ref 1	<0.11	<0.006	0.204	52.7	<0.006	5.66	61400	5.39
Pond 1	1.71	1.05	15.2	1250	0.808	5.78	26900	77.6
Pond 2	<0.11	<0.006	0.304	226	<0.006	3.84	30400	32.9
T1S1	--	--	--	--	--	--	--	--
T1S2	0.422	0.099	8.70	501	0.143	8.31	37000	134
T7S2	1.82	0.213	6.40	1430	0.293	12.6	75700	53.4
T7S3	2.71	0.400	10.1	8230	0.721	13.5	77000	138
T8S1	5.02	0.490	28.0	1350	1.09	10.9	51700	96.0
T8S2	14.7	1.75	34.8	5750	2.69	17.0	59400	180
T8S3Flow	<0.11	<0.006	<0.172	108	<0.006	12.4	68100	7.70
T8S4	6.31	0.723	18.8	6370	1.42	14.7	83900	148
T9S1Flow	3.94	0.017	0.193	199	<0.006	12.2	66800	10.1
T10S1	12.9	1.48	53.6	4650	2.65	21.6	85200	174
T10S2	6.07	0.473	22.3	1230	1.2	14.8	63800	78.0
T10S3Flow	<0.11	<0.006	0.954	269	<0.006	12.6	68400	13.5
T10S4	28.1	3.66	47.3	11400	8.11	31.5	96500	327
T11S1	--	--	--	--	--	--	--	--
T11S2Flow	<0.11	<0.006	1.69	388	<0.006	13.2	66800	12.7
T12S1Flow	<0.11	0.088	1.05	436	<0.006	12.4	74000	23.6
T13S1Flow	<0.11	0.019	0.684	184	<0.006	12.3	70300	19.5
T14S1Flow	7.60	0.057	1.08	242	<0.006	12.3	76200	18.4
Effluent	<0.11	0.054	1.52	423	<0.006	13.9	76300	29.0

Taloyoak Trace Metals in Water, Aug 29, 2011 Raw Data Continued

Sample Description	Mercury (Hg)	Molybdenum (Mo)	Nickel (Ni)	Potassium (K)	Rubidium (Rb)	Selenium (Se)	Silver (Ag)
Units	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*
Laboratory of Origin	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*
Method Detection Limit	*0.003*	*0.005*	*0.082*	*0.115*	*0.100*	*0.021*	*0.005*
Influent	0.085	<0.005	3.86	14500	14.8	0.426	<0.005
Ref 1	0.067	<0.005	0.398	6060	0.212	<0.021	<0.005
Pond 1	0.074	<0.005	7.53	13600	8.13	0.706	<0.005
Pond 2	0.044	<0.005	1.32	3260	1.86	<0.021	<0.005
T1S1	--	--	--	--	--	--	--
T1S2	0.103	<0.005	3.08	9620	7.26	0.494	<0.005
T7S2	0.055	<0.005	2.98	1100	1.90	0.178	<0.005
T7S3	0.028	<0.005	3.88	5350	2.72	0.36	<0.005
T8S1	0.068	<0.005	6.55	3340	8.73	0.044	<0.005
T8S2	0.094	<0.005	14.5	3280	15.0	0.338	<0.005
T8S3Flow	0.077	<0.005	1.56	2510	<0.1	0.105	<0.005
T8S4	0.036	<0.005	8.29	2510	4.41	0.099	<0.005
T9S1Flow	0.089	<0.005	3.02	2510	<0.1	0.140	<0.005
T10S1	0.020	<0.005	17.0	14700	16.4	0.611	<0.005
T10S2	0.077	<0.005	5.80	7400	9.99	0.157	<0.005
T10S3Flow	0.030	<0.005	1.69	2660	<0.1	0.104	<0.005
T10S4	0.043	4.62	16.5	17100	41.1	0.770	<0.005
T11S1	--	--	--	--	--	--	--
T11S2Flow	0.106	<0.005	1.64	2700	<0.1	0.036	<0.005
T12S1Flow	0.110	<0.005	1.83	3190	0.768	<0.021	<0.005
T13S1Flow	0.111	<0.005	1.81	3090	0.716	<0.021	<0.005
T14S1Flow	0.077	<0.005	3.94	3230	0.764	<0.021	<0.005
Effluent	0.047	<0.005	2.67	4220	1.61	0.063	<0.005

Taloyoak Trace Metals in Water, Aug 29, 2011 Raw Data Continued

Sample Description	Sodium (Na)	Strontium (Sr)	Thallium (Tl)	Titanium (Ti)	Uranium (U)	Vanadium (V)	Zinc (Zn)
Units	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*
Laboratory of Origin	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*	*Environment Canada*
Method Detection Limit	*7.286*	*0.055*	*0.007*	*0.598*	*0.005*	*0.006*	*0.059*
Influent	60400	82.3	<0.007	10.8	0.166	0.438	7.29
Ref 1	64000	70.2	<0.007	<0.598	0.418	0.231	0.465
Pond 1	78300	92.8	<0.007	46.5	3.79	2.71	18.7
Pond 2	40500	81.3	<0.007	1.47	2.33	0.344	3.74
T1S1	--	--	--	--	--	--	--
T1S2	63000	124	<0.007	8.91	0.582	1.02	7.10
T7S2	110000	171	<0.007	36.7	2.2	1.95	8.38
T7S3	95800	177	<0.007	51.3	0.775	4.69	6.35
T8S1	35600	136	<0.007	101	1.68	5.51	10.2
T8S2	44500	116	<0.007	347	2.27	13.8	13.4
T8S3Flow	111000	179	<0.007	0.642	3.45	0.137	1.92
T8S4	98700	194	<0.007	141	5.93	6.13	10.5
T9S1Flow	110000	181	<0.007	<0.598	3.59	0.028	1.89
T10S1	325000	239	<0.007	286	1.47	15.8	14.2
T10S2	75700	195	<0.007	89.7	1.17	7.26	10.0
T10S3Flow	107000	191	<0.007	1.39	3.81	0.128	3.97
T10S4	166000	288	0.103	652	4.12	34.4	25.9
T11S1	--	--	--	--	--	--	--
T11S2Flow	108000	201	<0.007	1.45	4.13	0.181	1.55
T12S1Flow	123000	199	<0.007	3.11	4.51	0.276	3.28
T13S1Flow	124000	202	<0.007	1.04	3.93	0.304	1.45
T14S1Flow	124000	202	<0.007	1.98	3.98	0.548	4.01
Effluent	129000	229	<0.007	5.02	4.17	0.945	9.67

Appendix E: SubWet user manual

SubWet (version 2.0): modelling software for subsurface wetlands

Operations manual

Glossary of symbols applied in SubWet 2.0

AA: area (m^2)

AC: ammonification rate coefficient (1 / 24h)

AF: inverse phosphorus adsorption capacity (mg/L)

AMM-A, AMM-B, AMM-C, AMM-D, AMM-E, AMM-IN, AMM-OUT: ammonium-N concentrations in boxes A, B, C, D, E and in inflowing and out flowing water (mg N/L)

AMFI: ammonification (mg N / (L*24h))

AOX: Average oxygen concentration in Box A (mg/L; range 0-20)

AP: the particulate matter in percentage (%)

BOD_5-A, BOD_5-B, BOD_5-C, BOD_5-D, BOD_5-E, BOD_5-IN, BOD_5-OUT: biological oxygen demand concentrations in boxes A, B, C, D, E and in inflowing and out flowing water (mg O_2 / L)

BOV: box volume (m^3)

BOX: Average oxygen concentration in Box B (mg/L; range 0-20)

COX: Average oxygen concentration in Box C (mg/L; range 0-20)

DC: denitrification rate coefficient (1/24h)

DE: depth (m)

DENI: denitrification (mg N / (L*24h))

DOX: average oxygen concentration in Box D (mg/L; range 0-20)

EOX: average oxygen concentration in Box E (mg/L; range 0-20)

FL: flow length (m)

FW: flow width (m)

HC: the hydraulic conductivity (m/24h)

HF: the recommended horizontal flow (m/24h)

HL: hydraulic loading (m^3 / (24h x m^2))

INOO: the Michaelis-Menten expression for the influence of the oxygen concentration on the oxidation rate of organic matter as BOD_5 (-)

INOX: the Michaelis-Menten expression for the influence of the oxygen concentration on the nitrification rate (-)

KO: Michaelis-Menten constant for the influence of oxygen on the nitrification rate (mg/L)

LE: length (m)

MA: Michaelis-Menten constant for nitrification (mg/L)

MN: Michaelis-Menten constant for denitrification (mg/L)

NC: nitrification rate coefficient (1/24h)

NIOX: nitrification (mg N / (L*24h))

NIT-A, NIT-B, NIT-C, NIT-D, NIT-E, NIT-IN, NIT-OUT: nitrate-N concentrations in boxes A,B,C,D,E and in inflowing and out flowing water (mg N / L)

NP: number of paths (-)

OC: oxidation rate coefficient for organic matter, expressed as BOD_5 (1/24h)

OO: Michaelis-Menten constant for influence of oxygen on the oxidation rate of organic matter, expressed as BOD_5 (mg/L)

ORMD: oxidation of organic matter as BOD_5 ((mg O_2 / (L*24h))

ORN-A, ORN-B, ORN-C, ORN-D, ORN-E, ORN-IN, ORN-OUT: concentrations of organic nitrogen compounds in boxes A,B,C,D,E and in inflowing and out flowing water (mg N / L)

PA: plant uptake rate coefficient for ammonium (1/24h)

PF: precipitation factor

POAD: adsorption of phosphorus (mg P / (L*24h))

POM: fraction of BOD_5 as suspended matter (no unit; range 0-1)

PON: Fraction of organic-N matter as suspended matter (no unit, range 0-1)

POP: Fraction of phosphorus as suspended matter (no unit, range 0-1);

POR: porosity no unit; range 0-1; default value 0.46

PN: plant uptake rate coefficient for nitrate (1/24h)

PP: plant uptake rate coefficient for phosphorus (1/24h)

PUAM: plant uptake of ammonium (mg N / (L*24h))

PUNI: plant uptake of nitrate (mg N / (L*24h))

PUPO: plant uptake of phosphorus (mg P / (L*24h))

QIN = RF: flow of water, expressed as m^3/24 h; possible range 1- 1 000 000)

RF: recommended flow rate included precipitation (m^3/24h)

RTB: retention time in one box = 1/5 of the wetland volume (24h)

RTT: retention time in the wetland (24h)

S: slope (cm/m)

SF: selected flow rate of water to be treated (m^3/24h)

TA: temperature coefficient for ammonification (-)

TD: temperature coefficient for denitrification (-)

TEMP: average temperature in centigrade as function of time

TN: temperature coefficient for nitrification (-)

TO: temperature coefficient for oxidation of organic matter expressed as BOD_5 (-)

TPO-A, TPO-B, TPO-C, TPO-D, TPO-E, TPO-IN, TPO-OUT: concentrations of total phosphorus in boxes A, B, C, D, E and in inflowing and out flowing water (mg P / L)

VO: volume (m^3)

WI: width (m)

Introduction

SubWet is a horizontal subsurface flow modelling program developed to support the decision-making process by assisting experts and water managers in the design of constructed wetlands for the treatment of municipal wastewater effluents. Furthermore, SubWet 2.0 can also be used as a troubleshooting tool for improving the efficiency of low or non-performing systems. Lastly this software package is useful for training purposes in modelling artificial wetlands.

SubWet was originally designed for warm climate applications, but the recent SubWet 2.0 version has been modified to allow its application to cold climate areas. Cold climate wetlands are defined as those were the surface temperature range varies from well below freezing in winter months to temperatures above 20°C during the summer (applicable to temperate and arctic climates). This modification was accomplished by calibrating the model with data collected from "natural" tundra wetlands currently in use for the treatment of municipal effluents within the Kivalliq region of Nunavut, Canada for the treatment of municipal effluents.

The SubWet model was initially intended to provide support for the design of constructed wetlands by providing environmental engineers and planners answers to the size of wetlands needed to accommodate anticipated flow rates and desired levels of treatment. The application of this software to "natural" tundra wetlands is beyond the original purpose it was designed for, however, the calibration of this model with Arctic data has demonstrated its ability to model treatment performance within "natural" tundra wetlands and thus provide an additional predictive tool to aid northern stakeholders in the treatment of municipal effluents.

The SubWet 2.0 model can be used as a predictive tool for changes to the:

A) **Hydraulic Retention Time** (HRT): The residency time that the effluent remains within the wetland can greatly influence the overall treatment achieved. The HRT can be altered through a variety of operational parameters such as the construction of detention berms to slow the rate of flow through the wetland to the alteration of flow volumes associated with the decanting of upstream pre-treatment lagoons and seasonal events influencing precipitation and spring freshet. SubWet will allow managers to predict the impact to treatment based on an alteration to the HRT.

B) **Loading Rates**: The ability of wetlands to successfully treat municipal effluents can be influenced significantly by altering the aerial loading rate. The aerial loading rate when expressed as the volume of effluent percolating into the wetland over a specific time frame is often referred to as the hydraulic loading rate (HLR). The HLR is often expressed as cm (depth) of effluent per area (e.g., hectare) of wetland. The infiltration of the effluent is often influenced by soil characteristics (e.g. grain size, pore volume, etc.) and the suspended or dissolved mass within the effluent (e.g., turbidity, or organic matter). When the mass of organic matter in the effluent is incorporated into the equation, the loading rate is referred to as the organic loading rate. The organic loading rate is a measure of the mass of organic matter applied to a specific unit area. This mass is often calculated from the BOD_5 which is a measure of the amount of oxygen needed to degrade the organic matter over a period of five days. The organic loading rate is therefore expressed as kg BOD_5 /ha per day. SubWet can be used to predict treatment levels for the effluents based on alterations to the aerial loading rates.

C) **Assessing size of treatment area**: SubWet can also be used as a predictive tool to help managers determine the size of wetland needed to meet treatment objectives. This will assist managers in determining if the current wetland size can accommodate projected growth in population and anticipated effluent volumes. SubWet can also be used to predict treatment performance anticipated from alterations to the size of the treatment area that could be accomplished through the construction of infiltration / dispersion ditches and structures that divert flow to other parts of the wetland that are not currently involved in treatment of the effluent, but could be if flows were diverted to these areas.

D) **Existing and future potential of wetlands**: SubWet can be used by resource managers to demonstrate the current treatment benefit acquired from the use of individual wetlands and can also be used as a predictive tool to forecast the potential these areas could provide. This will help resource managers in cost benefit analysis when planning for future needs.

Model Components:

The model is composed of the following components:

1. **Design parameters**: these numeric values describe basic features of the wetland in terms of its length, width, depth, hydraulic conductivity and others features which will physically define the wetland. The SubWet model uses these numeric values to generate wetland features such as areal size, wetland void volume and recommended flow rates.

2. **Forcing Functions**: dictate specific parameters the model is to work within. For example, forcing functions set the number of days the model is to simulate, the initial water quality parameters of the effluent entering the wetland, anticipated oxygen levels throughout the length of the wetland and the calculated water volume of the wetland and the retention time in one box (RTB). The Forcing functions input window allows the user to adjust the concentration of the water quality parameters anywhere within the simulated period (e.g., number of days the model simulates), thus allowing adjustments to be made to reflect changing effluent concentrations over defined periods of time.

3. **Initial values**: refers to the initial values the user defines for each of the five boxes (RTB). Note: that these values in the first box are generally chosen to reflect values that are slightly less than the water quality parameters of the effluent entering the wetland. The values chosen for Box 5 (last one) are generally slightly elevated above the water quality parameter concentrations measured exiting the wetland or reflective of the desired target concentrations. Boxes 2, 3, and 4 represent intermediate values between Box 1 and Box 5 that are reflective of a stepwise reduction. It should also be noted that it is not necessary to acquire great accuracy when choosing these values

when running the model to steady state. Greater precision in the choice of values entered into each of the five boxes will reduce the amplitude of the fluctuations in the early days of the simulation, but will have little influence on the final steady state values determined by the model, even if Boxes B, C, D, and E all contained the same value as Box A.

4. **Parameters**: refer to the rate constants (coefficients) required by the differential equations that SubWet uses to model wetland processes. The range for each coefficient has been identified from published literature and is summarized in the SubWet model and can be viewed by moving the cursor overtop of the bracketed parameter short form within this window (e.g., the short form for the nitrification rate is "NC"). Default parameters (coefficients) have been determined for "Cold Climate" wetlands and a different set of default parameters has been determined for "Warm Climate" wetlands. It should be noted that both cold climate and warm climate default parameters fall within the normal range that is summarized within the SubWet model. The parameters are used to calibrate the SubWet model to cold or warm climates and can even be used to refine the calibration of the SubWet model to individual sites. Basic knowledge of wetland processes, particularly concerning the organic carbon cycle and the nitrogen cycle are needed in order to understand the interplay between these two processes and how to best adjust the corresponding coefficient parameters for greater model calibration.

5. **Simulation**: model outputs allows the users to generate the predicted outcomes for biochemical oxygen demand (BOD_5), nitrate (NO_3^-), ammonium (NH_4^+), total phosphorus (TP) and organic nitrogen (Org-N). The graphs generated for these values can be expressed as a concentration (mg/L) or as a percent (%) removal. The graphs can also display predicted (simulated) results against observed (measured) results and in this way provide an indication of the overall accuracy of the simulated (modeled) results.

Operation of the SubWet 2.0 Model

The following provides a step-by-step overview of the basic operation of the SubWet model. In this section, data generated from the natural tundra wetland utilized by the community of Chesterfield Inlet, Nunavut will be used as a case study to illustrate how the SubWet model can be applied. The Chesterfield Inlet data set can be loaded into SubWet – see below under Section 2: Initial Screen.

1. System requirements and loading of software

SubWet 2.0 is designed to work on a MS Window platform of MS Windows 98 version or higher. This program will automatically install under the directory of Program Files in Windows by following the automatic instruction procedure. SubWet can be directly executed from the Setup file on the CD if the installation does not occur automatically. After the instillation, you can run the program from the start menu in the programs folder. The first window to present is illustrated in Figure 1 below.

A list of nine additional support documents in a PDF format will also be uploaded onto the hard drive of your computer into the same program folder that houses the SubWet program. These support documents cover a wide range of topics dealing with the operation of SubWet to background information on modelling concepts, methods and definitions.

2. Initial Screen

The initial screen showing upon startup of the SubWet model is illustrated in Figure F-1. This screen will allow the user to define the initial settings of the model. The word "File" is located in the top left hand corner of this window. Moving the cursor to this word will display a drop down menu that will allow the following options to be chosen:

a) *New Project*: clears any previously entered or stored data set and prepares the model to receive new data
b) *Save Project*: this function will allow you to save current values into a data set that can be later retrieved and modified

c) *Load Project*: this function will allow you to retrieve and load previously saved data sets
d) *Print Options*: will allow you to print your data set in either a tabular or graphical format
e) *Close Project*: will close the SubWet the currently loaded data set. You will be asked if you would like to save your project if you have not already done this
f) *Exit*: will close the SubWet program

Note: the data files for Chesterfield Inlet and Baker Lake are used in this manual to illustrate the operation of SubWet. These files can be loaded into SubWet via the "load project" option identified above and by choosing the data base you would like to enter. These files are being provided along with the electronic version of this manual. The names of the data files are:

Chesterfield Inlet: **chesterfield.mdl**
Baker Lake: **baker.mdl**

Figure E-1: Initial access window for SubWet 2.0

In addition to the above selections, the user will be asked to decide if SubWet is to be run with either the Cold Climate default parameters or the Warm Climate default parameters. For the purpose of this model, cold climate is defined as sites with temperatures varying between 0°C and up to 22°C in summer; subsurface water temperatures is always above freezing in winter (except in extremely high latitudes where wetlands may freeze in winter, e.g., above 60 degrees North). Warm climate areas are those which typically range in temperatures between 26°C to 34°C.

3. Design window

The next window to appear after making the choice for the Cold Climate or Warm Climate mode will be the design window as illustrated in Figure E-2. The white blank boxes on the left hand side of this window identify specific information about the wetland that is needed to run this program. The information request refers to the physical dimensions of the wetland (width, length and depth of soil matrix) along with

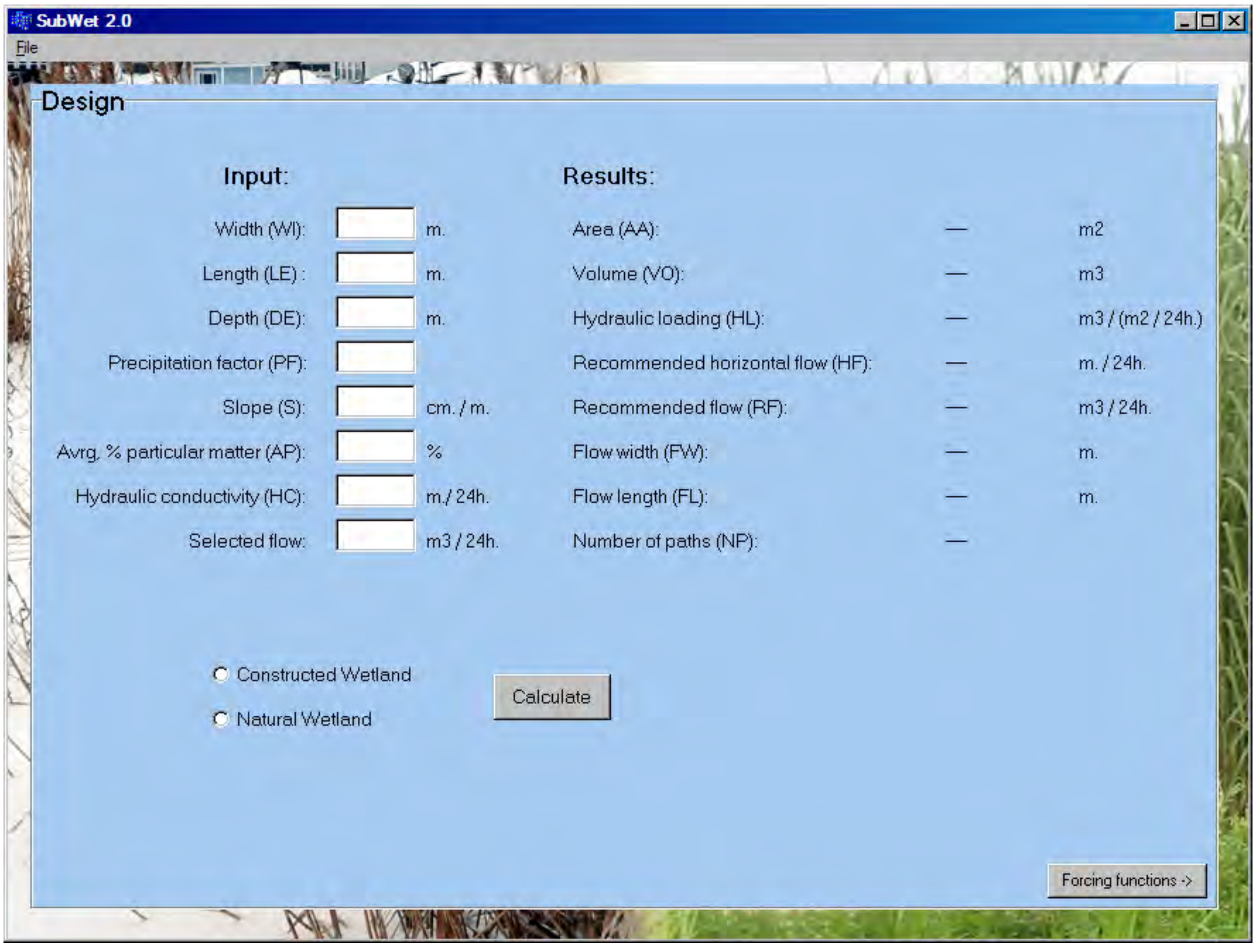


Figure E-2: The design window prior to inputting the information requested under "Input" column on the left hand side.

information regarding precipitation, slope, the percent particulate matter of the effluent being treated, the hydraulic conductivity of the soil matrix and the anticipated flow (volume of effluent entering the wetland on a daily basis). Once these values are entered, you will need to choose to run the simulation for either a constructed wetland or a natural wetland. The next step is then to click on the calculate button which will then generate values for the "Result" section located on the right hand side of this window. The choice between constructed wetlands and natural wetlands will influence the result parameters (e.g., recommended horizontal flow (HF), flow width (FW) and number of paths (NP)).

The SubWet model considers **constructed wetlands** to be man-made features designed with specific dimensions and often filled with crushed stone, gravel or sand as the wetland's subsurface matrix and vegetated with either cattails (*Typha*) or reeds (*Phragmites*), however a variety of species besides the two listed can be used. Because of the artificial substrate, SubWet makes the assumption that the percent particulate matter (AP) within the effluent entering the wetland will be the controlling factor regulating the speed which the effluent travels through the subsurface matrix. SubWet refers to this rate as the "Recommended Horizontal Flow (HF)". To determine the HF, SubWet uses the empirical formula HF = 25 – (8*AP). So for example, if the percent particulate matter is 3% then the HF would equal 1 m / 24h [e.g., 25 – (8*3) = 1 m / 24h].

SubWet defines **natural wetlands** as depressions or lowlands vegetated with water tolerant plant species; most often grasses, sedges and cattails. Natural wetlands do not have well defined borders and often have soil matrixes of varying depths with variable hydraulic conductivities. Although flow volume, flow paths and flow speeds through the natural wetlands are often difficult to estimate, SubWet still requires an estimate of the hydraulic conductivity of the soil matrix. An estimate of the hydraulic conductivity (HC) is particularly important for operation of the SubWet model since the model assumes that HC will be the factor that limits the rate at which the effluent travels through the subsurface matrix of natural wetlands. Therefore, in the design window (Figure E-2 above), SubWet always makes the Recommended Horizontal Flow (HF) automatically equal to the Hydraulic Conductivity (HC) and does not utilize the empirical formula employed when using the constructed wetland mode.

Data gathered from the Chesterfield Inlet wetland, Nunavut was used as an example of a low lying arctic tundra (natural) wetland. Data generated from the Chesterfield wetland was entered into the SubWet design window and the results calculated from this data set are illustrated in the "Results" section on the right hand side of Figure E-3.

Figure E-3: Input of Chesterfield data set along with calculated results.

The Chesterfield Inlet was chosen for illustrative purposes since the effluent entering this natural wetland was similar to the average composition for most municipal effluents and because the wastewater chemistry of the treated effluent exiting the Chesterfield wetland was also similar to the wastewater parameters commonly achieved by conventional municipal wastewater treatment facilities.

Areal size of wetland: the length (LE) and width (WI) input parameters of the design window were used to determine the areal size (AA) of the wetland in square meters. Determining this value for constructed wetlands is straight forward and often produces fairly accurate size estimates. However, natural wetlands are often irregular in shape which makes determination of the wetland size challenging and less precise. The user will need to estimate the average length and average width of the natural wetland with the acceptance that it will be challenging to obtain the same level of precision that can be achieved for constructed wetlands. In fact, this is one limitation when applying SubWet to a natural wetland. However, it must be remembered, that most mathematical models such as SubWet can at best only provide an estimate of treatment, meaning that a 15 to 20% plus or minus error is often considered acceptable. If the user has access to other georeferencing data that can be used to generate a more accurate estimate of wetland size, then this area estimate could be used to better determine what width and length measurements would generate the area (AA) output that more accurately reflects the georeferenced wetland size estimate. For example if the wetland area was determined (from georeferencing) to be closer to 57174 m^2, then the average width might be closer to 78 m and the corresponding length to 733 m (e.g., 78 m * 733 m = 57174 m^2).

Wetland depth (DE): refers to the depth of the soil matrix which is occupied by the roots of the vegetative cover. In constructed wetlands planted with cattails and reeds the active rooted zone often ranges between 0.5 to 1.2 metres below the surface. In natural wetlands or marshes, the depth of the active rooted zone may be shallower and closer to 0.25 to 0.6 m in depth. Tundra wetlands from Arctic regions often have shallow soils that are underline by bedrock or permafrost and thus the active rooted zone is often 0.3 m or less in depth.

Precipitation factor (PF): SubWet allows the user to adjust for the influence of precipitation. The amount of new "clean" water entering the wetland from precipitation events can lower the overall strength of the wastewater through the process of dilution. This can be particularly important for some warm climate areas known to have rainy and dry seasons. In northern tundra wetlands, the primary precipitation event is often related to spring freshet associated with the rapid melt of snow and ice that accumulated over the winter season.

The application of the precipitation factor in warm climate areas is relatively straight forward. Precipitation and evapotranspiration are often similar and thus the net effect is minor since each cancels out the influence of the other. In cases where the two cancel each other out, the net effect is that the wastewater is not diluted by precipitation and the precipitation factor is 1.0. In warm climate areas (e.g., tropical regions) the rainy season may have precipitation that averages 60 mm per month, while the evapotranspiration is only 30 mm per month. As an example, the precipitation factor can be calculated in a hypothetical wetland of 1 ha in size which receives wastewater at an inflow rate of 50 m^3/24h with a wetland hydraulic retention time of 10 days. If this hypothetical wetland received 60 mm of rain per month while losses through evapotransporation were only 30 mm per month then this would mean that the net increase in water from precipitation would be 30 mm per month (i.e., 60 – 30 = 30 mm new water). Converting the 30 mm to metres equals 0.03 m. Applying a precipitation depth of 0.03 metres over the area of 10,000 m^2 (i.e., 1 ha) means that the total volume of new water from precipitation is 0.03 m * 10,000 m^2 = 300 m^3 per month (i.e., 30 days) or 100 m^3 per 10 day period. In other words the 500 m^3 of waste water which is in the wetland during these ten days would be diluted a factor of (500+100)/ 500 = 1.2. In many cases a precipitation factor of 1.0 can be applied as an appropriate approximation since precipitation is usually not much greater than the evapotranspiration, and even in this example, where the precipitation is twice the evapotranspiration, the factor is only 1.2.

Care should be taken when applying the precipitation factor since each time you apply this factor (e.g., click on the hot button for this factor – located at the bottom of the forcing function window) the concentration of effluent parameters (e.g., BOD_5, nitrate, ammonium, total phosphorus, organic nitrogen, POM, PON, POP) are divided by the value of the precipitation factor. For example, if the precipitation factor is equal to 2, all effluent parameters mentioned above are divided by 2 with the result that the concentration shown in the forcing function window will be half of its original value. Note, if the precipitation factor is clicked on a second time, then the values will be halved again, resulting in a concentration one quarter of the initial value. So, each time the precipitation factor is click on, it will divide the values in the forcing function window by the value of the precipitation factor. This means that if care is not taken and the precipitation factor is inadvertently clicked on more than once the values in the forcing function window will not be correct. It should also be noted that this division occurs only in row one (e.g., Day 1 values), thus you will need to apply the precipitation factor **after** you have entered Day 1 values, but **before** you populate the remaining days by clicking on the "fill empty days" hot button located on the bottom of the forcing function window. If by chance you have already clicked on the "fill empty days" hot button and have populated all days, then the best way to handle this is to click on the "reset grid" hot button and by doing so remove the data in all cells (including day 1) and re-enter day 1 values and then click on the "apply precipitation factor" hot button and once done, click on the "fill empty days" hot button to repopulate the values for all remaining days.

Slope (S): is particularly important for natural wetlands since the flow rate is governed by gravity. The flow rate is however also governed by the hydraulic conductivity of the subsurface matrix. In natural wetlands, particularly in tundra wetlands, hydraulic conductivity can be quite low; more will be said about this later. The slope is expressed as a change in elevation per unit length; most often stated as cm/m and for most wetlands this value is between 0.5 and 5 cm/m.

% Particulate matter (AP): refers to the percentage of particulate matter within the effluent. In most wetlands (constructed and natural) the percent particulate matter of the effluent should be below 2.5% to avoid plugging of the pore spaces within the subsurface matrix. This can be easily accomplished by ensuring the raw wastewater receives some form of treatment prior to its discharge into the wetland. This is often accomplished by the containment of the effluent within sewage lagoons where settable solids have a chance to fall out of solution. In cases where the AP > 2.5% the empirical equation (25-8*AP) m/24h can be used to estimate the upper limit of the horizontal flow rate. For example, if the %AP is 3% then the expected flow rate would be 25 - (8*3) = 1 m / 24h.

Hydraulic conductivity (HC): provides a measure of how rapidly the effluent can travel through the subsurface horizon. In constructed wetlands gravel or sand are often used as the soil matrix. The hydraulic conductivity, HC, of both of these materials is often very high and can reach rates as high as 10 m /24h. Natural wetlands often have a much lower HC. This is an important factor because the capacity of natural wetlands is often limited by HC. The capacity of natural wetlands can be estimated by the formula HC*S (as cm/m)*DE*WI m^3 / 24 h

Selected flow (SF): refers to the volume of wastewater entering the wetland per 24 hour period (e.g., m^3/24h).

Area (AA): is calculated as width (WI) * length (LE) and expressed in m^2.
Example: 69.4 m * 720 m = 49968 m^2.

Volume (VO): of the wetland is calculated as width (WI) * length (LE) * depth (DE) and expressed in m^3. Example: 69.4 m * 720 m * 0.3 m = 14990.4 m^3.

Hydraulic loading (HL): is calculated as HL = SF / AA = m^3 per 24 h / m^2.
Example: 36 m^3 / 24 h divided by 49968 m^2 = 0.0007 m / 24h.

Recommended horizontal flow (HF): in this Chesterfield Inlet example is limited by the low hydraulic conductivity and thus in this example the HF = HC = 2.4 m / 24h. Note, that for natural wetlands, the HF always equals HC.

The HF should also consider the influence of precipitation, particularly in constructed wetlands where HC is not a limiting factor. In wetlands were HC does not limit the HF, the HF can be calculated as PF * SF = RF. Example: 1.0 * 36 m^3 / 24 h = 36 m^3 / 24 h.

Note however, that in constructed wetlands the recommended horizontal flow is calculated using the empirical formula: (25-8*AP) m/24h when the percent particulate matter is greater than 2.5%.

Recommended flow (RF): The recommended flow is calculated as the selected flow (e.g., the daily volume of effluent entering the wetland in m^3/24h) multiplied by the precipitation factor (PF). If the precipitation factor is equal to 1.0, then the recommended flow (RF) is equal to the selected flow (SF) as shown in the following equation: RF = SF * PF or RF = SF * 1.0 which means that RF = SF. If however, the PF is greater than 1.0, then RF will just be the value of SF * AP. You will notice in the Design window that a new RF value will be calculated each time the precipitation factor is changed and the “Calculate” hot button (located at bottom centre of this window) is clicked. SubWet uses the calculated RF value in subsequent calculations internal to the model.

Flow Width (FW): is calculated as RF / (HC * S * DE). Example 36 (2.4*0.6*0.3) = 83.3 m. NOTE: that the FW is greater than the width of the wetland (WI) which is only 69.4 m wide. This width (69.4 m) would have a flow capacity less than the selected flow of 36 m^3/24h (ex. 69.4*2.4*0.6*0.3 = 30 m^3/24h). The SubWet model can in cases where the FW < SF accommodate for this condition by substituting the width with the length and the length with the width. In this way, the WI now becomes 720 m and the LE becomes 69.4 m. The program therefore chooses the length as the width and width as the length in cases were:

If WI > FW, FW is made to equal WI and FL is made to equal LE,

If WI < FW, FW is made equal to LE and FL is made to equal WI

Number of flow paths (NP): for natural wetlands the recommended number of flow paths is 1. However, the number of flow paths determined by SubWet can vary with constructed wetlands. SubWet will automatically generate the appropriate number of flow paths based on the parameter values entered into the "Design" window.

Once all the input parameters have been entered, the choice between constructed or natural wetlands made and the calculate button pressed, then the user is ready to move to the next window (forcing functions) by clicking on the "forcing functions" hot button located at the bottom right hand side of the Design window.

4. Forcing Functions window

The data entered into the forcing function window establishes the key conditions operative within SubWet program for a particular wetland. For example, these conditions dictate the number of simulations the model will perform (e.g., number of simulated days), the volume of effluent the wetland can physically hold (e.g., void space), and key water quality parameters of the effluent entering the wetland. The data entered (or generated) within this window will be used by SubWet to determine modeled treatment outcomes. The various parameters identified in the forcing functions window, as illustrated in Figure E-4 will be discussed below.

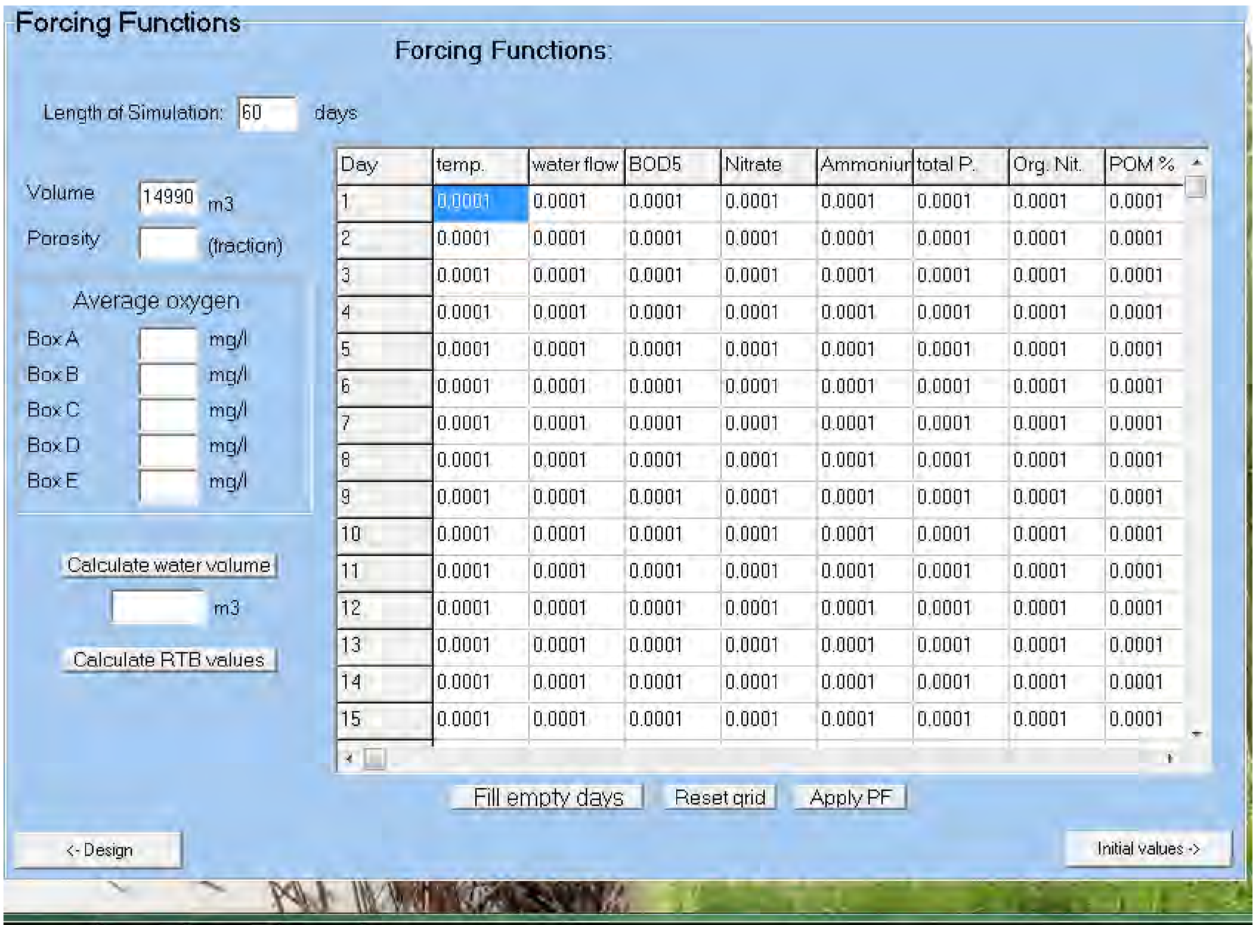


Figure E-4: The forcing function window prior to data entry. (note, not all columns are shown in this illustration. Figures E-5a and E-5b provide a more complete overview of all columns)

Volume (m^3): You will find that SubWet automatically fills this box with the wetland volume determined in the previous "Design" window. In the Chesterfield Inlet example, the value of 14,990.4 m^3 calculated in the "Design" window has been automatically carried forward to this window (Forcing Function). The value of 14990.4 m^3 is an estimate of the wetland volume determined by multiplying the average wetland width (WI = 69.4m) by length (LE = 720 m) by depth (DE = 0.3m).

Porosity (fraction): note the user will need to supply this value as a fraction. For example if the porosity is 27.5%, then the value will be entered as 0.275. SubWet requires this value in order to calculate the actual volume of effluent the wetland can hold within the void spaces of the subsurface matrix. This void space calculation is performed by SubWet when the user clicks on the hot button called "Calculate water volume".

Calculate water volume (m^3): as mentioned above, the SubWet program will calculate this value by multiplying the wetland volume (m^3) value by the porosity value. For example: 14990.4 m^3 * 0.275 = 4122.36 m^3. This calculation is accomplished by clicking on the hot button identified as "Calculate water volume".

Water Flow: This refers to the "Selected Flow" value which reflects the daily volume of effluent entering the wetland. In the Chesterfield Inlet example the wetland receives a total of 36 m^3 per day (24h). This value needs to be carried forward manually by the user and placed into the corresponding white blank input cell located in the central portion of the "Forcing functions" window (Note: this corresponds to the second column from the left). This value needs to be inputted before the RTB (e.g., retention time in one box) calculation can be made by SubWet. See RTB below for more detail.

Calculate RTB values (days): This hot button will calculate the retention time the effluent is expected to reside in one box of the wetland. The SubWet program divides all wetlands into five (5) boxes of equal size. The program assumes the effluent will travel sequentially from the first to the second and ultimately to the fifth box of the wetland. SubWet employs a modified "Tank in Series dispersion Model" to reflect that the effluent does not travel through the wetland as plug flow. SubWet has assumed that a total of five tanks in series best reflect the conditions within wetlands (both natural and constructed). SubWet sets the number of boxes (tanks) to "5" for pragmatic reasons. A higher number of boxes would require a more sophisticated modeling approach that currently offered by SubWet, and yet a lower value would yield less accurate results. Thus setting SubWet to run with 5 boxes is a tradeoff between the requirements for greater model complexity ease of use, while maintaining acceptable accuracy. The value for the "water flow" (see above) needs to be filled in before the RTB can be calculated.

Once the water flow value has been entered, clicking on the Calculate RTB values hot button will generate the RTB which will be automatically posted by SubWet in the eleventh (11th) and last column of white input boxes in the centre of the Forcing functions window. The RTB is therefore a product of the "calculated water volume" (see above) and the "water flow" (see above). The RTB reflects a hydraulic retention time for each of the five individual boxes within SubWet. For example, in the Chesterfield Inlet example, the wetland has the capacity (e.g., water volume) to hold 4122.36 m^3 of effluent. The time needed (e.g., hydraulic retention time) to exchange this volume with an inflow of 36 m^3/24h is 4122.36 m^3 / 36 m^3/24h = 114.5 days. If the wetland capacity was hypothetically divided into five equal volumes then the number of days the effluent would reside within one of the five boxes would be 114.5 / 5 = 22.9 days, the same value generated by SubWet for the retention time in one box for the Chesterfield example.

Length of Simulation (days): The user is required to enter the number of days they want to simulate. It is important to choose a value that is larger than the hydraulic retention time of the entire wetland. In the Chesterfield Inlet example this would mean that the length of simulation must be greater than 114.5 day and in practice it appears that the value required for the simulation is at least 275 days for the Chesterfield Inlet example. All values less than 275 produce an error message highlighted in RED font stating "Warning: simulation length too small to accommodate the current RTB values". The goal is to choose a simulation length that will allow the model to reach a steady state condition where the output values are more or less stable and vary little from one day to the next. It will be important to allow the model to reach a steady state condition in order to allow SubWet to generate the most precise estimate possible. You will notice the importance of this since in the early days of the simulation (e.g., prior to reaching steady state) the output values fluctuate widely. Once steady state is reached, the wide fluctuations are reduced significantly.

Average Oxygen: The five boxes located on the left hand side of the forcing functions window need to be filled by the user. Once again, SubWet has divided the wetland into five boxes (compartments) of equal size and the user is to place into Boxes A to E the oxygen concentrations they believe are representative for each of the five wetland compartments (boxes). The oxygen concentration in each of the five wetland compartments is an important consideration since many of the transformation processes, such as nitrification (ammonium is oxidized to nitrate) and the decomposition of organic matter (expressed as BOD_5 concentration) require oxygen in order to proceed and if the supply of oxygen is not sufficient, the rate of the process may decrease. The most accurate way to determine the oxygen concentration is to measure oxygen in the field at a location that represents the mid depth point of the wetland. For example, if the substrate of the wetland is 0.3 m deep, then take your oxygen measurement at a depth of 0.15 m.

However, it may not always be practical or possible to directly measure the oxygen concentration within the wetland and in these situations a general rule of thumb is to assume the oxygen concentration is between 70 to 90 percent saturation. In the Chesterfield Inlet example, the temperature of the wetland is 7.48 °C which means that the oxygen concentration at saturation (determined from reference charts) would be approximately 12 mg/L and thus a value of 10 mg/L seems reasonable. Also note, that in most cases it is expected that the oxygen concentration will be suppressed in the first couple of boxes closes to where the effluents enters the wetland. It is at this "front end" location that one would expect nitrification and the decomposition of organic matter to be the greatest, since the ammonium and organic matter concentration of the effluent will be the greatest at this location. Oxygen concentrations are expected to increase as the concentration of ammonium and organic matter decreases as the effluent travels through the wetland. The estimation of the oxygen concentrations should take into consideration the "strength" of the effluent entering the wetland. In some examples, such as the effluent from Baker Lake, Nunavut, the effluent strength is very high and as such the predicted oxygen concentrations were much lower than 70% saturation. The Baker Lake data, along with the predicted oxygen concentrations are illustrated late in this manual (see Figure E-26a).

Forcing function Parameters: This refers to the blank boxes (cells) located in the center of the forcing function window. The parameters included are temperature, BOD_5, nitrate, ammonium, etc. The values entered in these boxes (with the exception of "water flow" and "RTB") refer to the measured (or anticipated) concentrations within the effluent entering the wetland. The concentration may not be known for some parameters such as organic nitrogen (Org. Nit.). In situations such as this, the analytical detection limit should be entered to avoid leaving the cell blank or placing in a value of zero which in either case would cause problems for the operation of the SubWet model.

Once these values are placed into row one (e.g., Day 1) of the input cells, the user will need to determine if they wish to apply a precipitation factor. If it is desirable to apply a PF, this is accomplished by clicking on the hot button "*Apply PF*" located at the bottom of the Forcing function window. NOTE: it will be important to apply the PF prior to populating the remaining cells since the PF will only alter row 1 (e.g., day 1 values). If all cells are populated before applying the PF, then only Day 1 (e.g., row one) will be altered. However, if the PF is applied before the remaining days (rows) are populated, then once row one values (e.g., Day 1) are altered, clicking on the hot button "*fill empty days*" will populate all cells with the Day 1 values altered by the PF. The PF basically reduces the original concentration of the effluent values entered into Day 1 cells. For example, a PF = 2 will divide the effluent wastewater quality parameters (BOD, Nitrate, Ammonium, Phosphorus, Org. Nit., POM%, PON%, POP%) by a factor of two and thus all values will be halved.

BOD_5: biochemical oxygen demand (5 day). Note this includes the oxygen demand occurring from the oxidation of both organic matter and nitrification ($cBOD_5$ equals BOD_5 minus the oxygen demand associated with nitrification). In units of O_2 consumed per litre

Nitrate: NO_3^- in mg/L

Ammonium: NH_4^+ in mg/L

Total Phosphorous: in mg/L

Organic Nitrogen: equal to TKN minus the concentration of ammonia (NH_3) and ammonium (NH_4^+)

POM%: Percent particulate organic matter. This is calculated by determining the dry weight of the suspended material filtered from a 1 L volume of effluent. The POM% is determined as the percentage of the dried material lost after ignition at 550 °C for a 1 hour period.

PON%: Percent organic nitrogen. This is the percentage of organic nitrogen that is associated with the suspended material filtered from a 1 L volume of effluent.

POP%: Percent phosphorus that is associated with the suspended material filtered from a 1 L volume of effluent.

Figures E-5a and E-5b below illustrate the "forcing functions" window completed with the data from the Chesterfield Inlet example (case study).

Once all the input parameters have been entered and the cells populated the user is ready to move to the next window (Initial values) by clicking on the "Initial values" hot button located at the bottom right hand side of the Forcing Functions window.

5. Initial values window

The user is required to provide estimated concentration values for the 5 day biochemical oxygen demand (BOD_5), nitrate (NIT), ammonium (AMM), total phosphorus (TPO), and organic nitrogen (ORN). As in previous windows, SubWet has divided the wetland into 5 equal compartments or boxes and has identified these boxes with the suffix of A, B, C, D, and E. The program consists of 25 differential equations and each equation requires an initial value, hence the 25 cells requiring a value in the "Initial values" window. The values chosen should exhibit a step wise reduction through Boxes A to E for each of the water quality parameters being modeled. The value of Box A should be slightly lower than the corresponding concentration for that water quality parameter stipulated in the previous “Forcing Functions” window. The value in Box E should be slightly higher than the desired or anticipated concentration expected to be achieved as the effluent exits the wetland. If the length of the simulation chosen (in the Chesterfield example, this was 600 days as chosen on the “Forcing Function” window) is long enough to reach a steady state,

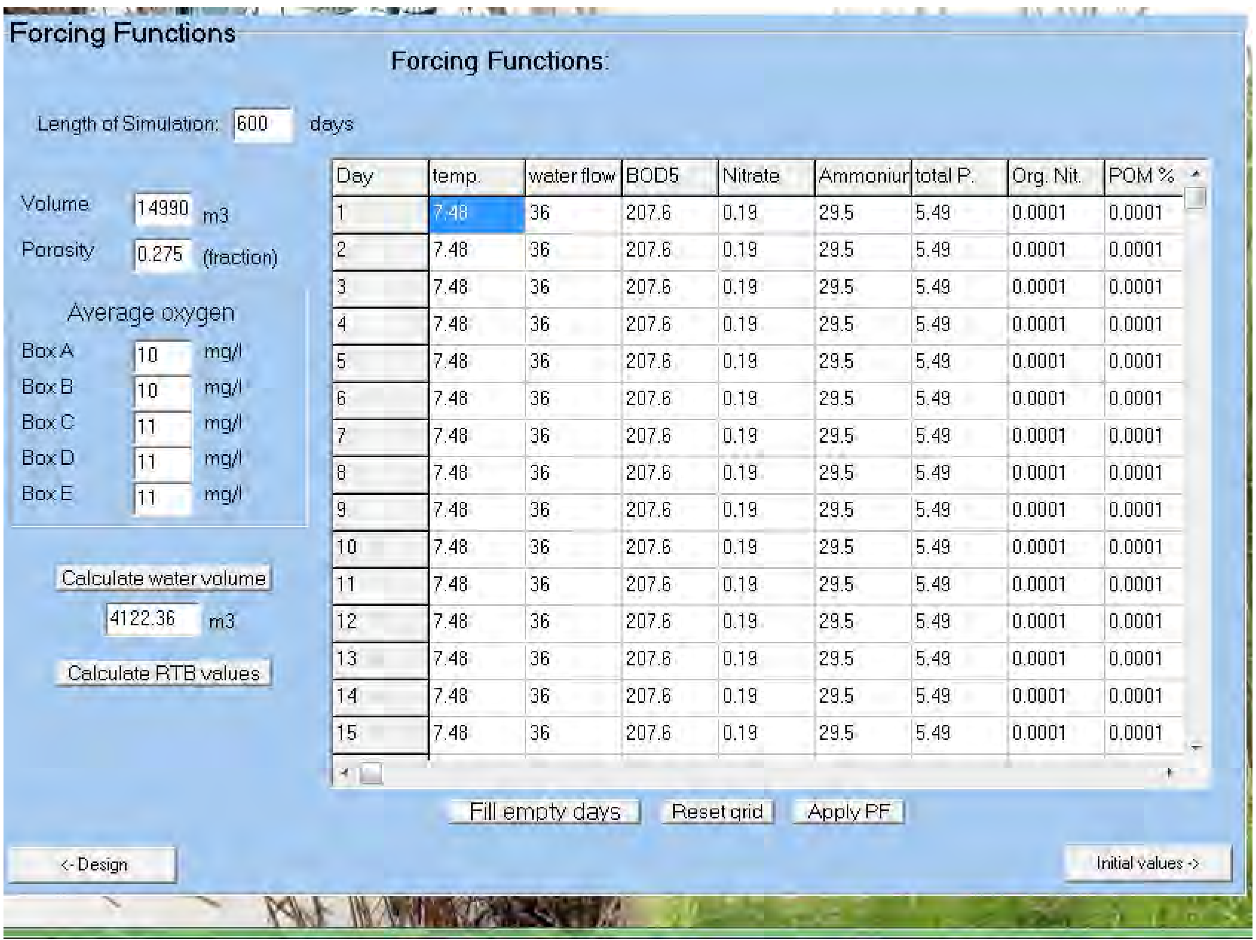


Figure E-5a: The forcing function window containing data from Chesterfield Inlet. All 600 days (not all shown) have been populated by clicking on the “fill empty days” hot button located at the bottom of the window. The precision only influences results prior to reaching a steady state condition. More will be discussed about this aspect in later case study examples. The initial values chosen for the Chesterfield Inlet example are illustrated in Figure E-6.

then the *initial values* of these water quality parameters does not need to be precise. Greater precision in the choice of these initial values will result in a reduction (dampening) in the amplitude of the fluctuations (oscillations) observed in the early portion of the simulated days prior to reaching a steady state value. Less precision in these values will result in greater fluctuations, however, neither of these conditions (large or small fluctuations) influence the final steady state concentration calculated by SubWet.

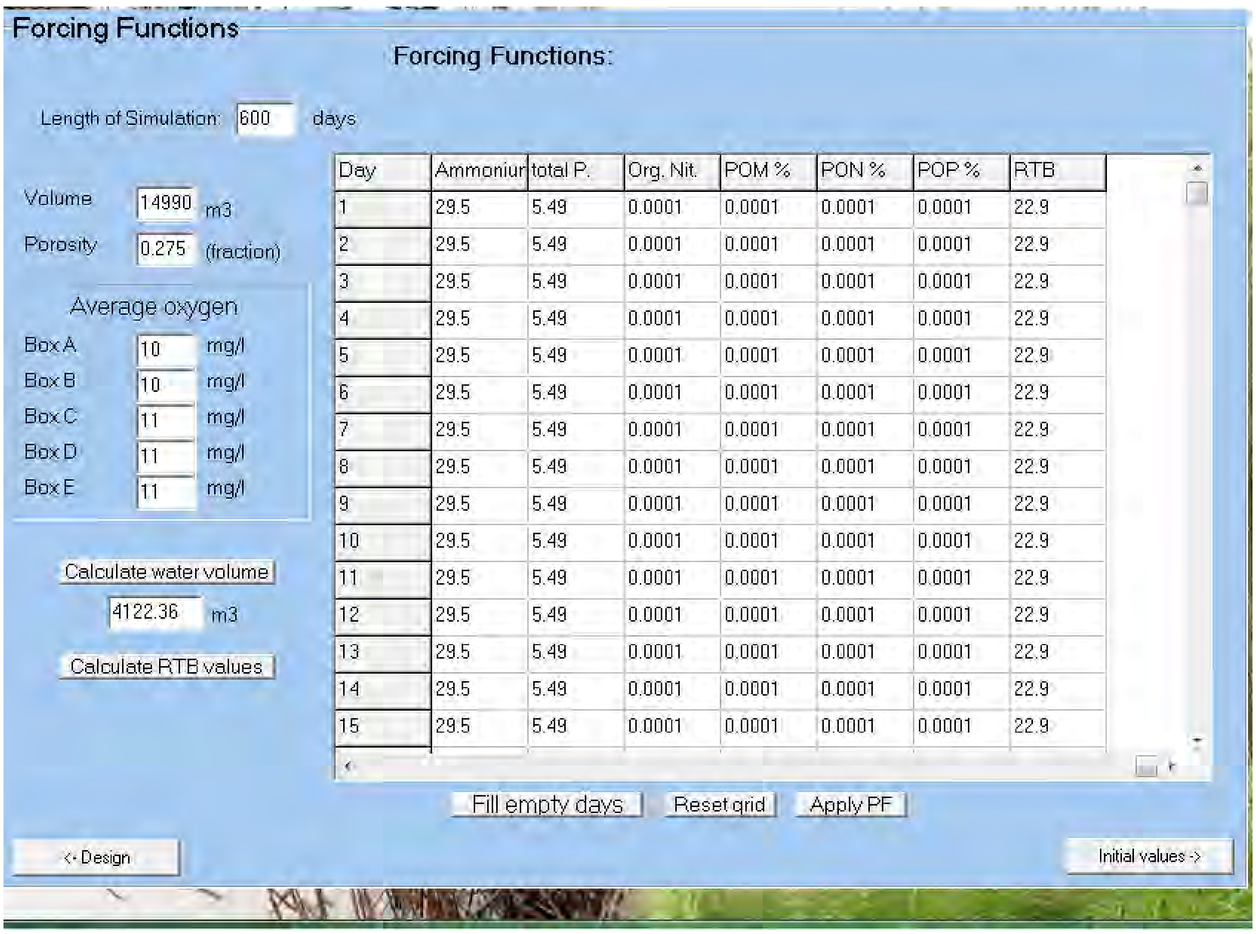


Figure E-5b: The forcing function window containing data from Chesterfield Inlet. This figure illustrates the right hand columns that could not be shown on Figure E-5a.

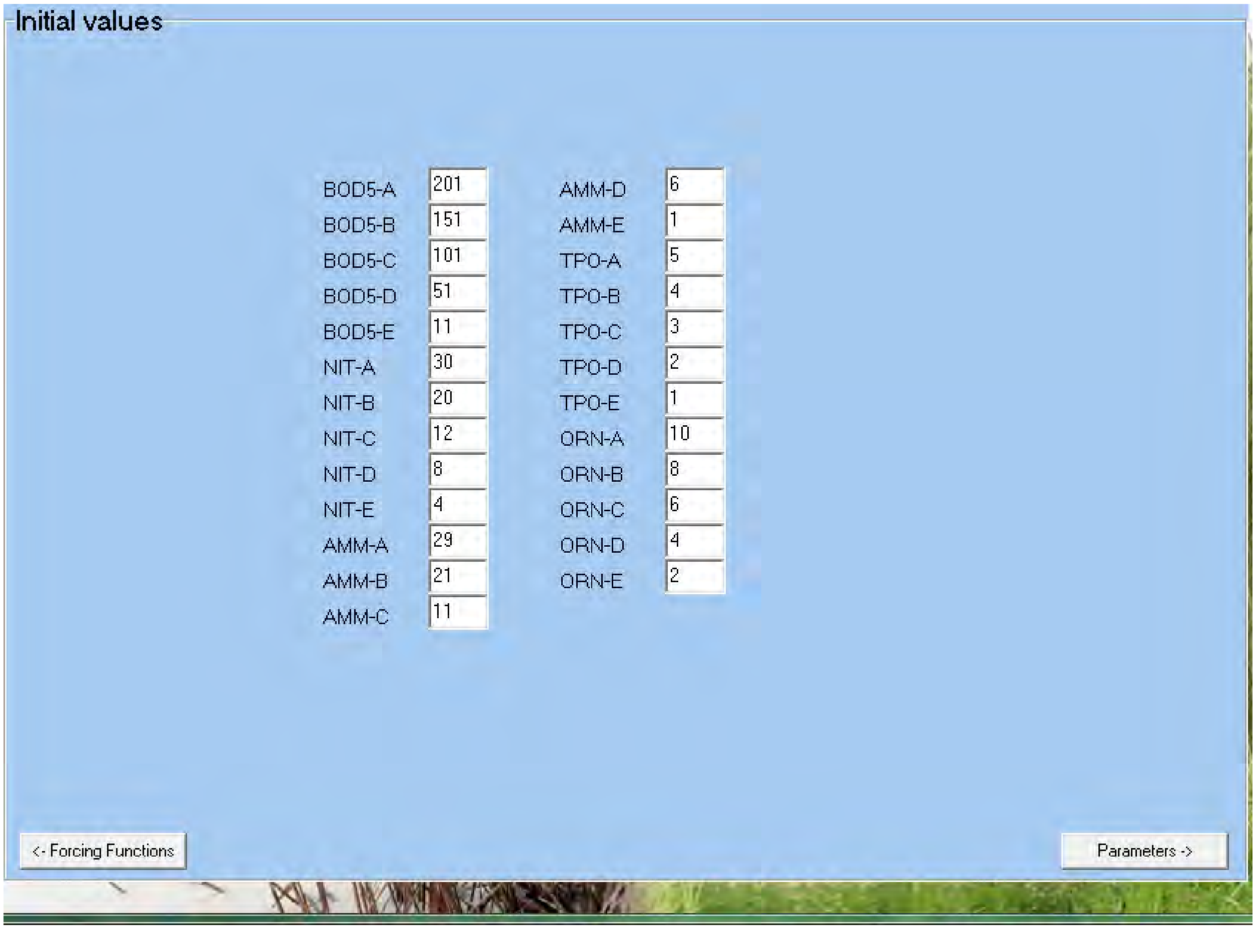


Figure E-6: Initial values for the Chesterfield Inlet example

> ***Once the initial values have been entered the user is ready to move to the next window (Parameters) by clicking on the "Parameters" hot button located at the bottom right hand side of the Initial Values window.***

6. Parameters Window

The Parameters window is where the user selects the rate coefficients utilized by the differential equations of the SubWet model. The values selected in this window are very important for the correct operation of SubWet and can also be used to calibrate the model to site specific wetlands. By moving the cursor over top of the bracket abbreviation associated with a particular parameter, the user will be able to see the appropriate range for that individual coefficient. For example, the coefficient's range for the "Max. decomposition rate for organic nitrogen (AC)" is 0.05 to 2.0. SubWet has been developed to model both cold and warm climate wetlands. This has been accomplished by determining the most appropriate coefficient value for operation as either a cold climate or a warm climate model for each parameter. As such, SubWet has been programmed with a specific set of cold climate default coefficient values and a specific set of warm climate default coefficient values. The choice to operate SubWet in a cold climate mode or a warm climate mode will dictate which of the two default (cold or warm) sets will be used. These values can be used to calibrate SubWet to an individual wetland by comparing the simulated treatment values (i.e., water quality parameters exiting the wetland) to the measured values for that particular wetland. Slight modifications to specific coefficient values will often improve the simulation by making the simulated output values closer to the measured values. More about the calibration of SubWet will be provided later in this overview. Figure E-7: Illustrates the coefficient values placed into the parameter window for the Chesterfield Inlet example.

Table E-1 summarizes the cold climate default coefficient values and Table E-2 lists the warm climate default coefficient values.

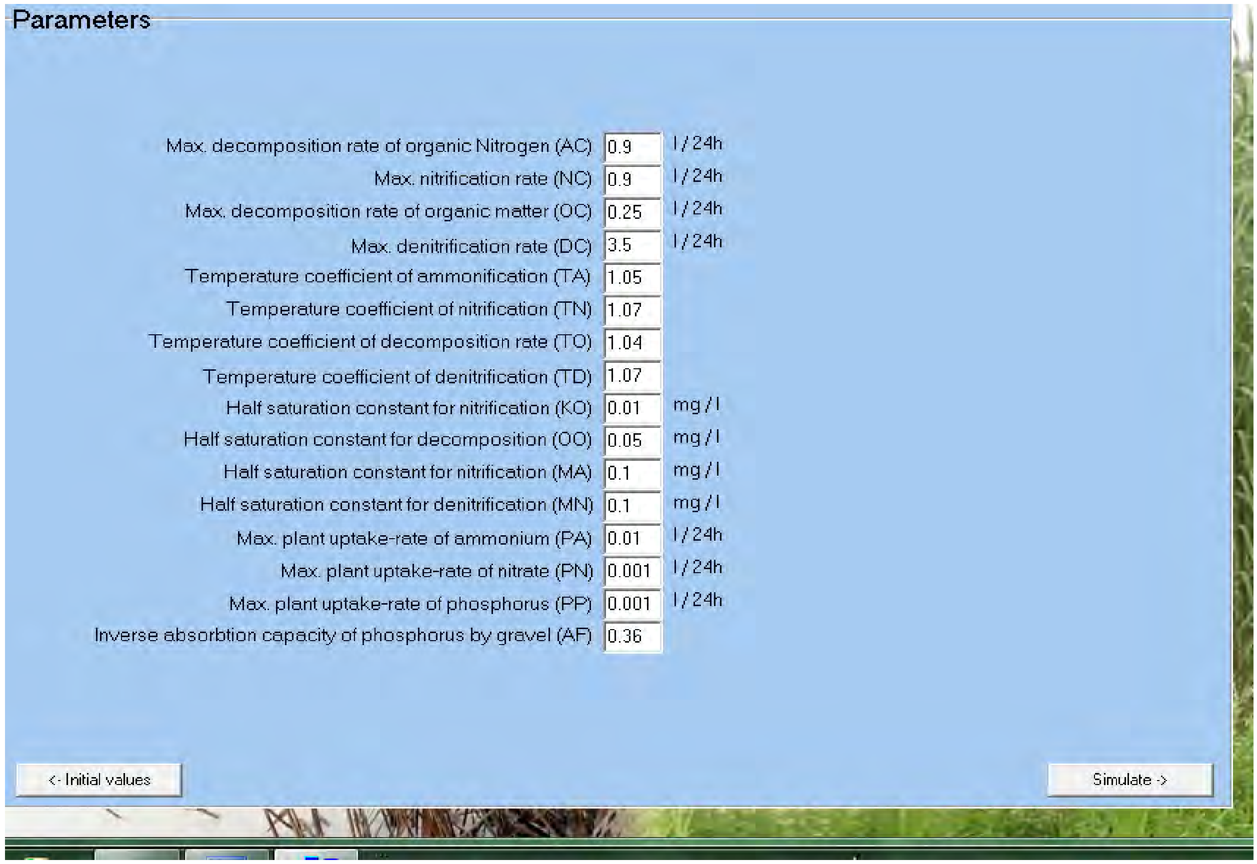


Figure E-7: Coefficient values for the Chesterfield Inlet example. Note: the values represented in this illustration are the default values for operation in the cold climate mode.

Table E-1: The default coefficient values for the operation of SubWet in a cold climate mode.

- AC = 0.05- 2.0 [default value 0.9 (1/24h)]
- NC = 0.1- 2.5 [default value 0.9 (1/24h)]
- OC = 0.05- 2.0 [default value 0.25 (1/24h)]
- DC = 0.00-5 [default value 3.5 (1/24h)]
- TA = 1.02- 1.06 [default value 1.05 (no unit)]
- TN = 1.02- 1.09 [default value 1.07 (no unit)]
- TO = 1.02- 1.06 [default value 1.04 (no unit)]

- TD = 1.05- 1.12 [default value 1.07 (no unit)]
- KO = 0.1-2 [default value 0.01 (mg/l)]
- OO = 0.1-2 [default value 0.05 (mg/l)]
- MA = 0.05-2 [default value 0.1 (mg/l)]
- MN= 0.01-1 [default value 0.1 (mg/l)]
- PA= 0.00-1 [default value 0.01 (1/24h)]
- PN=0.00-1 [default value 0.001 (1/24h)]
- PP= 0.00-1 [default value 0.001 (1/24h)]
- AF= 0-100 [default value 0.36]

Table E-2: The default coefficient values for the operation of SubWet in a warm climate mode.

- AC = 0.05- 2.0 [default value 0.5 (1/24h)]
- NC = 0.1- 2.5 [default value 0.8 (1/24h)]
- OC = 0.05- 2.0 [default value 0.5 (1/24h)]
- DC = 0.00-5 [default value 2.2 (1/24h)]
- TA = 1.02- 1.06 [default value 1.04 (no unit)]
- TN = 1.02- 1.09 [default value 1.047 (no unit)]
- TO = 1.02- 1.06 [default value 1.04 (no unit)]
- TD = 1.05- 1.12 [default value 1.09 (no unit)]
- KO = 0.1-2 [default value 1.3 (mg/l)]
- OO = 0.1-2 [default value 1.3 (mg/l)]
- MA = 0.05-2 [default value 1 (mg/l)]
- MN= 0.01-1 [default value 0.1 (mg/l)]
- PA= 0.00-1 [default value 0.01 (1/24h)]
- PN=0.00-1 [default value 0.01 (1/24h)]
- PP= 0.00-1 [default value 0.003 (1/24h)]
- AF= 0-100 [default value 1]

Once the parameter values have been entered the user is ready to move to the next window (Simulate) by clicking on the "Simulate" hot button located at the bottom right hand side of the Parameters window.

7. Simulate window

By now, all SubWet input values specific to the wetland being modeled should be entered. Once completed, the "Simulate" window can be used to run the SubWet simulations. SubWet models the decomposition of organic matter, expressed as BOD_5, the loss of nitrogen compounds in the form of nitrate, ammonium and organic nitrogen and the loss of total phosphorus from the effluent stream. In summary, SubWet models the changes in:

- BOD_5
- Nitrate
- Ammonium
- Total Phosphorus
- Organic Nitrogen

The simulated changes are expressed as either a predicted concentration for the treated effluent or as a percent removal which compares the concentration entering the wetland and the concentration exiting the wetland and expresses this as a percent change.

The simulated outputs are expressed in a graphical form that models predicted changes in the parameter over the length of the simulation. The simulated values are expressed in the colour RED. For comparative purposes, the observed (measured) values can also be represented on the same graph to allow users to visually see how closely the simulated values represent the true measured values. This however, can only be done if measured values exist. The advantage in making the comparison between simulated and measured values is that it provides an assessment as to how accurate the simulated values are. If the difference is greater than 20%, the user may want to adjust the coefficient values (Parameter window) through a trial and error approach in an attempt to determine if the simulated values can be modelled more closely to the measured values. In most cases this operation will improve the calibration of SubWet to individual wetlands and thus enhance the overall predictive capacity of the model. More will be discussed on how to calibrate SubWet in later sections of this manual.

The observed values can also be used to provide a visual expression of the difference between the simulated values and the desired treatment concentrations the user is hoping the wetland will achieve. In this situation, the desired or targeted values are placed into the "observed values" data sheet instead of the measured values.

Step Time: The user will need to set the step time prior to running any simulation. The step time is the number of iterations SubWet will make for each day simulated. For example if a step time of 70 is chosen, the SubWet will make 70 iterations for each calculation for each of the simulation days. For the Chesterfield Inlet example, the simulation length is 600 days, thus 70 iterations will be made for each of the 600 days. The program operates quickly and therefore it is recommended to choose a step time that is between 50 and 100 to ensure a proper numerical integration. Once completed the simulation can be performed by clicking on the hot button called "Simulate" that is located at the bottom of the simulate window.

Simulate: The simulate hot button can be clicked on once the step time has been entered. This will cause the program to execute all simulations. Viewing the simulated values can be accomplished on one of two ways: graphically and a tabulation of individual parameter values for each day of the simulation run.

Data Sheet: Clicking on the hot button called "data sheet" opens a table that contains the numeric values for each of the parameters for each day of the simulation length. This will provide the user with a specific numeric value for any parameter for any day. Note: it is these values (e.g., Data sheet) that are depicted graphically, not the additional values listed below.

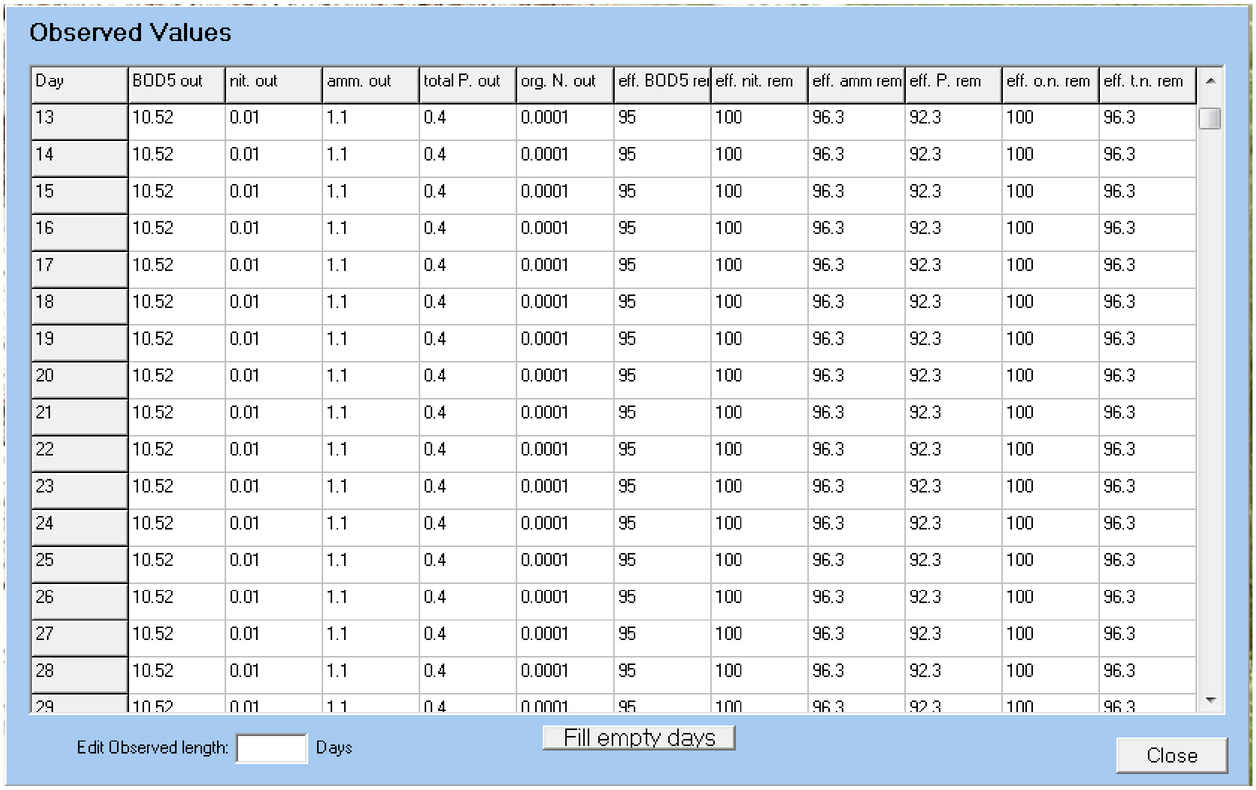
Additional Values: The additional values hot button is located on the bottom left hand side of the Simulate window. Once clicked on, a table of results will appear. This table is similar to the Data sheet values outlined above, with the addition that this table contains the numeric values for each modeled parameter for each of the five boxes (compartments) that the wetland has been divided into by the SubWet program. This will allow the user to view how each parameters behaves as the effluent travels from box A (first) to E (last).

Graphical: In most circumstances users will likely chose the graphical representations of the simulated data. The graphical displays are accessed by clicking on desired hot buttons on the left hand side of the simulate window (under the heading "Graph"). The "Y-axis max value" allows the user to set the maximum Y-axis value in order to ensure the corresponding graph can be viewed at the correct scale. For example, if the Y-axis value is set at 100, but the output value is 5, then it may be more appropriate to view the graphical output with a Y-axis maximum value set closer to 10. This value will likely need to be adjusted when changing between different simulated output graphs. While the user may wish to change the Y-axis value when moving between simulated graphs, there is no need to click on the simulation hot button when moving from one simulated graph to another, unless the step time is changed or some other input value is changed on previous windows such as a modification of the coefficient values on the Parameter window.

Observed values: as previously mentioned, the user may wish to have the measured or desired water quality parameters illustrated on the same graph as the simulated values. Once again, the simulated values are represented RED coloured line, while the observed values are represented BLUE line. In order to illustrate both simulated and measured on the same graph, two things need to occur. First, the user needs to input the measured values. This can be accomplished by clicking on the "Observed values" hot button located underneath the hot button called additional results on the bottom left hand side of the Simulate window. This will open a table similar to the data sheet table mentioned above, but different in that the table will be devoid of any values. The user can populate the table with either measured values, or desired (target) values. In most cases this is often accomplished by manually filling in row 1 (e.g., day 1) values. Once done, the "fill empty days" hot button located at the bottom of the table can be used to copy these values into all remaining days. Using the Chesterfield Inlet example, the simulation length is 600 day; this action will fill in all remaining 599 days. By entering the observed data in this manner, the graphical expression of this data will be a straight horizontal blue line that depicts the numeric value for the particular parameter being graphed. There will be no fluctuations in the graphical expression of this data since all values remain constant over the enter number of simulated days. If however, the user has measured data over multiple days of the simulation period then this data can be entered and the "fill empty day" function can be used to fill in the intervening days were data does not exist. In order for the simulated and observed data to be illustrated on the same graph, the box “show observed values on graphs” needs to be clicked on.

Illustrative Examples for the Simulate Window using the Chesterfield Inlet example

Observed Values: Figure E-8 illustrates the observed values for Chesterfield Inlet. Notice that not all 600 simulation days are shown and also note that the “Edit Observed length” box should be filled with the value of 600 days for this data set. This value will ensue that all 600 days will be evident in this table within the SubWet program. Notice that you will need to manually calculate the value for the percent removal (e.g., eff. BOD_5 rem). In the case of BOD_5 this is calculated by subtracting the final BOD_5 concentration exiting the wetland from the initial BOD_5 concentration entering the wetland and then dividing by the initial BOD_5 concentration (e.g., ((207.6 mg/L – 10.52 mg/L) / 207.6 mg/L) * 100 = 95% removal). The percent removal for nitrate, ammonium, phosphorus, organic nitrogen and total nitrogen can be calculated in a similar manner. Total nitrogen is equal to the sum of ammonia (NH_3 + NH_4^-) plus organic nitrogen plus oxidized nitrogen (NO_2^- + NO_3^-). So, in Chesterfield this would equal [29.5 mg/L (ammonium) + 0.19 mg/L (nitrate)] – [1.1 (nitrate)] / [29.5 mg/L (ammonium) + 0.19 (nitrate)] * 100 = 96.3%.


Observed Values

Day	BOD5 out	nit. out	amm. out	total P. out	org. N. out	eff. BOD5 re	eff. nit. rem	eff. amm rem	eff. P. rem	eff. o.n. rem	eff. t.n. rem
13	10.52	0.01	1.1	0.4	0.0001	95	100	96.3	92.3	100	96.3
14	10.52	0.01	1.1	0.4	0.0001	95	100	96.3	92.3	100	96.3
15	10.52	0.01	1.1	0.4	0.0001	95	100	96.3	92.3	100	96.3
16	10.52	0.01	1.1	0.4	0.0001	95	100	96.3	92.3	100	96.3
17	10.52	0.01	1.1	0.4	0.0001	95	100	96.3	92.3	100	96.3
18	10.52	0.01	1.1	0.4	0.0001	95	100	96.3	92.3	100	96.3
19	10.52	0.01	1.1	0.4	0.0001	95	100	96.3	92.3	100	96.3
20	10.52	0.01	1.1	0.4	0.0001	95	100	96.3	92.3	100	96.3
21	10.52	0.01	1.1	0.4	0.0001	95	100	96.3	92.3	100	96.3
22	10.52	0.01	1.1	0.4	0.0001	95	100	96.3	92.3	100	96.3
23	10.52	0.01	1.1	0.4	0.0001	95	100	96.3	92.3	100	96.3
24	10.52	0.01	1.1	0.4	0.0001	95	100	96.3	92.3	100	96.3
25	10.52	0.01	1.1	0.4	0.0001	95	100	96.3	92.3	100	96.3
26	10.52	0.01	1.1	0.4	0.0001	95	100	96.3	92.3	100	96.3
27	10.52	0.01	1.1	0.4	0.0001	95	100	96.3	92.3	100	96.3
28	10.52	0.01	1.1	0.4	0.0001	95	100	96.3	92.3	100	96.3
29	10.52	0.01	1.1	0.4	0.0001	95	100	96.3	92.3	100	96.3

Edit Observed length: Days

Fill empty days

Close

Figure E-8: Observed values for the Chesterfield Inlet example

Additional Values: Figure E-9 illustrates the numeric values for each output parameter modeled for all 600 days of the Chesterfield Inlet example for Boxes A - E. Figure E-9 has been divided into three separate figures (e.g., E-9a, E-9b, E-9c) in order to illustrate all columns contained in this data set. It is useful to be able to view the predicted concentrations of the five parameters in all five boxes, as a means of illustrating where the removal processes are most effective in the wetland, and where they are less effective. It may be possible to apply such information to improve the overall removal efficiencies by imposed changes in the composition of the wastewater, or by changes of the wetland (e.g., addition of oxygen). The predicted concentrations in the boxes obtained with the model simulations are listed in a table for each day in the simulation period, as follows: BOD_5-A, BOD_5-B, BOD_5-C, BOD_5-D, BOD_5-E, NIT-A, NIT-B, NIT-C, NIT-D, NIT-E, AMM-A, AMM-B, AMM-C, AMM-D, AMM-E, TPO-A, TPO-B, TPO-C, TPO-D, TPO-E, ORN-A, ORN-B, ORN-C, ORN-D and ORN-E. These results of the simulations are shown for all 600 days.

Additional results

Day	BOD5-A	BOD5-B	BOD5-C	BOD5-D	BOD5-E	NIT-A	NIT-B	NIT-C	NIT-D	NIT-E	AMM-A
585	102.6743	53.4178	29.0831	16.3383	9.3469	0.5777	0.2487	0.1127	0.056	0.0301	9.9103
586	102.6743	53.4178	29.0832	16.3373	9.3514	0.5777	0.2487	0.1127	0.056	0.0301	9.9103
587	102.6743	53.4178	29.0833	16.3364	9.3557	0.5777	0.2487	0.1127	0.056	0.0301	9.9103
588	102.6743	53.4178	29.0834	16.3354	9.3597	0.5777	0.2487	0.1127	0.056	0.0301	9.9103
589	102.6743	53.4178	29.0835	16.3344	9.3635	0.5777	0.2487	0.1127	0.056	0.0301	9.9103
590	102.6743	53.4178	29.0837	16.3335	9.367	0.5777	0.2487	0.1127	0.056	0.0301	9.9103
591	102.6743	53.4178	29.0838	16.3325	9.3703	0.5777	0.2487	0.1127	0.056	0.0301	9.9103
592	102.6743	53.4178	29.0839	16.3316	9.3733	0.5777	0.2487	0.1127	0.056	0.0301	9.9103
593	102.6743	53.4178	29.084	16.3308	9.376	0.5777	0.2487	0.1127	0.056	0.0301	9.9103
594	102.6743	53.4177	29.0842	16.3299	9.3784	0.5777	0.2487	0.1127	0.056	0.0301	9.9103
595	102.6743	53.4177	29.0843	16.3291	9.3805	0.5777	0.2487	0.1127	0.056	0.0301	9.9103
596	102.6743	53.4177	29.0844	16.3284	9.3823	0.5777	0.2487	0.1127	0.056	0.0301	9.9103
597	102.6743	53.4177	29.0845	16.3276	9.3838	0.5777	0.2487	0.1127	0.056	0.0301	9.9103
598	102.6743	53.4177	29.0847	16.327	9.385	0.5777	0.2487	0.1127	0.056	0.0301	9.9103
599	102.6743	53.4177	29.0848	16.3263	9.386	0.5777	0.2487	0.1127	0.056	0.0301	9.9103
600	102.6743	53.4177	29.0849	16.3258	9.3866	0.5777	0.2487	0.1127	0.056	0.0301	9.9103

Close

Figure E-9a: Additional results for Chesterfield Inlet example

Additional results

Day	AMM-B	AMM-C	AMM-D	AMM-E	TPO-A	TPO-B	TPO-C	TPO-D	TPO-E	ORN-A	ORN-B
586	3.367	1.1788	0.4418	0.1859	1.5665	1.0305	0.767	0.5709	0.423	1E-8	1E-8
587	3.367	1.1788	0.4418	0.1859	1.5665	1.0305	0.767	0.5709	0.423	1E-8	1E-8
588	3.367	1.1788	0.4418	0.1859	1.5665	1.0305	0.767	0.5709	0.4229	1E-8	1E-8
589	3.367	1.1788	0.4418	0.1859	1.5665	1.0305	0.767	0.5709	0.4228	1E-8	1E-8
590	3.367	1.1788	0.4418	0.1859	1.5665	1.0305	0.767	0.571	0.4228	1E-8	1E-8
591	3.367	1.1788	0.4418	0.1859	1.5665	1.0305	0.767	0.571	0.4227	1E-8	0.0001
592	3.367	1.1788	0.4418	0.1859	1.5665	1.0305	0.767	0.571	0.4227	1E-8	0.0001
593	3.367	1.1788	0.4417	0.1859	1.5665	1.0305	0.767	0.571	0.4227	1E-8	1E-8
594	3.367	1.1788	0.4417	0.1859	1.5665	1.0305	0.767	0.571	0.4227	1E-8	1E-8
595	3.367	1.1788	0.4417	0.1859	1.5665	1.0305	0.767	0.571	0.4227	1E-8	1E-8
596	3.367	1.1788	0.4417	0.1859	1.5665	1.0305	0.767	0.571	0.4227	1E-8	1E-8
597	3.367	1.1788	0.4417	0.1859	1.5665	1.0305	0.767	0.571	0.4228	1E-8	1E-8
598	3.367	1.1788	0.4417	0.1859	1.5665	1.0305	0.767	0.571	0.4228	1E-8	0.0001
599	3.367	1.1788	0.4418	0.1859	1.5665	1.0305	0.767	0.571	0.4228	1E-8	0.0001
600	3.367	1.1788	0.4418	0.1859	1.5665	1.0305	0.767	0.571	0.4229	1E-8	1E-8

Close

Figure E-9b: Additional results for Chesterfield Inlet example (continued).

Additional results

Day	AMM-E	TPO-A	TPO-B	TPO-C	TPO-D	TPO-E	ORN-A	ORN-B	ORN-C	ORN-D	ORN-E
586	0.1859	1.5665	1.0305	0.767	0.5709	0.423	1E-8	1E-8	1E-8	1E-8	1E-8
587	0.1859	1.5665	1.0305	0.767	0.5709	0.423	1E-8	1E-8	1E-8	1E-8	1E-8
588	0.1859	1.5665	1.0305	0.767	0.5709	0.4229	1E-8	1E-8	1E-8	1E-8	1E-8
589	0.1859	1.5665	1.0305	0.767	0.5709	0.4228	1E-8	1E-8	1E-8	1E-8	1E-8
590	0.1859	1.5665	1.0305	0.767	0.571	0.4228	1E-8	1E-8	1E-8	1E-8	1E-8
591	0.1859	1.5665	1.0305	0.767	0.571	0.4227	1E-8	0.0001	1E-8	1E-8	1E-8
592	0.1859	1.5665	1.0305	0.767	0.571	0.4227	1E-8	0.0001	1E-8	1E-8	1E-8
593	0.1859	1.5665	1.0305	0.767	0.571	0.4227	1E-8	1E-8	1E-8	1E-8	1E-8
594	0.1859	1.5665	1.0305	0.767	0.571	0.4227	1E-8	1E-8	0.0001	1E-8	1E-8
595	0.1859	1.5665	1.0305	0.767	0.571	0.4227	1E-8	1E-8	0.0001	1E-8	1E-8
596	0.1859	1.5665	1.0305	0.767	0.571	0.4227	1E-8	1E-8	1E-8	1E-8	1E-8
597	0.1859	1.5665	1.0305	0.767	0.571	0.4228	1E-8	1E-8	1E-8	1E-8	1E-8
598	0.1859	1.5665	1.0305	0.767	0.571	0.4228	1E-8	0.0001	1E-8	1E-8	1E-8
599	0.1859	1.5665	1.0305	0.767	0.571	0.4228	1E-8	0.0001	1E-8	0.0001	1E-8
600	0.1859	1.5665	1.0305	0.767	0.571	0.4229	1E-8	1E-8	1E-8	1E-8	1E-8

Close

Figure E-9c: Additional results for Chesterfield Inlet example (continued).

Figure E-10 illustrates the graph of simulated BOD_5 concentrations predicted over the course of the 600 day simulation period. Notice that the observed or measured values for Chesterfield Inlet were determined to be 10.5 mg/L (blue line). These values are represented in a straight line since they represent an average concentration of BOD_5 exiting the Chesterfield Inlet wetland during the period it was studied. The steady state concentration of BOD_5 predicted (simulated) by the SubWet model at the end of the 600 day simulation is 9.2 mg/L. Note that the Y-axis has been set to a value of 20 to ensure the graphical scale is suitable to properly view the results. The difference between observed and simulated is approximately 13% which is an acceptable range for most modelling programs. Note that the BOD_5 values fluctuate wildly during the first portion of the simulation and eventually become less variable as the simulation approaches a steady state. The amplitude of the fluctuations is influence by the values chosen for the “Initial values” window. As stated previously, the magnitude of these fluctuations can be attenuated by modifying these initial values. However, the magnitude of the amplitudes becomes important only when trying to model treatment performance before steady state is achieved.

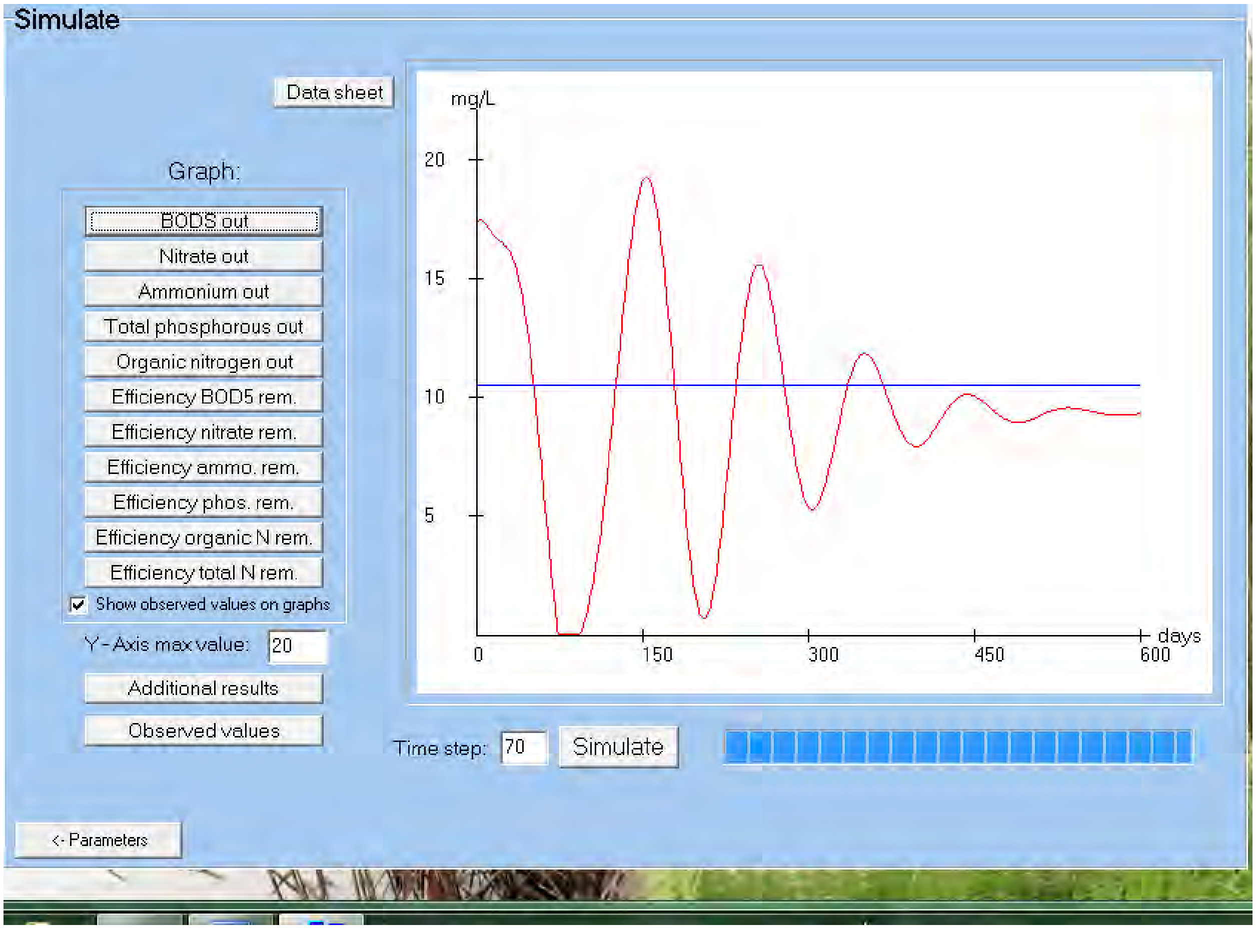


Figure E-10: BOD_5 results for Chesterfield Inlet expressed as a concentration in the final treated effluent exiting the wetland.

Figure E-11, compares the concentration of BOD_5 of the effluent entering the wetland to the BOD_5 concentration of the treated effluent exiting the wetland and expresses this comparison as a percent change (removal) in BOD_5. Notice that the high degree of agreement between the observed percent removal and the simulated percent removal. Note: in this example, the Y-axis has been set to a value of 100 to best accommodate the result which are close to a value of 95%.

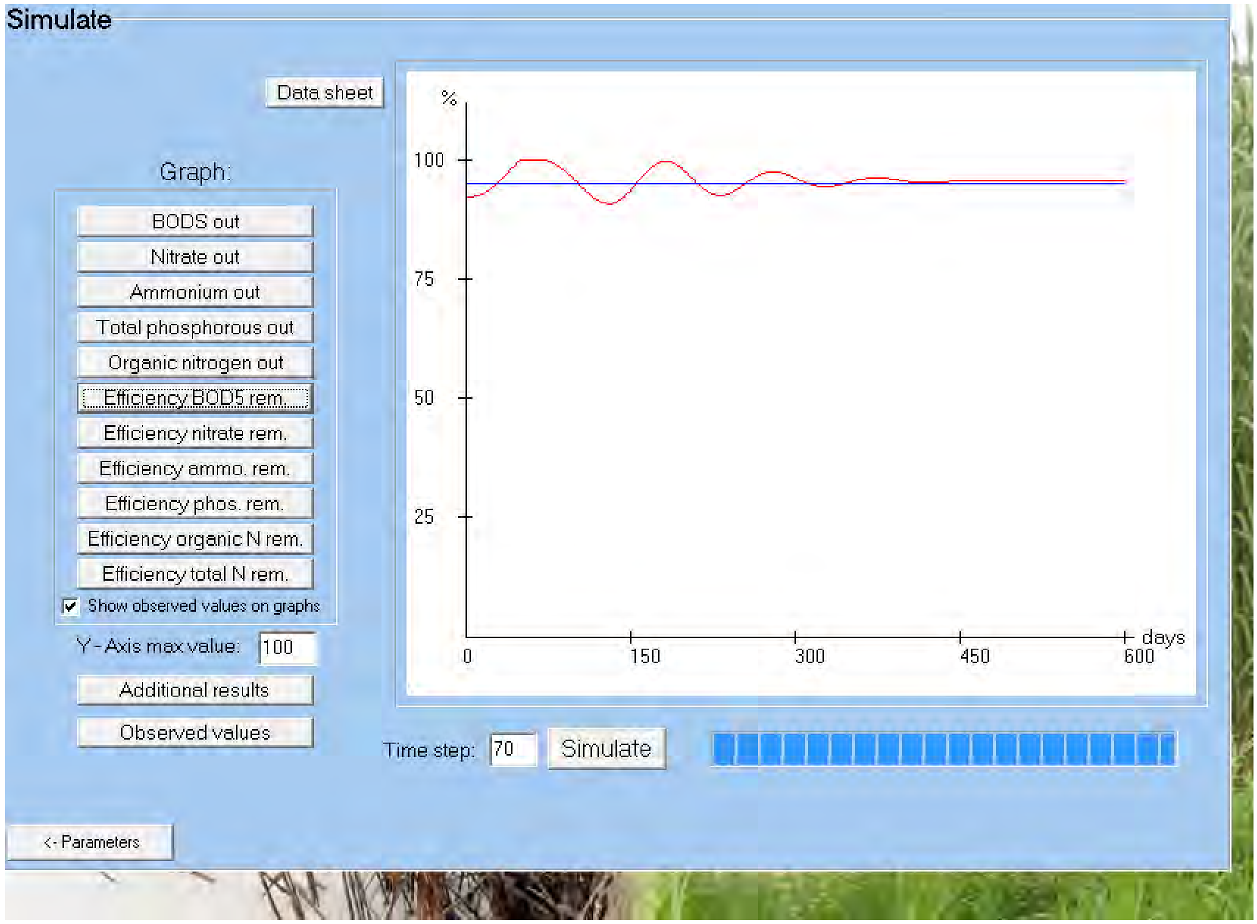


Figure E-11: A graphical comparison of the observed percent removal of BOD_5 to the simulated percent removal of BOD_5 using the Chesterfield Inlet example.

Nitrate, Ammonium, Total Phosphorus and Organic Nitrogen: all remaining parameters can be viewed in a manner similar to that used in the BOD_5 illustrations above.

Operating SubWet 2.0

The following section will provide insight into how SubWet can be expected to behave (perform) under varying conditions. This will be accomplished by addressing three basic questions:

a) *Initial Conditions*: How does the alteration of the initial conditions defined in the "Initial Values" window affect the simulated results?

b) *Forcing Functions*: How will changing effluent strength influence the simulated results and how can the ability to changes these values be used in a predictive manner to forecast the capacity of a wetland to achieve a desired level of treatment?

c) *Design values*: How will the treatment performance of the wetland vary when the dimensions of the wetland or the volume of effluent is altered? How can a change in design values be used to in a predictive manner to forecast the influence to wetland performance when these parameters are changed?

Initial Condition:

This next example is intended to demonstrate the importance of running the model to a steady state condition and to also indicate that the choice of the initial values will influence model results prior to a steady state condition but will ultimately have little impact on the simulated results once steady state is achieved.

In the Chesterfield Inlet example used previously, the selection of the initial values were chosen more or less randomly with the only intent that the value for Box A was slightly less than the parameter concentration (e.g., BOD_5) found in the effluent entering the wetland and the value chosen for Box E was slightly greater than the observed, anticipated or desired concentration of the parameter in the treated effluent exiting the wetland. The values initially chosen are illustrated in Figure E-12 and these values were used to generate the BOD_5 result shown in Figure E-13. Notice that the variability in the BOD_5 concentration was high prior to the model reaching steady state (e.g., day 1 to approx. day 450), and once steady state was reached the simulated BOD_5 concentration became fairly stable.

The magnitude in variability during the early days of the simulation can be lessened by choosing initial values that are a closer approximation to the concentrations expected to be in each of the five boxes. One way to do this is to run the simulation as normal, and then to replace the randomly chosen "Initial values" with the simulated values generated for the last day of the simulation (e.g., day 600) which are found in the "Additional Results" window (Figure E-14, NOTE: only the first 11 of the 25 rows are shown). The newly updated "initial values" are now shown in Figure E-15. Re-running the simulation with the newly chosen "initial values" produces BOD_5 concentrations that are less variable in the early days of the simulation run (Figure E-16). When comparing Figure E-13 to Figure E-16, you will notice that although the modification of the "initial values" resulted in less variability, it did little to change the final simulated concentration once SubWet reached a steady state condition. These findings are true for not only BOD_5 but for all other simulated parameter results. Therefore the choice of "initial values" will influence the variability in simulated results prior to the model reaching steady state but will have little influence on the final simulated results once the steady state is reached.

It should be noted that this refinement is needed only once and that repeating this step after the first time, does not further refine the final results.

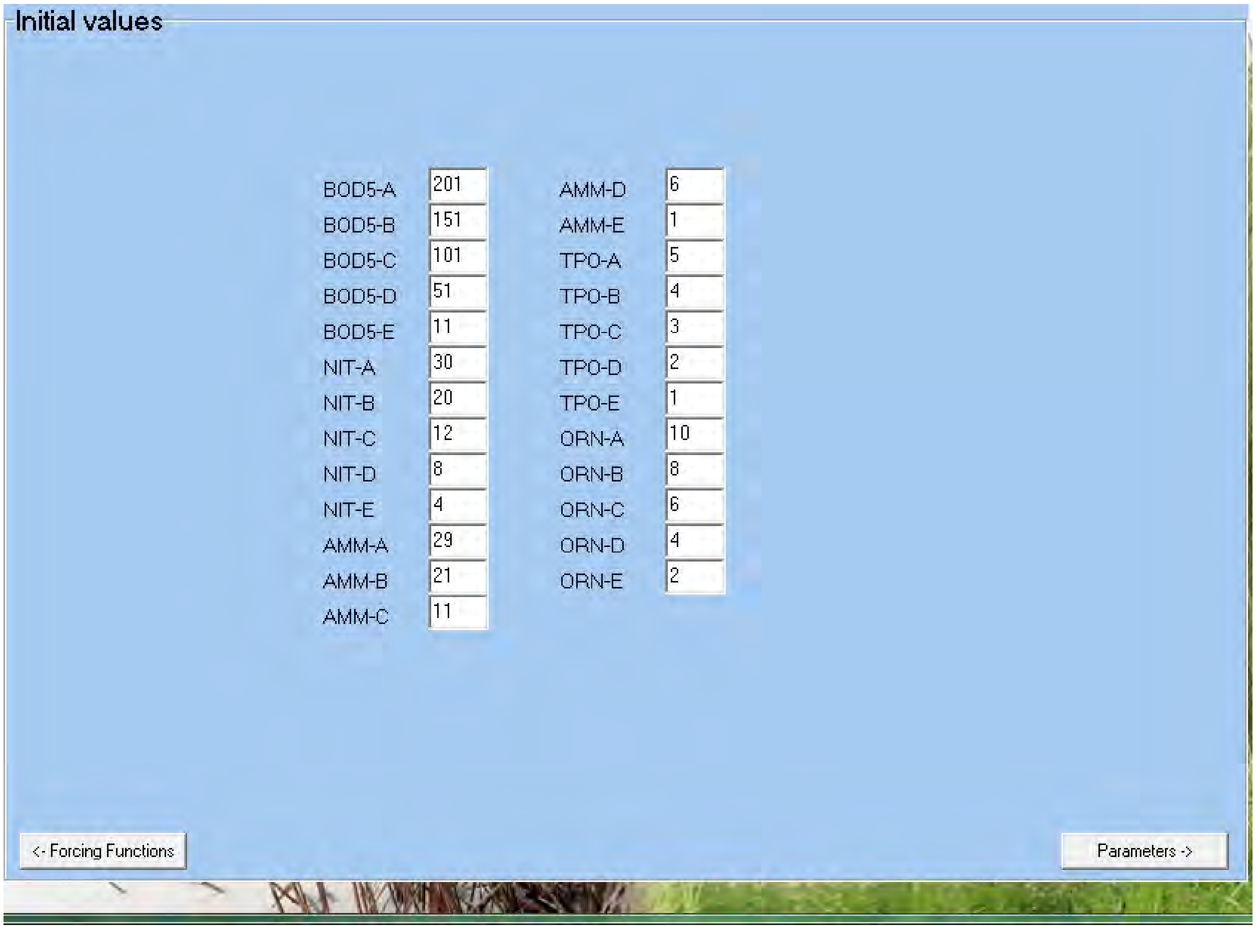


Figure E-12: Initial values chosen by a "best guess" method.

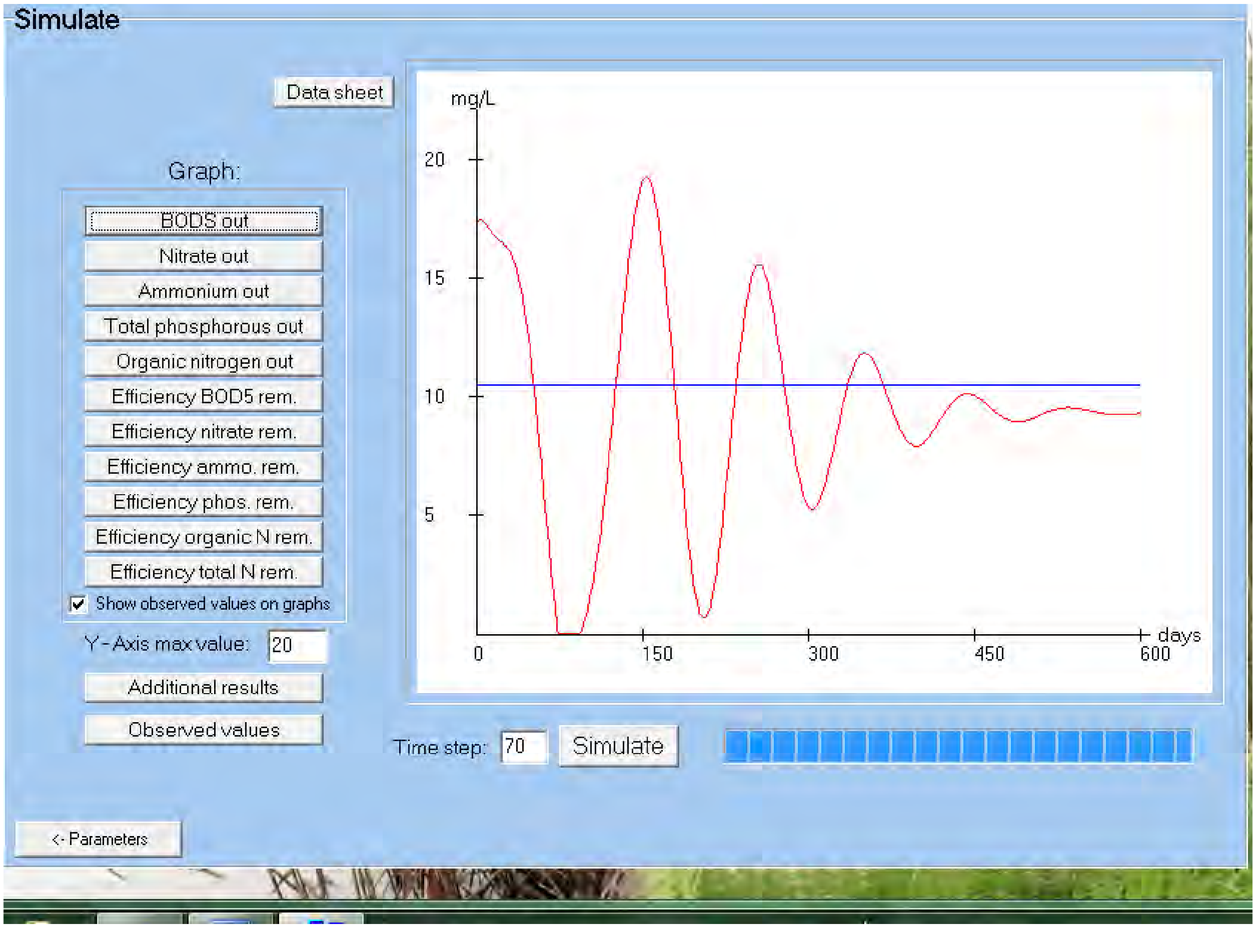


Figure E-13: Simulated BOD_5 values generated with Initial values chosen using a "best guess" method. Notice the high degree of variability prior to the model reaching steady state.

Additional results

Day	BOD5-A	BOD5-B	BOD5-C	BOD5-D	BOD5-E	NIT-A	NIT-B	NIT-C	NIT-D	NIT-E	AMM-A
585	102.6743	53.4178	29.0831	16.3383	9.3469	0.5777	0.2487	0.1127	0.056	0.0301	9.9103
586	102.6743	53.4178	29.0832	16.3373	9.3514	0.5777	0.2487	0.1127	0.056	0.0301	9.9103
587	102.6743	53.4178	29.0833	16.3364	9.3557	0.5777	0.2487	0.1127	0.056	0.0301	9.9103
588	102.6743	53.4178	29.0834	16.3354	9.3597	0.5777	0.2487	0.1127	0.056	0.0301	9.9103
589	102.6743	53.4178	29.0835	16.3344	9.3635	0.5777	0.2487	0.1127	0.056	0.0301	9.9103
590	102.6743	53.4178	29.0837	16.3335	9.367	0.5777	0.2487	0.1127	0.056	0.0301	9.9103
591	102.6743	53.4178	29.0838	16.3325	9.3703	0.5777	0.2487	0.1127	0.056	0.0301	9.9103
592	102.6743	53.4178	29.0839	16.3316	9.3733	0.5777	0.2487	0.1127	0.056	0.0301	9.9103
593	102.6743	53.4178	29.084	16.3308	9.376	0.5777	0.2487	0.1127	0.056	0.0301	9.9103
594	102.6743	53.4177	29.0842	16.3299	9.3784	0.5777	0.2487	0.1127	0.056	0.0301	9.9103
595	102.6743	53.4177	29.0843	16.3291	9.3805	0.5777	0.2487	0.1127	0.056	0.0301	9.9103
596	102.6743	53.4177	29.0844	16.3284	9.3823	0.5777	0.2487	0.1127	0.056	0.0301	9.9103
597	102.6743	53.4177	29.0845	16.3276	9.3838	0.5777	0.2487	0.1127	0.056	0.0301	9.9103
598	102.6743	53.4177	29.0847	16.327	9.385	0.5777	0.2487	0.1127	0.056	0.0301	9.9103
599	102.6743	53.4177	29.0848	16.3263	9.386	0.5777	0.2487	0.1127	0.056	0.0301	9.9103
600	102.6743	53.4177	29.0849	16.3258	9.3866	0.5777	0.2487	0.1127	0.056	0.0301	9.9103

Close

Figure E-14: The results shown for the last day of the simulation are in row 600. These are the values that should be used as the "Initial Values" for the purpose of reducing variability in the simulated results prior to the model reaching steady state. Note: this figure shows only the first 11 of 25 columns that can be seen in this window.

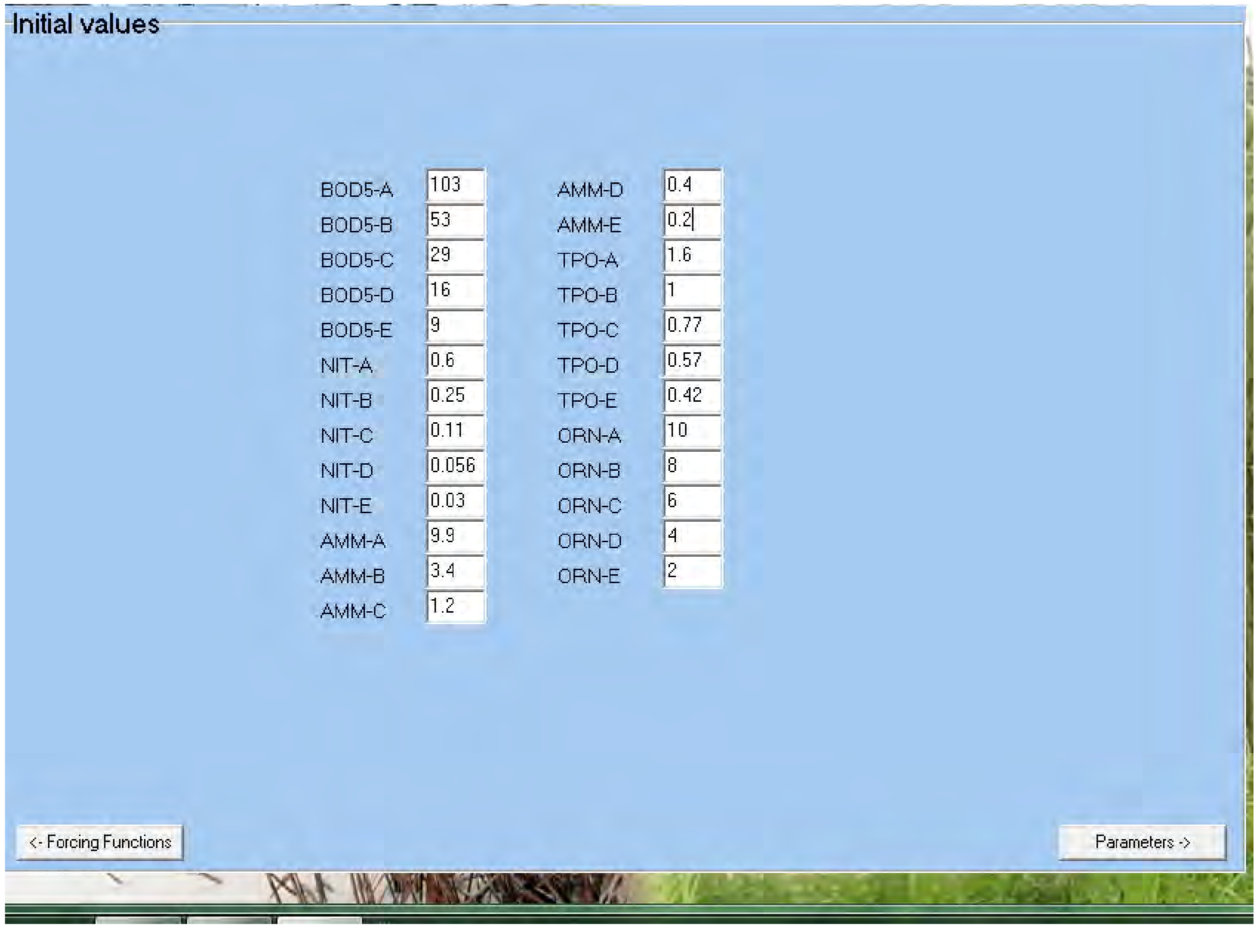


Figure E-15: Notice that the original initial values generated by a “best guess” method originally shown in Figure 12 have now been replaced with the values from the last day shown in the “Additional Results” window (see Figure E-14).

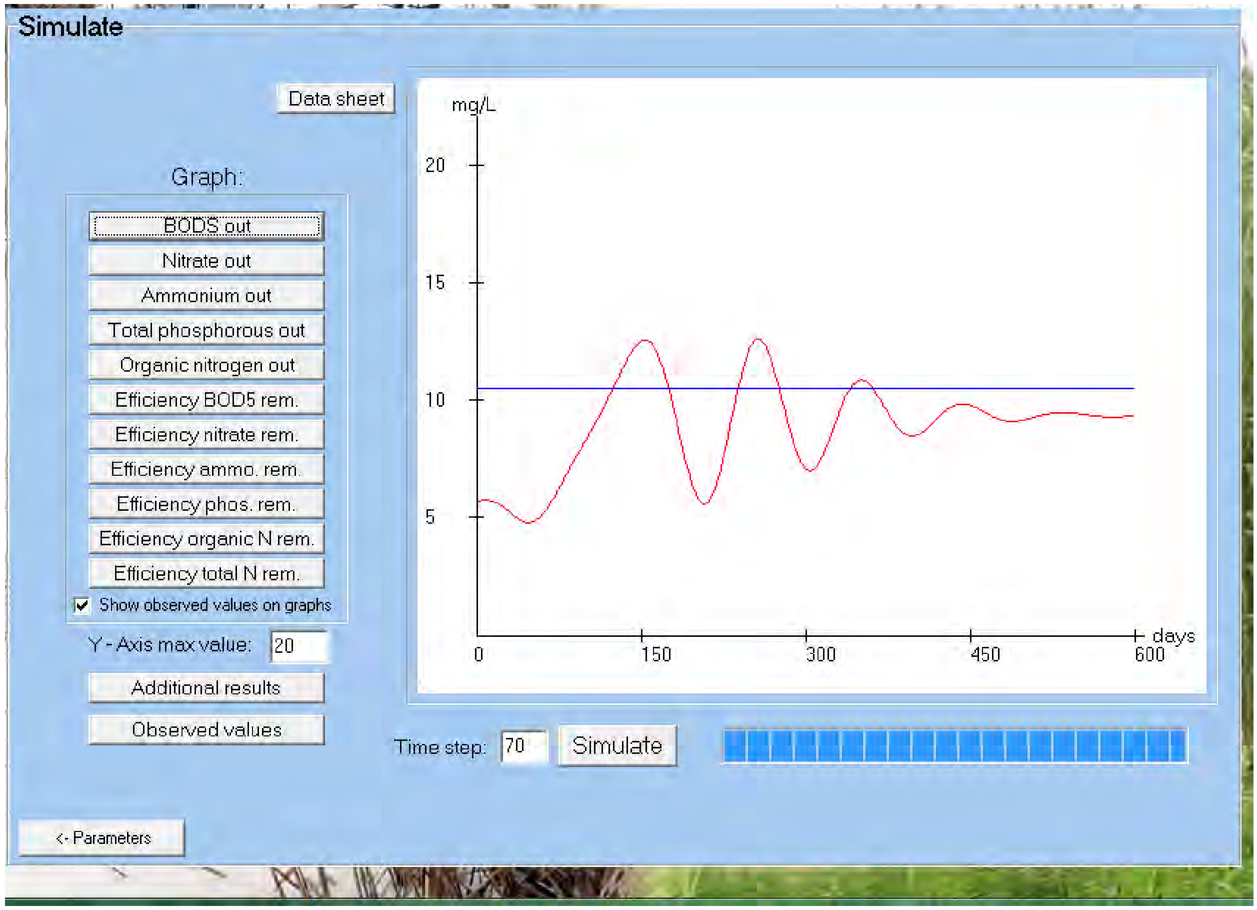
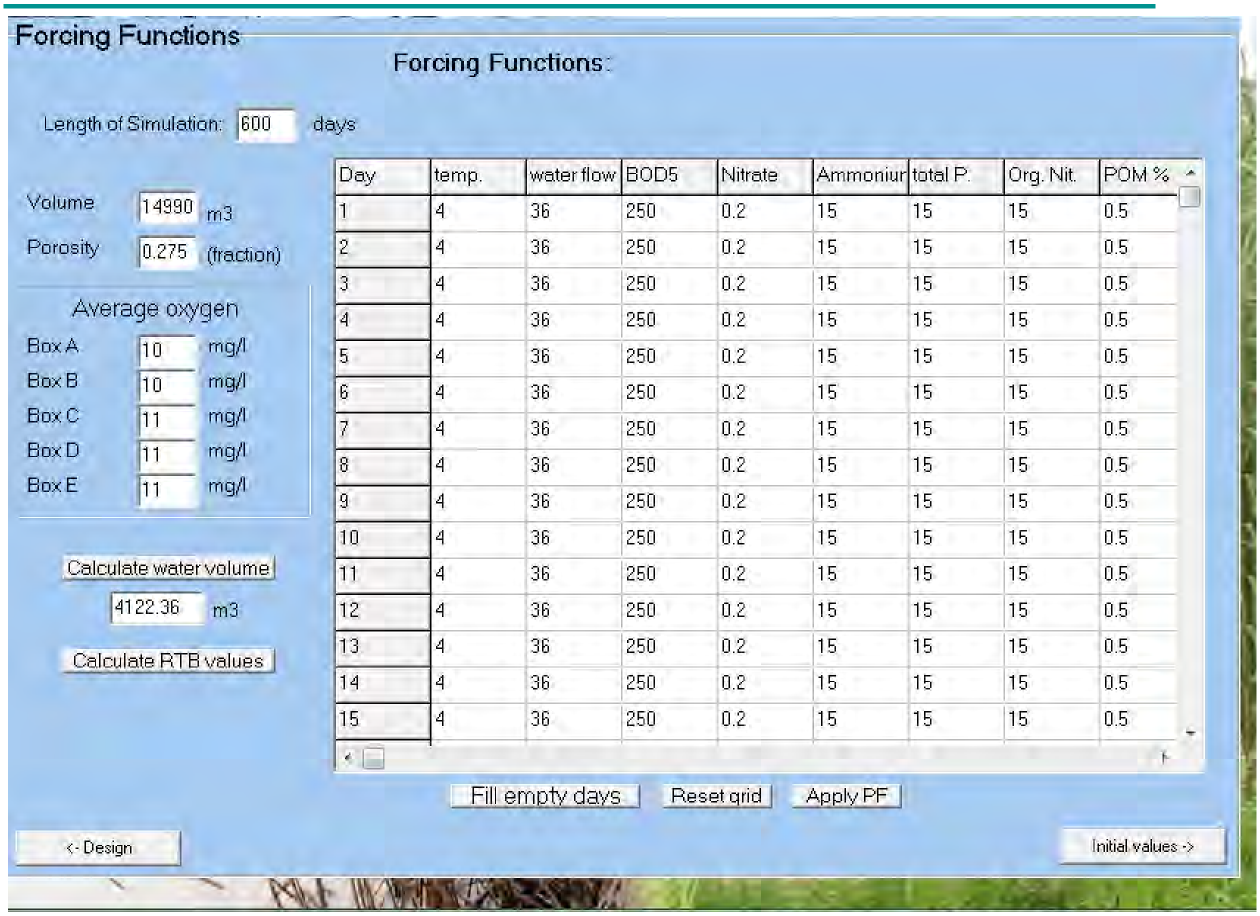


Figure E-16: The simulated BOD_5 results generated by selecting the initial values from the Additional Results window. Note that the variability of BOD_5 concentrations has been reduced in comparison to Figure E-13; however, the final BOD_5 concentration when SubWet reaches steady state has changed little.

Forcing Functions: In this example, we will examine how SubWet performs when the characteristics of the effluent entering the wetland are changed and when the temperature of the wetland is reduced. To accomplish this, we will look at a hypothetical scenario where the storage time of the Chesterfield Inlet effluent within the sewage lagoon is shortened and when the overall temperature is reduced. This could represent a hypothetical condition where the storage space of a sewage lagoon is insufficient and the stored effluent needs to be released to the wetland earlier in the year meaning that the time available for ammonification within the sewage lagoon is reduced and the overall temperature in the wetland is cooler during the time when the effluent is released from the lagoon into the wetland. In this hypothetical scenario the shorter storage time had meant that the concentration of organic nitrogen is elevated at approximately 15 mg/L (as opposed to 0.0001 mg/L in the true Chesterfield Inlet data shown previously). Conversely, as a result of decreased ammonification the concentration of ammonium is only 15 mg/L which is approximately half of the true value (originally shown as 29.5 mg/L). Also, because the effluent is released (in this hypothetical example) earlier in the year, the temperature is now 4 °C as opposed to 7.48°C as previously shown. In addition, the shorter storage time in the sewage lagoon means that the BOD_5 is slightly elevated to 250 mg/L (originally 207.6 mg BOD_5/L) and the POM, POP and PON are all at a concentration of 0.5% (up from the original value of 0.0001%) and the nitrate concentration is elevated slightly to 0.2 mg/L (up from 0.19 mg/L) and the concentration of total phosphorus is up to 15 mg/L (up from 5.49 mg/L). In summary the forcing functions utilized in this hypothetical example are illustrated in Figure E-17.



Day	temp.	water flow	BOD5	Nitrate	Ammoniur	total P.	Org. Nit.	POM %
1	4	36	250	0.2	15	15	15	0.5
2	4	36	250	0.2	15	15	15	0.5
3	4	36	250	0.2	15	15	15	0.5
4	4	36	250	0.2	15	15	15	0.5
5	4	36	250	0.2	15	15	15	0.5
6	4	36	250	0.2	15	15	15	0.5
7	4	36	250	0.2	15	15	15	0.5
8	4	36	250	0.2	15	15	15	0.5
9	4	36	250	0.2	15	15	15	0.5
10	4	36	250	0.2	15	15	15	0.5
11	4	36	250	0.2	15	15	15	0.5
12	4	36	250	0.2	15	15	15	0.5
13	4	36	250	0.2	15	15	15	0.5
14	4	36	250	0.2	15	15	15	0.5
15	4	36	250	0.2	15	15	15	0.5

Figure E-17: The forcing functions for a hypothetical example in which the Chesterfield Inlet effluent is released earlier from the sewage lagoon. Note that PON and POP are also 0.5% although they are not shown in this figure. RTB is unchanged at about 22 days.

As anticipated, SubWet has predicted that the increased effluent strength and reduced temperature has lowered the overall treatment efficiency resulting in slightly higher BOD_5 concentration (15.6 mg/L up from 9.4 mg/L) exiting the wetland (see Figure E-18) and the overall BOD_5 removal efficiency has decreased slightly from 95% to 94%. This minor reduction in the efficiency is natural as the temperature is slightly lower and the organic nitrogen (now 15 mg N /L against previously 0.0001 mg N /L) reduces the overall availability of oxygen for decomposition. The resulting ammonium-N concentration exiting the wetland is also slightly higher at about 0.3 mg ammonium N /L as opposed to the 0.2 mg ammonium- N /L seen before the modification of the forcing functions. The organic nitrogen decomposes to 15 mg ammonium N /L, which implies that the total amount of ammonium, which must be nitrified is unchanged, but the 15 mg ammonium N /L is coming stepwise during the treatment and is therefore added later, which will slow down the nitrification rate slightly as it is roughly proportional to the ammonium-N concentration. Although this results in a slightly higher concentration of nitrate from 0.3 to 0.4 mg Nitrate per litre, the overall nitrification rate is still high.

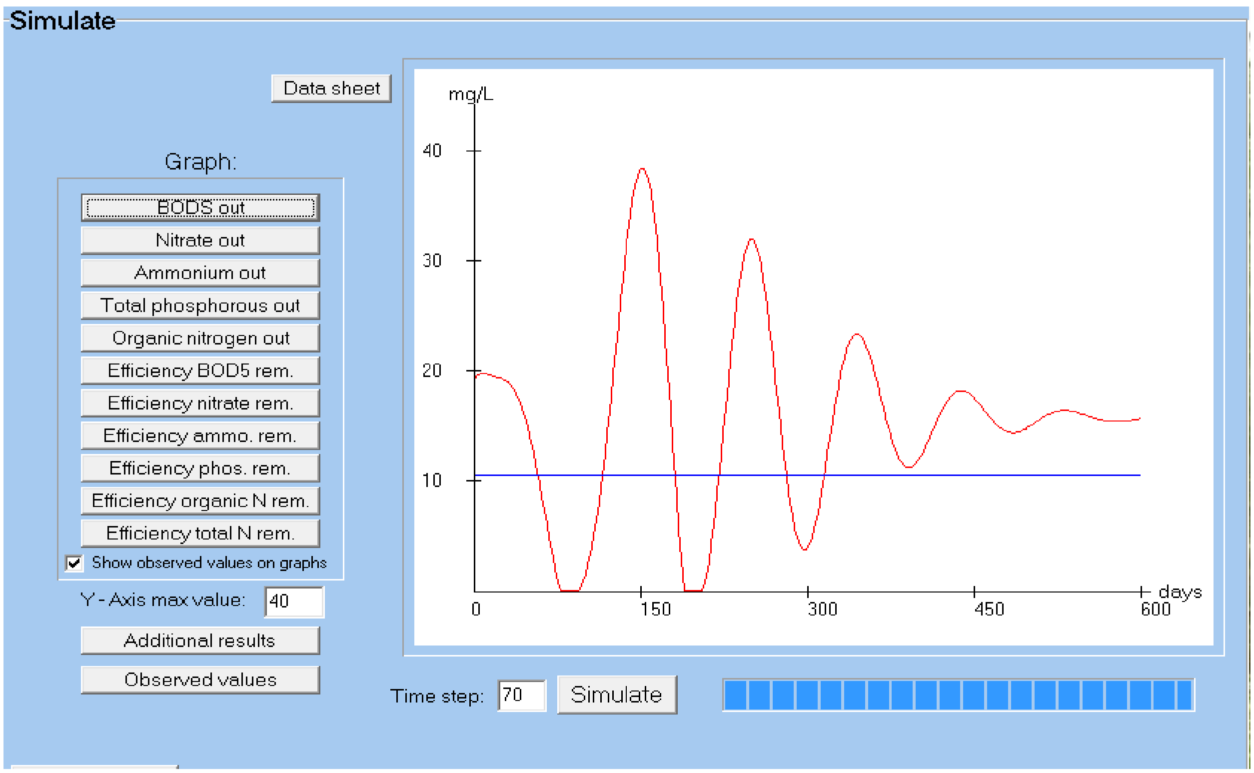


Figure E-18: A hypothetical scenario where the Chesterfield Inlet effluent is held for a shorter period of time within the sewage lagoon and is release to the wetland earlier in the spring time resulting in a slightly higher concentration in the BOD_5 (e.g., 15.6 mg/L) exiting the wetland.

Design Values: In this next scenario, we will first look at the impact of increasing the volume of effluent entering the wetland physical and later look at the impact to treatment efficiency caused by altering physical dimensions of the wetland. This scenario is designed to illustrate how SubWet can be used in a predictive manner to explore what would happen if the population of the community was to grow with the result that more effluent is generated on a daily basis and what would be needed to accommodate this increase production of effluent.

If the volume of effluent entering the wetland on a daily basis (using the Chesterfield Inlet data base for this example) is doubled from 36 m^3 per day to 72 m^3 per day SubWet predicts that the concentration of BOD exiting the wetland will increase from approximately 9.4 mg BOD_5 / L to around 31 mg/L (see Figure E-19). Doubling the volume of effluent entering the wetland means that the retention time in one box (RTB) is correspondingly reduced from approximately 22 days to around 11 days. This makes sense since doubling the flow means that the time the effluent resides in the wetland is reduced by half. It should be noted that reducing the physical dimension of the wetland by half has the same effect as doubling the volume of effluent entering the wetland. Both these actions ultimately influence the residency time of the effluent in the wetland and thus impacts the time available for biological processes to occur.

If doubling the volume of effluent entering the wetland (from 36 to 72 m^3/d) reduces the treatment of BOD_5 from 9.4 mg/L to 31 mg/L, it is likewise true that doubling the physical dimension of the wetland from a capacity of 4122.36 m^3 (e.g., 69.4 m wide; 720 m long; 0.3 m deep; porosity = 0.275) to a capacity of 8244.72 m^3 (note: length has been doubled to 1440 m long) will once again increase the RTB to approximately 22 days and increase the efficiency of BOD_5 treatment from 31 mg/L back down to 9.3 mg/L. In a similar manner, SubWet can be used to determine what size of wetland is needed to achieve a desired level of treatment. For example if the desired treatment target for BOD_5 was 15 mg/L, this can be achieved by reducing the wetland length to 570 m results which reduces the overall volume of the wetland by 21% (e.g., volume = 3264 m^3). Thus only 79% of the current wetland size is needed to achieve the BOD_5 target of 15 mg/L.

Although the doubling of the effluent volume from 36 m^3 to 72 m^3/d reduces the overall treatment of BOD_5 (e.g., 31 mg/L within this example), the overall treatment of ammonium-N, nitrate-N, phosphorus and organic nitrogen remains acceptable (see Figure E-20 for ammonium and Figure E-21 for phosphorus).

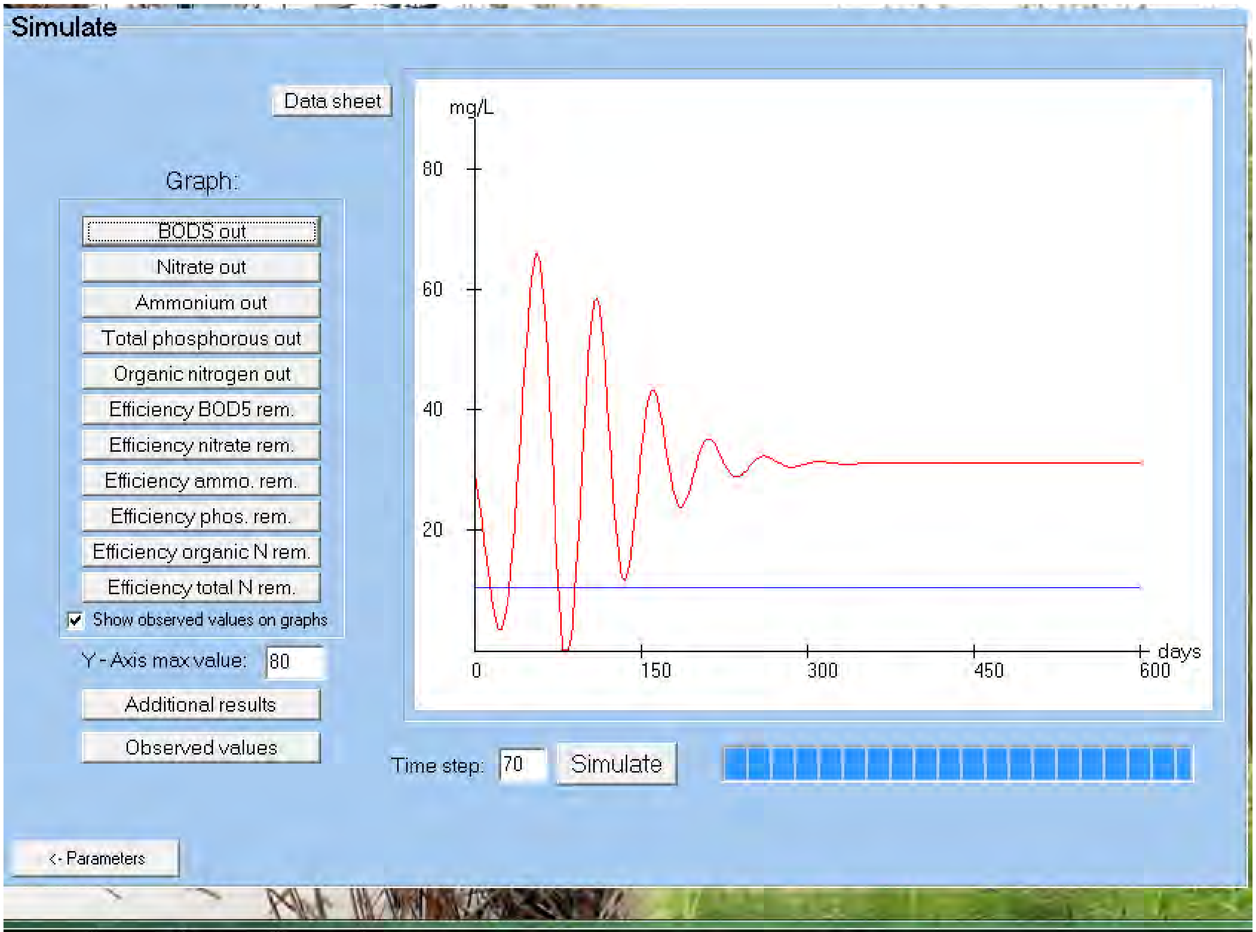


Figure E-19: In this scenario, the volume of effluent from Chesterfield Inlet has been doubled from 36 m^3/d to 72 m^3/d resulting in the BOD_5 increasing from 9.4 mg/L to 31 mg/L.

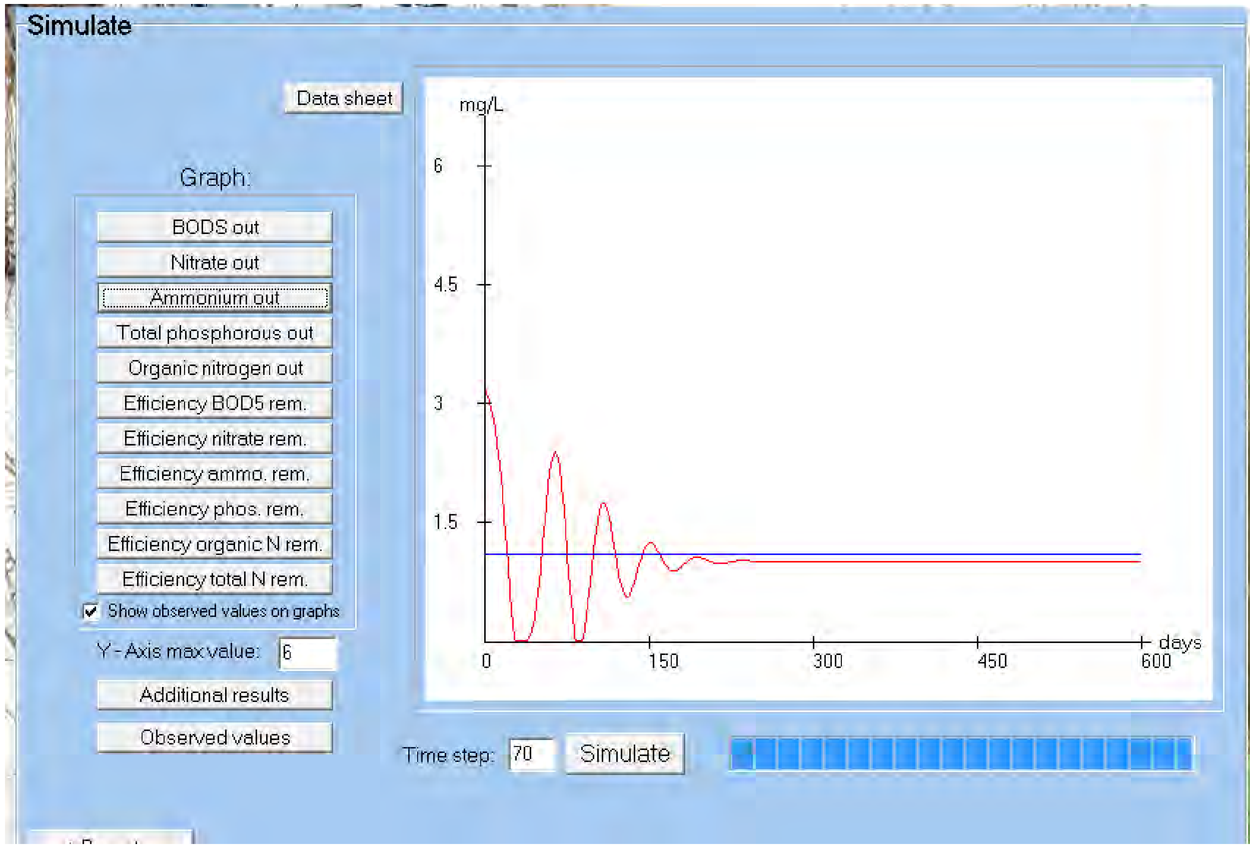


Figure E-20: In this scenario, the volume of effluent from Chesterfield Inlet has been doubled from 36 m^3/d to 72 m^3/d resulting in the ammonium concentration increasing slightly from 0.54 mg/L to 1.0 mg/L.

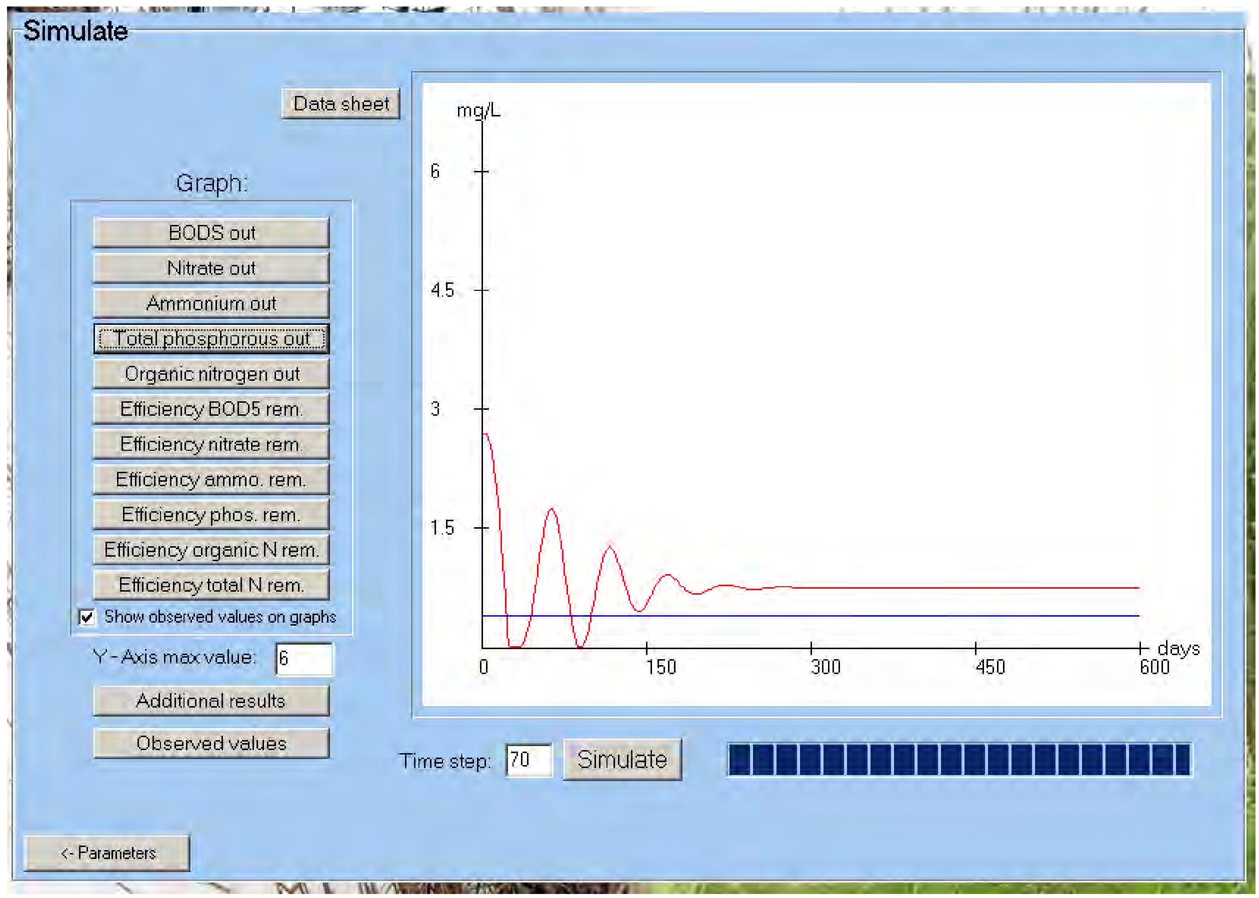


Figure E-21: In this scenario, the volume of effluent from Chesterfield Inlet has been doubled from 36 m^3/d to 72 m^3/d resulting in the phosphorus concentration increasing slightly from 0.42 mg/L to 0.75 mg/L.

Calibration of SubWet 2.0

The default coefficient parameters developed for operation of SubWet in either a cold or warm climate mode are generally a good starting point for operation of the SubWet program. It should be understood that the simulated results will in most cases vary from observed results. The reasons for this are many, but most often related to the inability of mathematical formulae to model complex environmental processes and for sake of simplicity most of these models rely heavily on relatively few parameters; thus many influential parameters are either not measured or not known. It is generally accepted that the standard deviation around sampling and analytical procedures is typically between 10-12% and thus the standard deviation to be expected for comparisons between measured values and model simulated values can generally be expected to be in the range of 15 to 20% [e.g., $(12^2 + 12^2)^{0.5} = 17\%$]. With this in mind, simulated results that are within 80% of the measured values are generally considered to be reasonable approximations. However, if greater agreement is desired or if the agreement is less than with 80% then SubWet can be calibrated to the conditions of a specific wetland by modification of the coefficient parameters listed in the Parameter window. The cold climate default coefficient parameter values within SubWet are based on five natural wetland data sets from Nunavut within the Canadian Arctic while the warm climate parameter values are based on constructed wetland data sets from the United Republic of Tanzania, eastern Africa. Therefore the parameter values for the cold climate mode and the warm climate mode represent average, or typical parameter values for operation of SubWet under cold or warm climate conditions. These cold climate and warm climate default parameters are an initial "good start" choice when first attempting to simulate the treatment of municipal effluents, however, each wetland is unique and the user may be able to find a better agreement between observed (measured) values and simulated values after calibration. This however, implies that some initial testing of the effluent exiting the wetland needs to be undertaken so that observed values are available for the user to assess how closely the simulated values are matching the observed values. In practice, the greater the data base of observed values (both spatial and temporal), the great the chance for achieving a calibration that better simulates real world conditions.

Two different data sets are used below to illustrate how the SubWet model can be calibrated to specific wetlands. The first data set was generated from the natural tundra wetland located near the hamlet of Chesterfield Inlet situated in the Kivalliq region (western Hudson Bay) of Nunavut, Canada. The second data set originates from the natural tundra wetland near the hamlet of Baker Lake, also in the Kivalliq region of Nunavut, Canada.

Chesterfield Inlet Data Set

The following example with the Chesterfield Inlet data set illustrates how SubWet 2.0 can be calibrated to a tundra wetland. Table E-3 compares the values simulated by SubWet to the values observed in the field. An examination of these values reveals that for the most part there is a close approximation of the simulated to the observed results. If an attempt were made to achieve greater similarity via calibration then the focus would most likely be on the BOD_5 and Ammonium constituents. The values in Table E-3 indicate that SubWet is over estimating the decomposition of organic matter (e.g., removal of BOD_5) and over estimating the rate of nitrification (e.g., conversion of ammonium to nitrate). This suggests that the coefficients for the decomposition of organic matter and nitrification are too high and should be lowered.

Table E-3: Comparison of simulated and observed values for the Chesterfield Inlet data set.

	Simulation Results	Observed Values
BOD5	9.4	10.5
Ammonium-N	0.19	1.1
Nitrate-N	0.02	0.01
Total N	0.22	1.1
Phosphorus	0.42	0.4

The magnitude by which these coefficients are altered will most likely be approached by those just beginning to use SubWet in a trial and error manner where one coefficient at a time is altered and the simulation re-run and the graphical expression of the “simulated” to “observed values” re-examined. Fortunately SubWet performs all simulations rapidly, allowing the user to quickly try a variety of alterations until they find the values that provide the greatest correlation between simulated and observed results. It has been determined that for this data set a change in the decomposition rate of organic matter (OC) from 0.25 to 0.235 and a change in the nitrification rate (NC) from 0.9 to 0.42, and a change in the half saturation constant for nitrification (KO) from 0.01 to 1.4 produces simulation values for BOD_5 and ammonium that are much closer to the observed values.

Figure E-22 illustrates the change in the coefficient parameter values in the Parameter window. Table E-4 summarized the differences between simulated and observed after calibration of the Chesterfield Inlet wetland data set. As shown, the calibration effort has resulted in a greater agreement between the BOD_5 and ammonium constituents. The simulated nitrate concentration has increased, but this is considered a minor variance since nitrate concentrations (both simulated and observed) are below 0.1 mg/L.

Figure E-23 illustrates the simulated BOD_5 in comparison to the observed values after calibration and Figure E-24 illustrates the simulated ammonium values in comparison to the observed values after calibration.

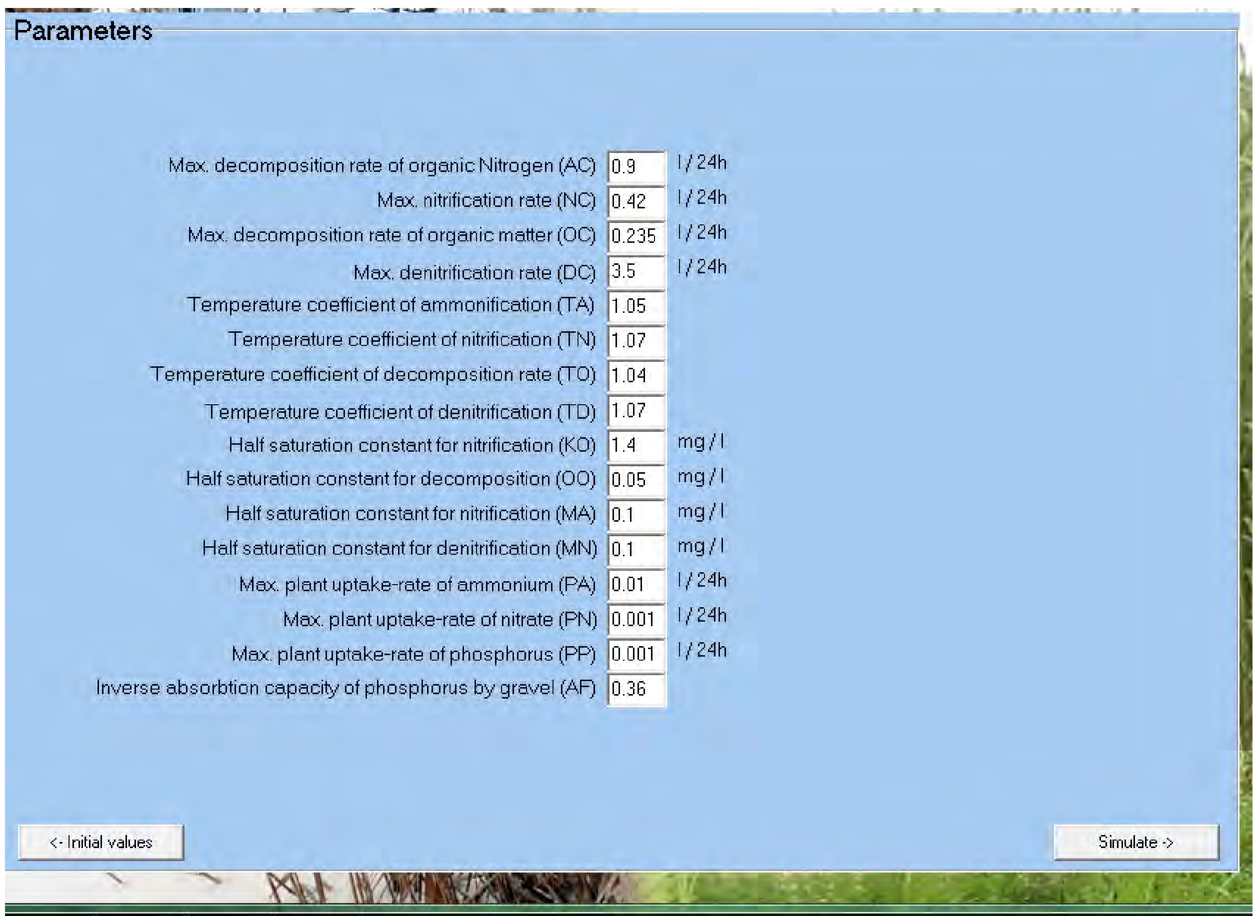


Figure E-22: Note how the values for NC, OC and KO have been modified during the calibration of SubWet to the Chesterfield Inlet wetland.

Table E-4: Comparison of simulated and observed values for the Chesterfield Inlet data set after modifying the NC, OC and KO coefficients.

	Simulation Results	Observed Values
BOD5	10.4	10.5
Ammonium-N	1.1	1.1
Nitrate-N	0.06	0.01
Total N	1.2	1.1
Phosphorus	0.42	0.4

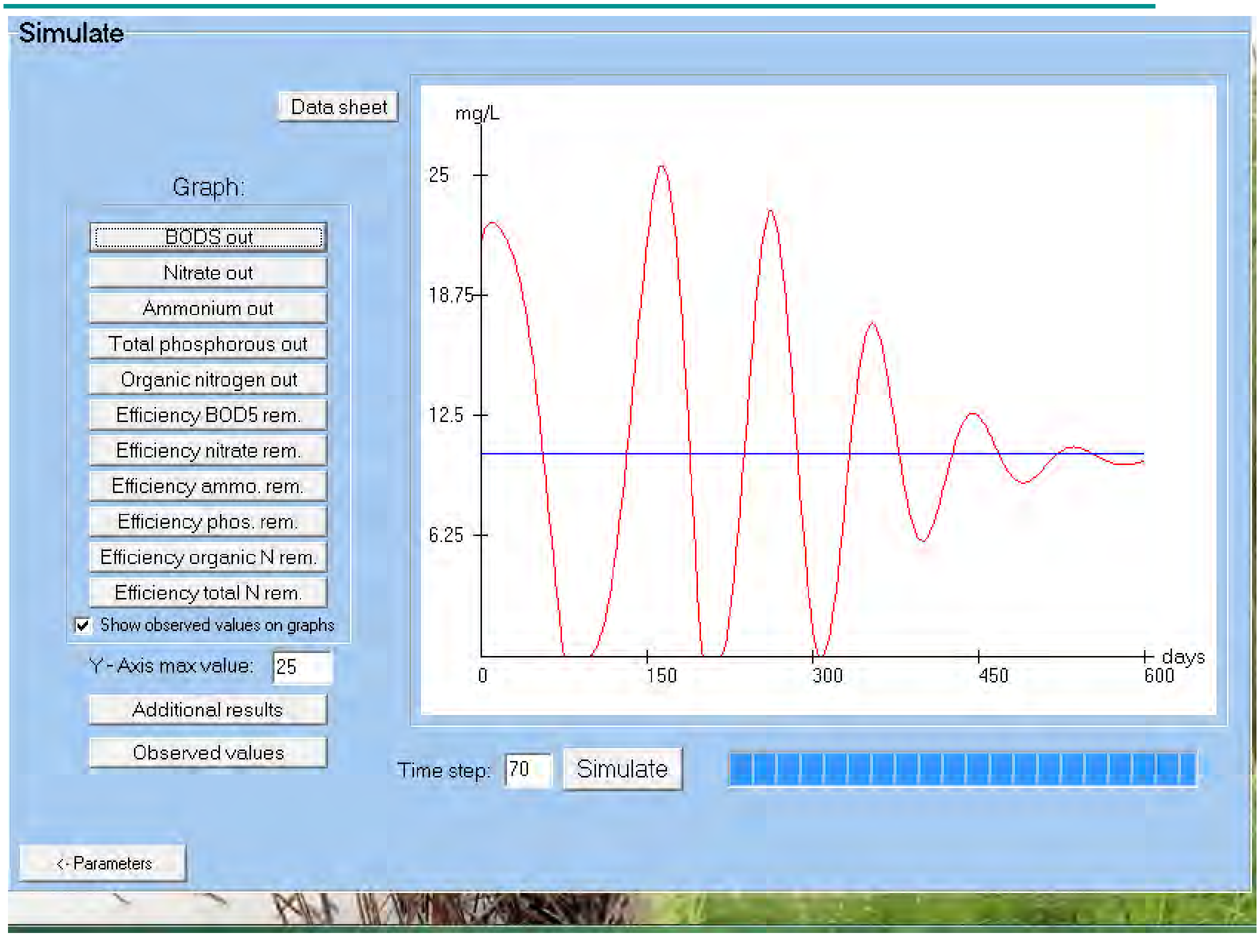


Figure E-23: A comparison of simulated BOD_5 values to the observed values after calibration of the SubWet 2.0 model.

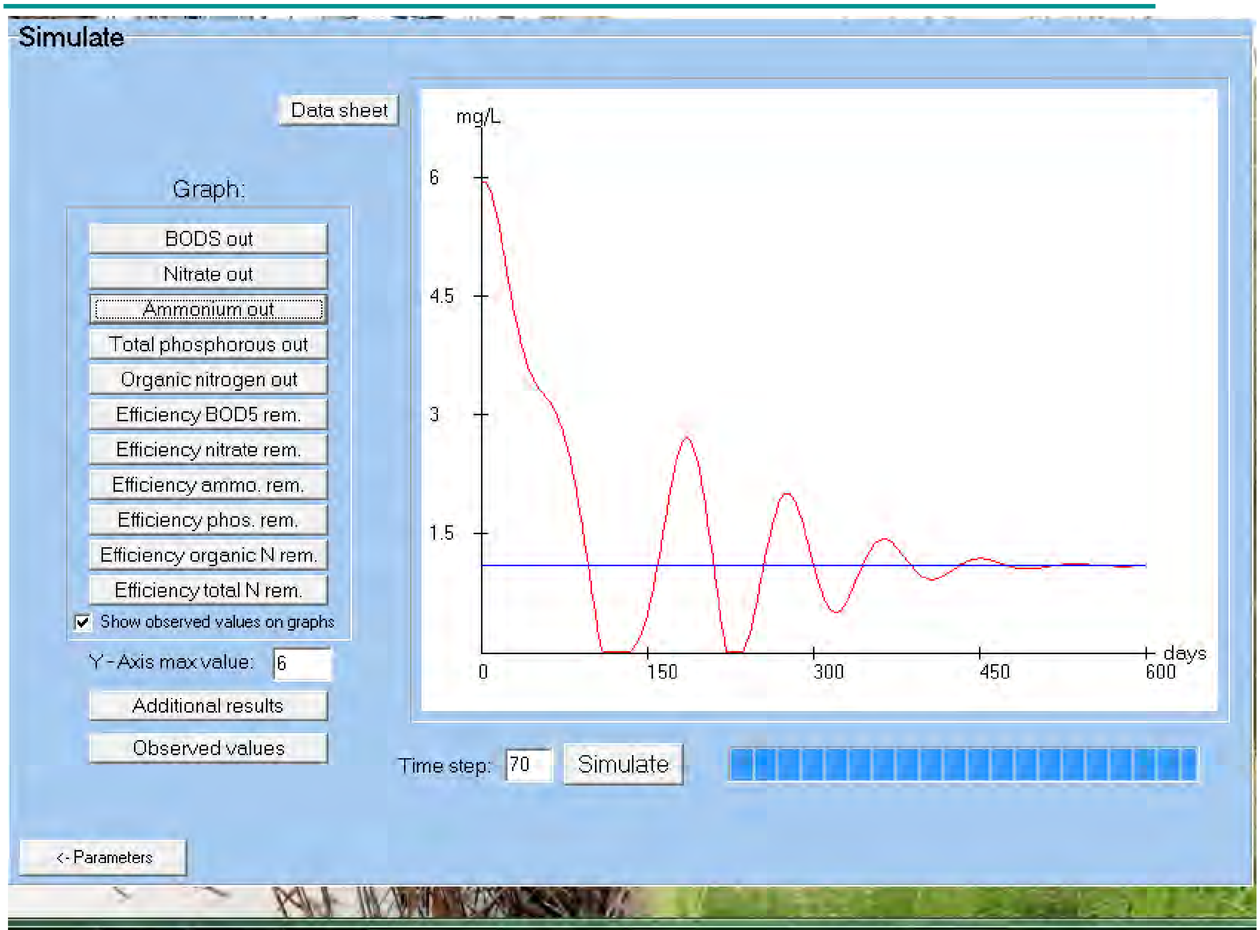


Figure E-24: A comparison of simulated ammonium values to the observed values after calibration of the SubWet 2.0 model.

Baker Lake Data Set

The data set from Baker Lake is interesting in that the BOD_5, ammonium and organic nitrogen concentrations of the effluent entering the wetland are much higher than normally encountered in municipal wastewater effluents. In addition the physical size of the Baker Lake wetland is typically smaller than many other wetlands in Nunavut, Canada. Because of this, the default coefficient parameters for the cold climate operation of the SubWet model do not provide an adequate simulation for most of the simulated wastewater parameters. Note: the data set for the Baker Lake example can be loaded into SubWet 2.0 by clicking on the word “File” at the top left hand corner of the Design window and selecting "load project" and choosing the Baker Lake file called "Baker.mdl".

Figure E-25 provides the initial data required by the "design window". The forcing function values outlining the concentration values of the effluent entering the wetland are outlined in Figure E-26a and E-26b. Note that the effluent is particularly high in BOD_5 (405 mg/L), ammonium (80.7 mg/L), total phosphorus (12.6 mg/L), and organic nitrogen (57.4 mg/L)

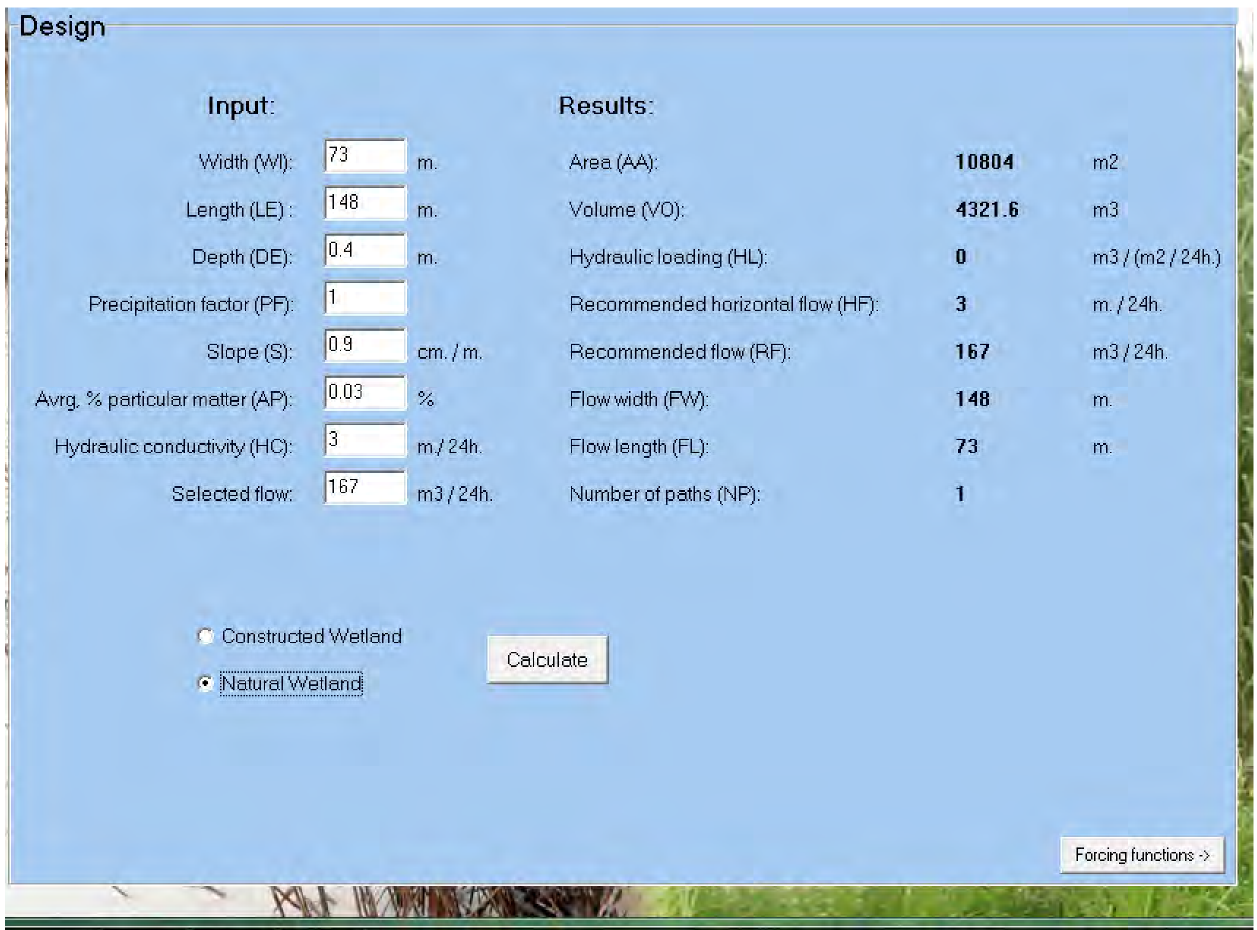
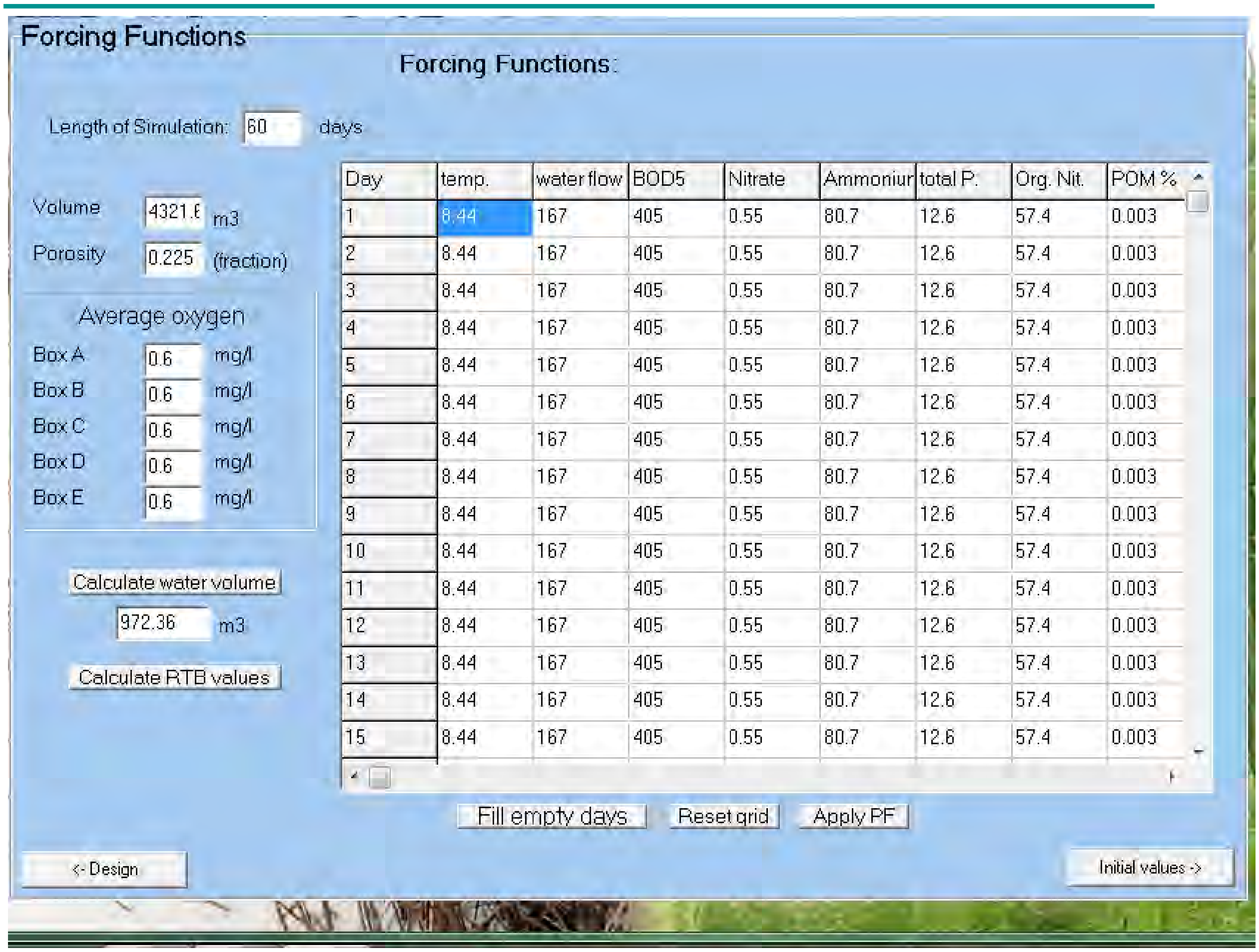


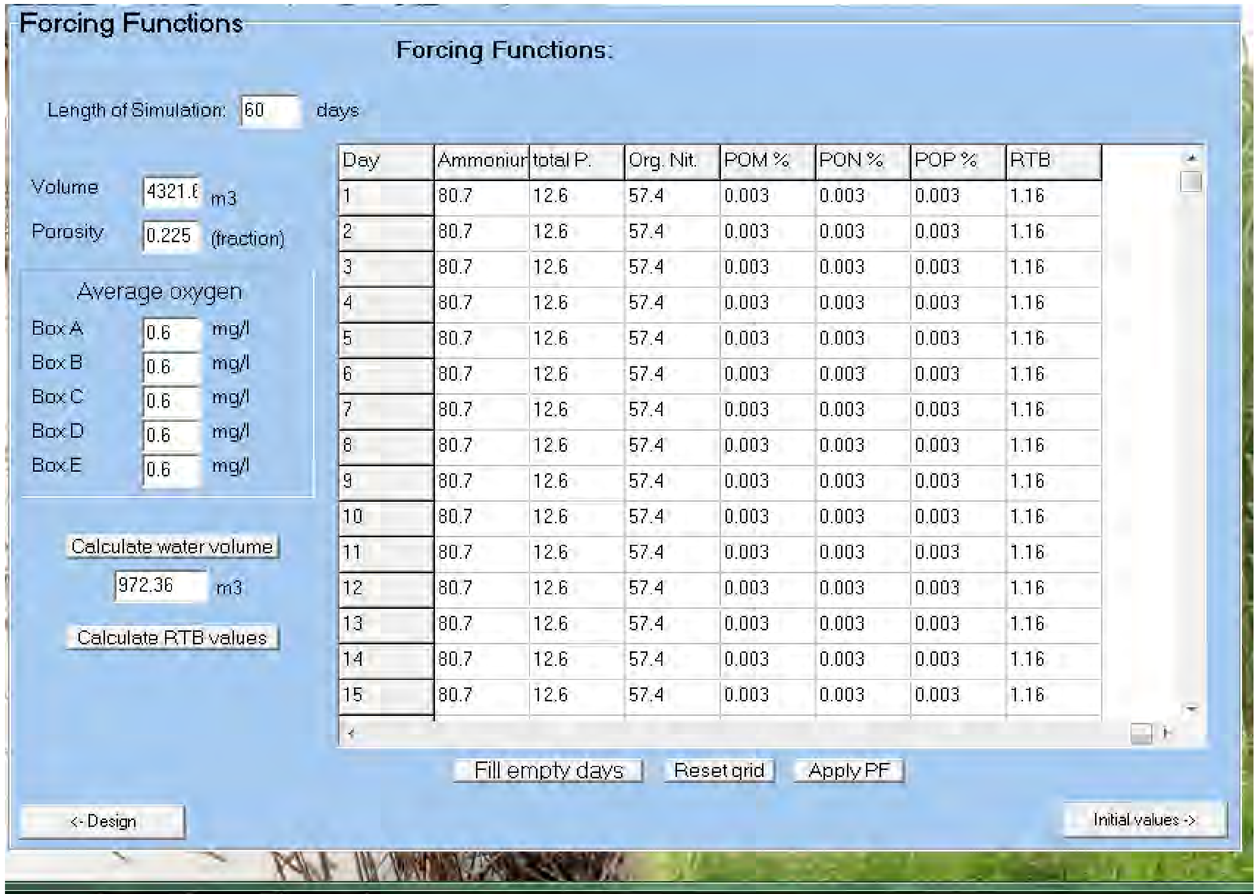
Figure E-25: Physical parameters related to the Baker Lake, Nunavut wetland site.



Day	temp.	water flow	BOD5	Nitrate	Ammoniur	total P.	Org. Nit.	POM %
1	8.44	167	405	0.55	80.7	12.6	57.4	0.003
2	8.44	167	405	0.55	80.7	12.6	57.4	0.003
3	8.44	167	405	0.55	80.7	12.6	57.4	0.003
4	8.44	167	405	0.55	80.7	12.6	57.4	0.003
5	8.44	167	405	0.55	80.7	12.6	57.4	0.003
6	8.44	167	405	0.55	80.7	12.6	57.4	0.003
7	8.44	167	405	0.55	80.7	12.6	57.4	0.003
8	8.44	167	405	0.55	80.7	12.6	57.4	0.003
9	8.44	167	405	0.55	80.7	12.6	57.4	0.003
10	8.44	167	405	0.55	80.7	12.6	57.4	0.003
11	8.44	167	405	0.55	80.7	12.6	57.4	0.003
12	8.44	167	405	0.55	80.7	12.6	57.4	0.003
13	8.44	167	405	0.55	80.7	12.6	57.4	0.003
14	8.44	167	405	0.55	80.7	12.6	57.4	0.003
15	8.44	167	405	0.55	80.7	12.6	57.4	0.003

Figure E-26a: Characteristics of the effluent entering the Baker Lake wetland (remainder of window shown in Figure E-26b, below)

Note that the average oxygen concentration for all five boxes (Box A to E) has been set at the low value of 0.6 mg/L. The oxygen concentration has been set low since the effluent has such a high concentration of BOD_5, ammonium and organic nitrogen and the high oxygen consumption which will be associated with these processes. It is anticipated that the subsurface environment may be approaching an anoxic condition. This low value has been applied to all five boxes, since the wetland is relatively small and the observed (measured) values for the effluent exiting the wetland indicates that the 'strength" of the effluent remains high throughout its travel through the wetland (i.e., overall treatment is poor).



Day	Ammoniur	total P.	Org. Nit.	POM %	PON %	POP %	RTB
1	80.7	12.6	57.4	0.003	0.003	0.003	1.16
2	80.7	12.6	57.4	0.003	0.003	0.003	1.16
3	80.7	12.6	57.4	0.003	0.003	0.003	1.16
4	80.7	12.6	57.4	0.003	0.003	0.003	1.16
5	80.7	12.6	57.4	0.003	0.003	0.003	1.16
6	80.7	12.6	57.4	0.003	0.003	0.003	1.16
7	80.7	12.6	57.4	0.003	0.003	0.003	1.16
8	80.7	12.6	57.4	0.003	0.003	0.003	1.16
9	80.7	12.6	57.4	0.003	0.003	0.003	1.16
10	80.7	12.6	57.4	0.003	0.003	0.003	1.16
11	80.7	12.6	57.4	0.003	0.003	0.003	1.16
12	80.7	12.6	57.4	0.003	0.003	0.003	1.16
13	80.7	12.6	57.4	0.003	0.003	0.003	1.16
14	80.7	12.6	57.4	0.003	0.003	0.003	1.16
15	80.7	12.6	57.4	0.003	0.003	0.003	1.16

Figure E-26b: Characteristics of the effluent entering the Baker Lake wetland (continuation of Figure E-26a, above)

Note that the relatively high volume of effluent entering the wetland daily (e.g., recommended flow = 167 m^3/24h as shown in both Figures E-25 and E-26a). The combination of the high daily inflow of effluent and the small physical dimension of the wetland means that the "retention time in one box" is correspondingly small and equals 1.16 days. The hydraulic retention time for the whole wetland would therefore be 5*RTB or 5*1.16 = 5.8 days. Therefore defining the 'length of simulation' at a value of 60 days should be more than enough time for SubWet to reach steady state.

Lastly, note that this example has values for POM%, PON% and PON%, unlike the Chesterfield Inlet example which did not have values for these parameters and thus used the default "limit of detection" values where are set at 0.0001%.

The initial simulations were performed with the default coefficient parameters set for the operation of SubWet in the cold climate mode. These values are summarized in Figure E-27. It will be shown below that this set of default parameters does not produced simulated nitrogen values that are close to the observed values for this wetland.

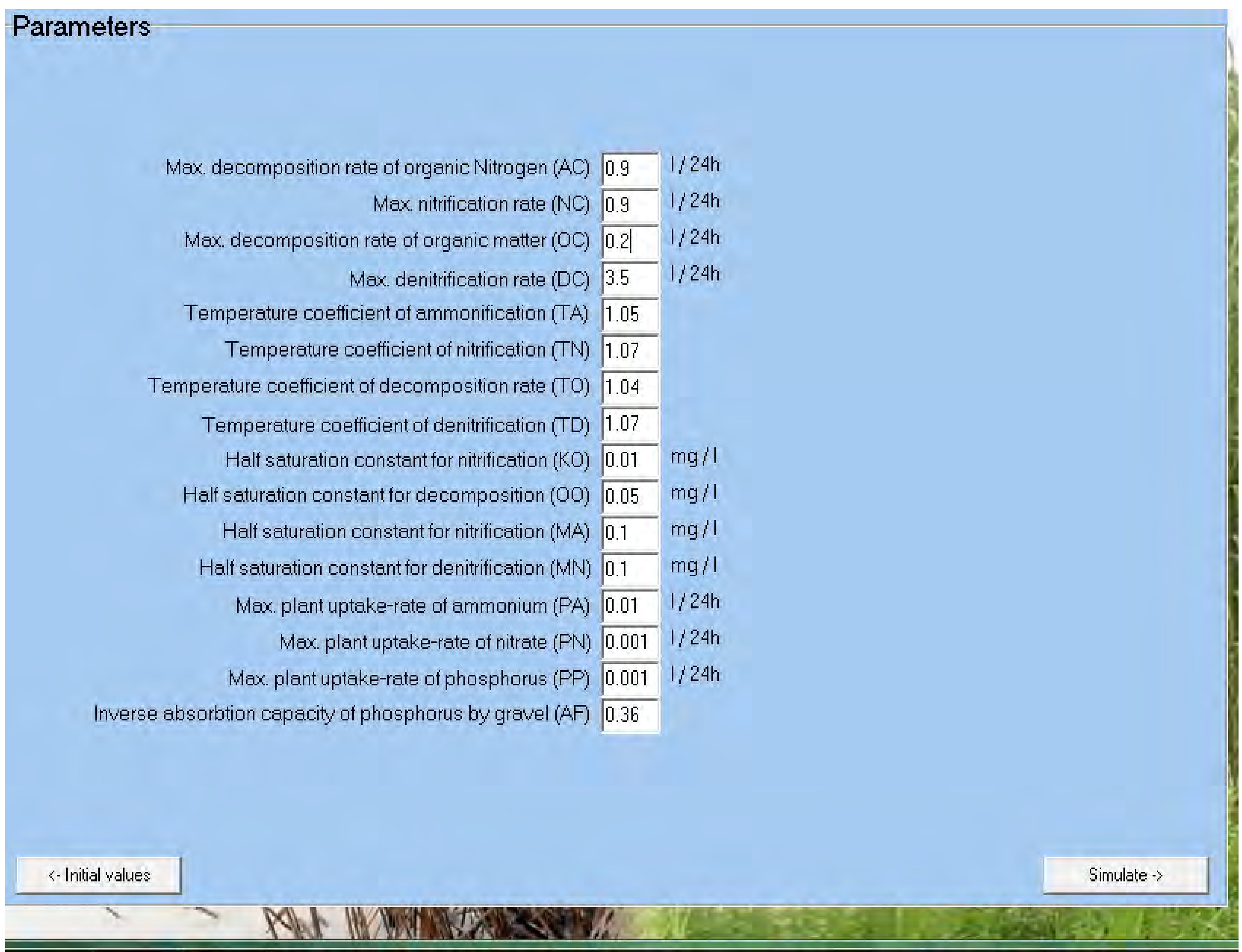


Figure E-27: The cold climate default coefficient parameters were initially used in the Baker Lake example for the first simulation of the data.

As will be shown below, the simulated BOD_5 and total phosphorus values are relatively close to the observed values for BOD_5 and total phosphorus, however, the values for nitrate, ammonium and organic nitrogen are not acceptable, but can be improved when SubWet is calibrated for Baker Lake.

Figure E-28 illustrates that the simulated values for BOD_5 are within 15% of the observed values [e.g., 281 (simulated) – 247 (observed) = 34 mg/l or less than 15% difference].

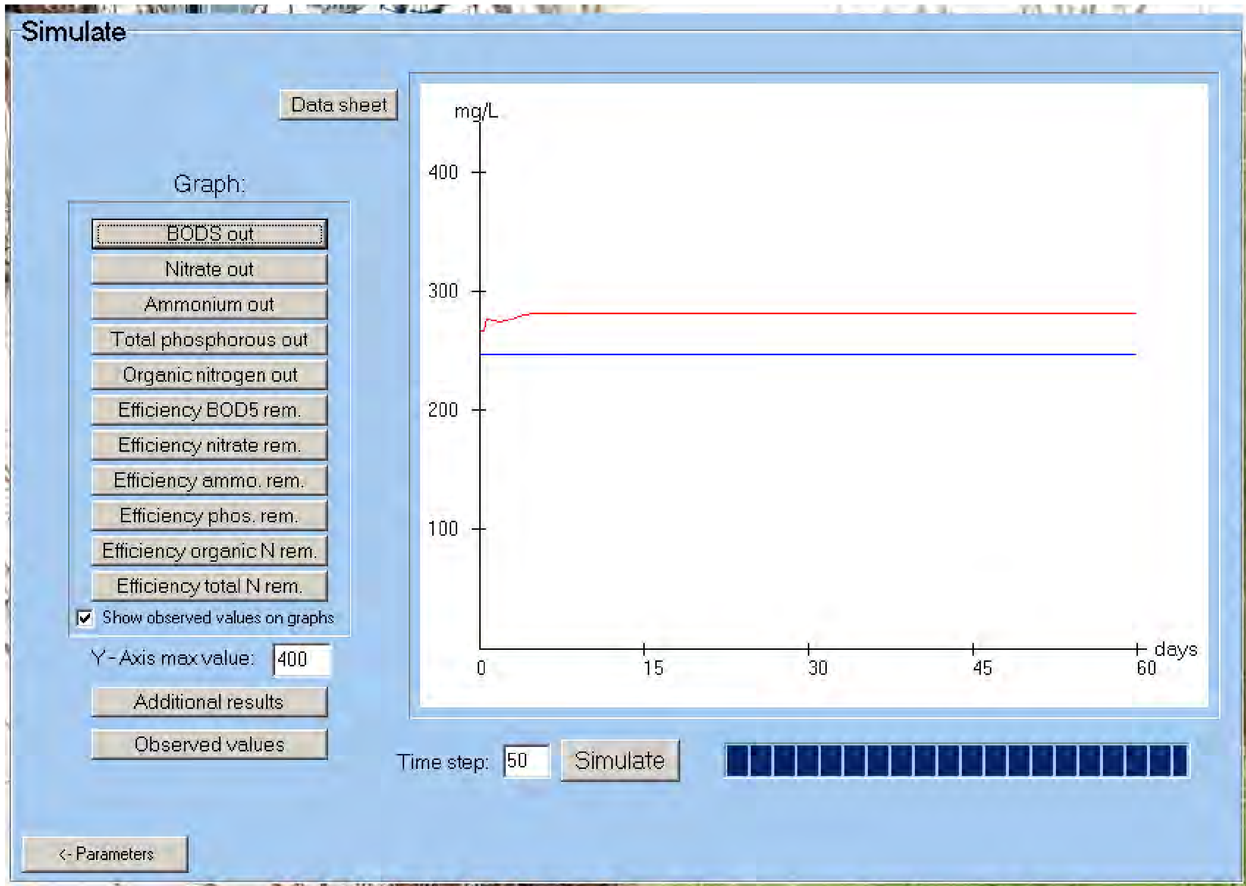


Figure E-28: Simulated BOD_5 values (red) in comparison to the observed values (blue) prior to calibration. The difference is less than 15% and as such the simulated values are acceptable.

In a similar manner the simulated results for total phosphorus are also relatively close [e.g., 9.4 (observed) – 8.3 (simulated) = 1.1 mg/l or less than 13% difference] as shown in Figure E-29. Because of the closeness between simulated and observed, there is no need to calibrate SubWet for total phosphorus.

Table E-5 summarizes the differences between the observed and simulated results for BOD_5, ammonium, nitrate, organic nitrogen, total phosphorus along with the rates of ammonification (expressed as mg organic nitrogen converted to ammonium), nitrification (expressed as mg ammonium converted to nitrate) and denitrification (expressed as mg nitrate converted to dinitrogen gas). The values represented in Table E-5 correspond to values prior to calibration of the SubWet program.

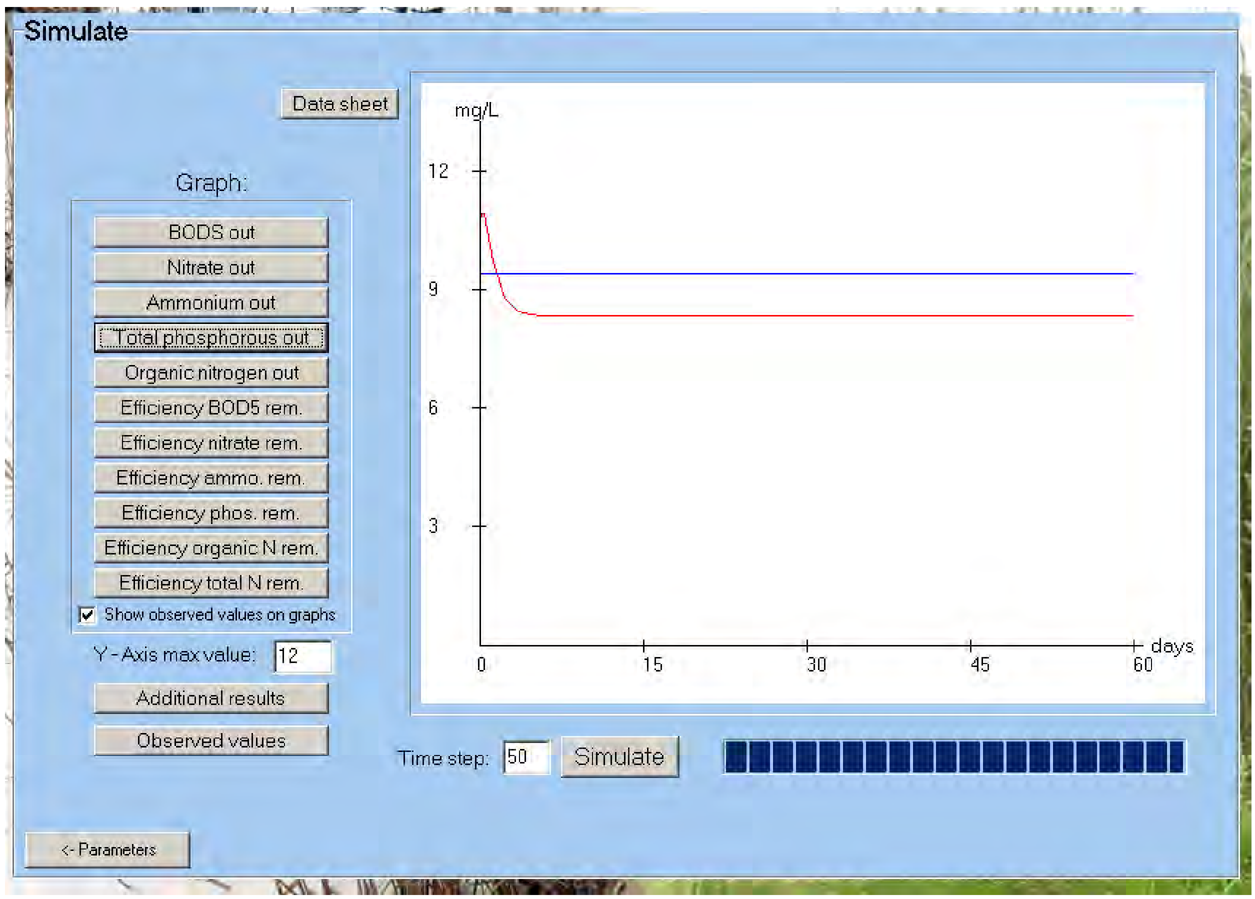


Figure E-29: Simulated total phosphorus values (red) in comparison to the observed values (blue) prior to calibration. The difference is less than 13% and as such the simulated values are acceptable.

Table E-5: Comparison of treatment results (observed and simulated) prior to calibration of SubWet.

Item	Observed value	Simulated value	Deviation %
BOD5	247	281	15
Ammonium	61.9	84.3	36
Nitrate	0.52	4.5	-
Organic nitrogen	0.0	5.5	-
Phosphorus	9.4	8.3	13
Ammonification	57.4	51.9	10
Nitrification	76.4	49.8	36
Denitrification	75.5	44	42

Although the simulated results for BOD_5 and total phosphorus are relatively close to the actual observed concentration within the effluent exiting the wetland, the nitrogen compounds show less agreement between simulated and observed results suggesting that SubWet requires calibration for these compounds.

For example, the simulated value for nitrate is approximately 4.5 mg/L and yet the observed value is 0.52 mg/L. The difference is unacceptably too great and must be due to an underestimation of the denitrification rate or an overestimation of the nitrification rate. The simulated nitrate concentration is a product of both denitrification (conversion to nitrogen gas) which removes nitrate from the effluent stream and nitrification (conversion of ammonium to nitrate) which produces nitrate.

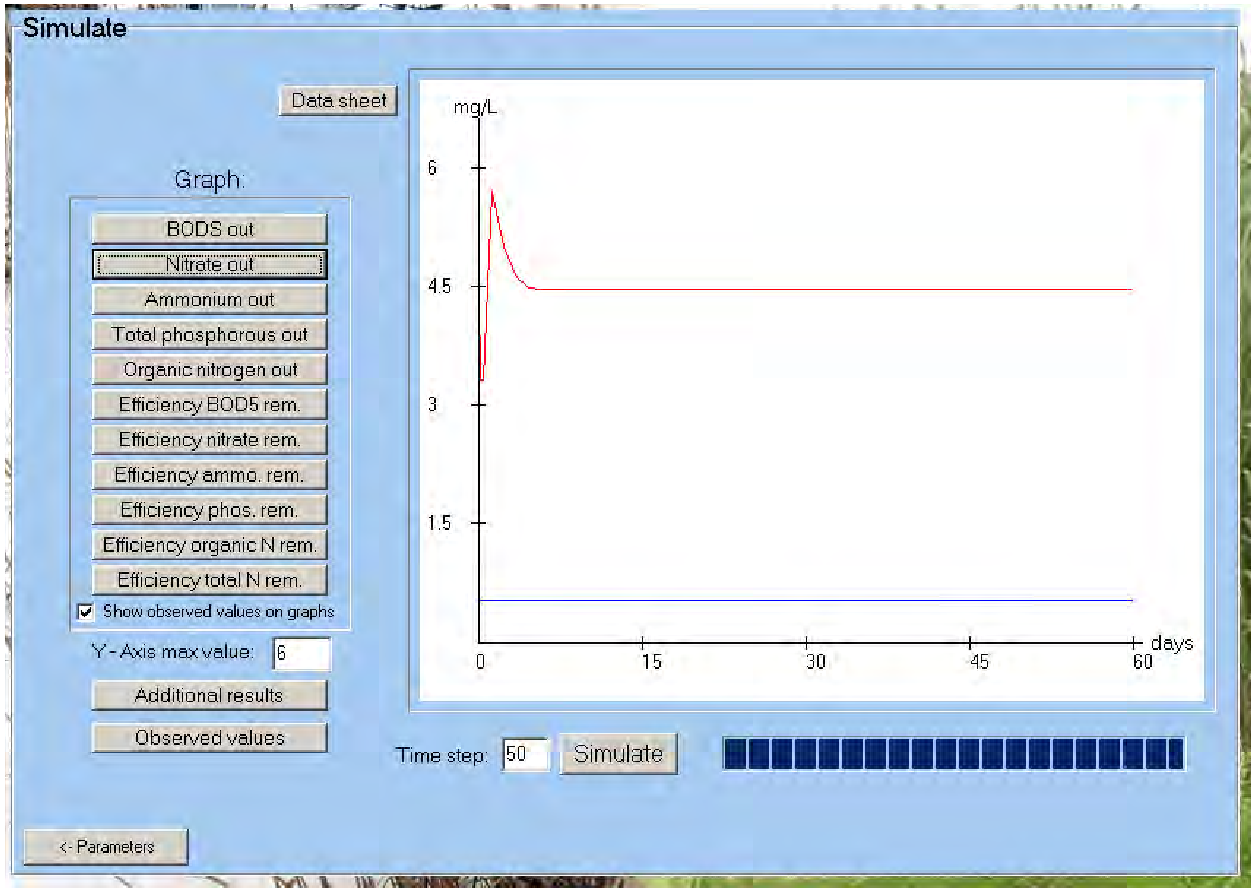


Figure E-30: Simulated nitrate values (red) in comparison to the observed values (blue) prior to calibration. The difference is much greater than 20% and as such the simulated values are unacceptable.

Likewise the SubWet results for ammonium (Figure E-31) once again shows a large discrepancy between the simulated ammonium concentration (approx 84 mg/L) in comparison to the observed value which is closer to 62 mg/L. The simulated results for organic nitrogen are illustrated in Figure E-32. The initial concentration of organic nitrogen within the effluent entering the wetland was approximately 57 mg/L and although the difference between the simulated (5.5 mg/L) and observed results (0 mg/L) of the effluent exiting the wetland is closer than found for nitrate and ammonium, calibration of SubWet would likely improve the predictability for organic nitrogen.

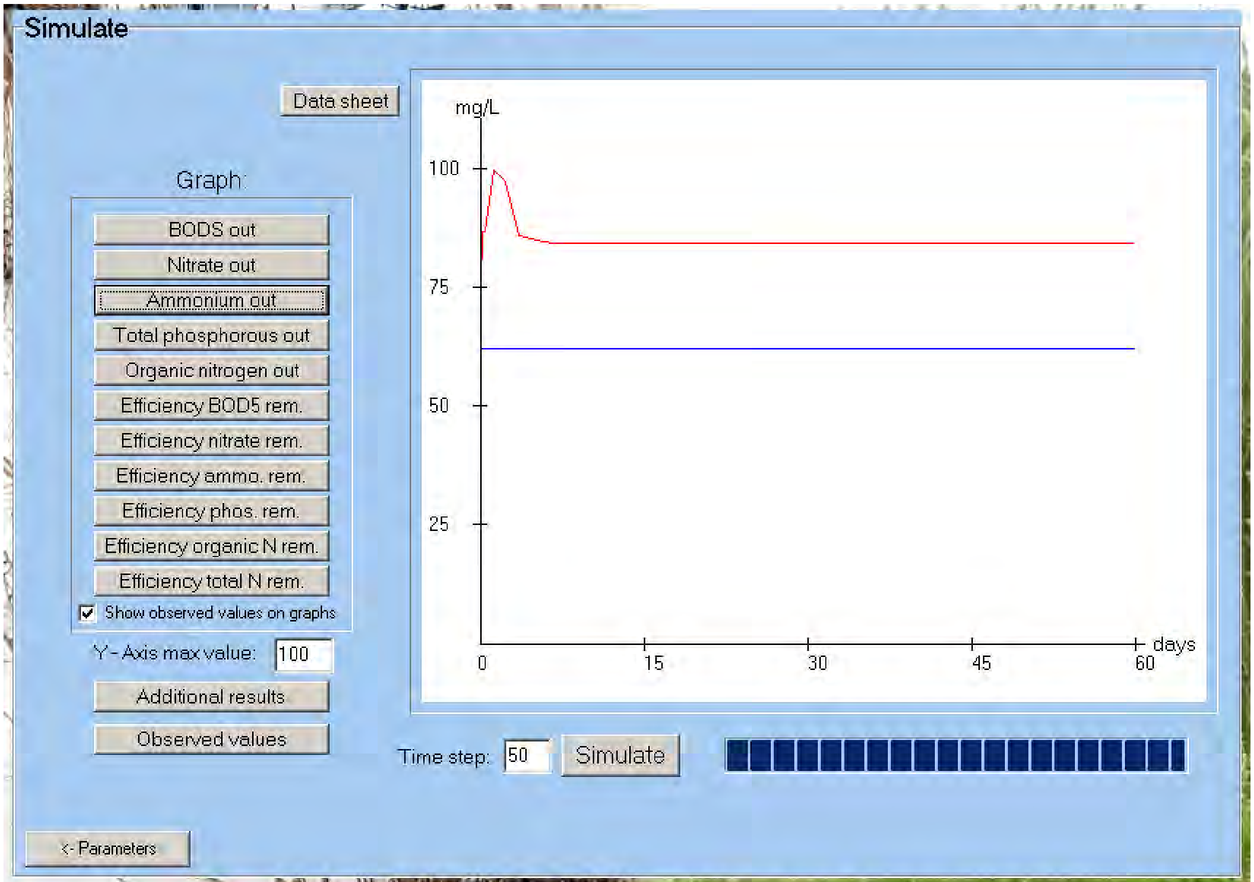


Figure E-31: Simulated ammonium values (red) in comparison to the observed values (blue) prior to calibration. The difference is much greater than 20% and as such the simulated values are unacceptable.

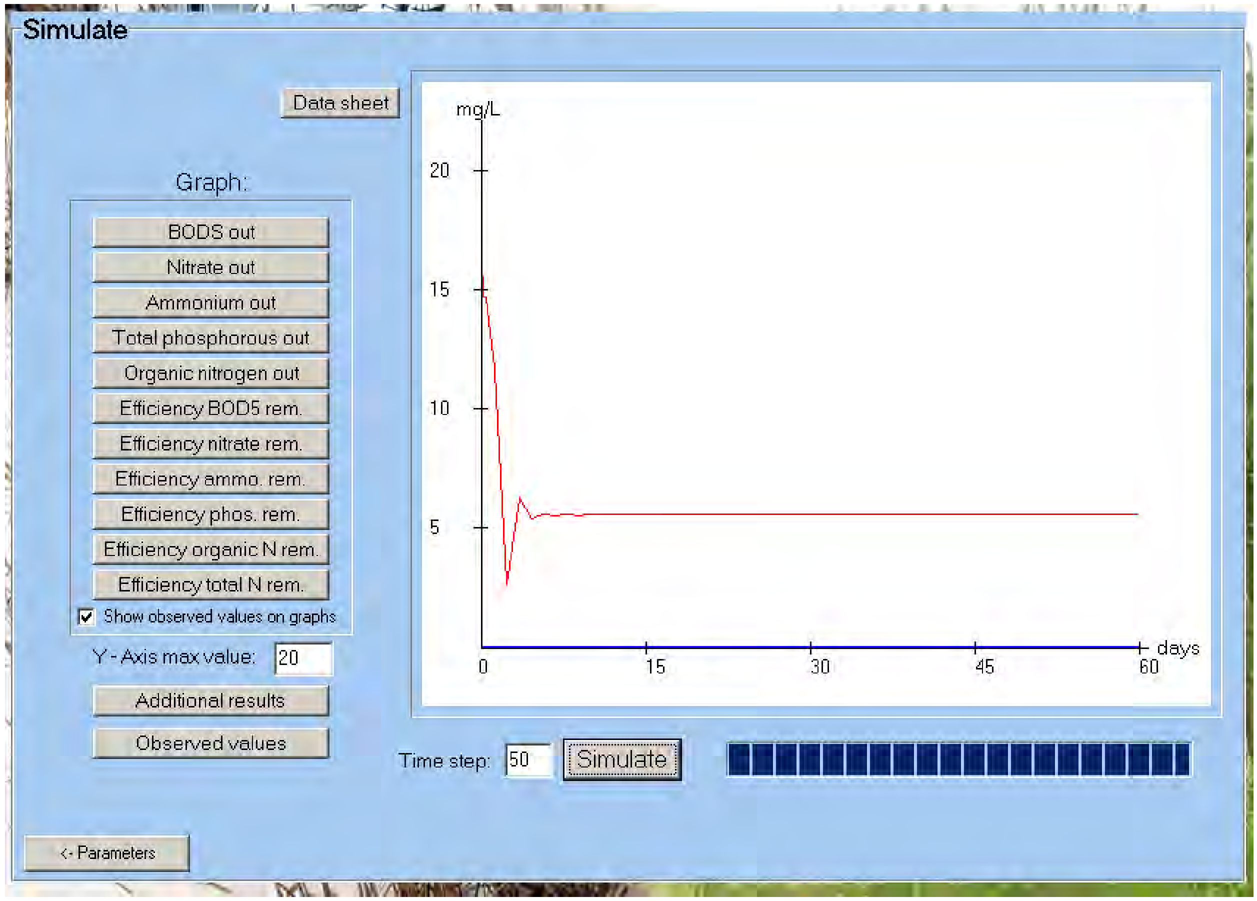


Figure E-32: Simulated organic nitrogen values (red) in comparison to the observed values (blue) prior to calibration. The difference is less than 20%, however, calibration of SubWet would likely improve the overall predictive ability of this parameter by this model.

A comparison of the observed (measured) concentrations of the nitrogenous compounds within the effluent (pre and post treatment) to the SubWet simulated results can provide insight into which processes (e.g., ammonification, nitrification, denitrification) require calibration within SubWet. Once identified, the cold climate default coefficient parameters (located within the parameters window of SubWet) can be modified and the simulation re-run until the best calibration is achieved. Table E-6 summarizes the concentrations of organic nitrogen, ammonium and nitrate within the effluent both entering the wetland (pre-treatment) and exiting the wetland (post-treatment) and identifies the net change in these compounds (e.g., mg/L ammonium loss during treatment). A review of this data indicates that the simulation is under estimating the rate of nitrification since the predicted concentration of ammonium increases (e.g., 81 to 84 mg/L) when in fact the observed values indicate it actually declines (e.g., 81 to 62 mg/L).

Table E-6: A comparison of observed (measured) and simulated removal rates for nitrogen compounds within Bake Lake (Nunavut) effluent after wetland treatment (using cold climate default parameters) prior to calibration. This comparison is being made to determine which processes within the SubWet 2.0 model could be improved through calibration to the Baker Lake wetland. Note: observed and simulated values were obtained from the "Observed values" and "Data sheet" charts accessed through the simulate window of SubWet.

	Org N	*Ammonification* →	Ammonium	*Nitrification* →	NO_2^- / NO_3^-	*Denitrification* →	N_2 (gas)
Obs Δ (mg/L)	57.4 to 0		81 to 62		0.55 to 0.52		
Obs Mass Δ (mg/L)	(+57.4)		(+19)		(+0.03)		
Total Obs loss from **Ammonification** (mg/L)		**57.4**					
Total Obs loss from **Nitrification** (mg/L)				(57.4 + 19) = **76.4**			
Total Obs loss from **Denitrification** (mg/L)						(57 + 19 + 0.03) - 0.52 = **75.5**	
Sim Δ (mg/L)	57.4 to 5.5		81 to 84		0.55 to 4.5		
Obs - Sim Mass Δ (mg/L)	(+51.9)		(-3)		(-3.95)		
Total Sim loss from **Ammonification** (mg/L)		**51.9**					
Total Sim loss from **Nitrification** (mg/L)				(51.9 - 3) = **48.9**			
Total Sim loss from **Denitrification** (mg/L)						(51.9 - 3 - 3.95) = **44**	

Likewise, the rate of denitrification is also too low. The observed loss of nitrate is low, changing only 0.03 mg/L in concentration, however, the SubWet simulation predicted a dramatic increase from 0.55 to 4.5 mg/L. The rate of ammonification predicted by SubWet appears to be more appropriate and simulated results are approximately 10% of the observed results and within the range of acceptability. However, the observed results indicate a complete removal of organic nitrogen from the effluent stream, while SubWet predicts a lower removal rate that results in a final effluent concentration of approximately 5.5 mg/L. Thus the rate of ammonification could also be improved slightly through calibration, although not completely necessary. A review of the overall loss of all nitrogenous compounds (e.g., denitrification) determined through observation (measured) indicates that the concentration was reduced by approximately 75.5 mg/L whereas SubWet predicts only a concentration decrease of 44 mg/L; a significant underestimation of the overall capacity of the wetlands efficiency. In summary, the data suggests that the greatest calibration grains can be made by altering the coefficient parameters associated with both nitrification and denitrification and to a lesser extent ammonificaton in a manner that increases the rate of conversion. However, one should understand the interplay between nitrification and the decomposition of organic matter (e.g., BOD_5) remembering that both these processes are competing for oxygen and thus increasing the rate of nitrification may limit the availability of oxygen for the decomposition of organic matter and result in a higher predicted BOD_5 concentration. The best way to approach the required modifications is to start with the modification of the coefficient parameter associated with denitrification and once done then to increase rates of the parameters associated nitrification and lastly with ammonification.

The rate of denitrification can be increased by: i) increasing the value for the "denitrification rate" (DC) parameter, ii) reducing the "half saturation constant for denitrification" (MN) and iii) reducing the "temperature coefficient of denitrification" (DC) to better reflect the wetland temperature of 8.4°C.

The rate of nitrification can be increased by increasing the value for the "nitrification rate" (NC) parameter. The rate of ammonification can be increased by increasing the "decomposition rate of organic nitrogen" (AC) parameter.

It should be noted that increasing nitrification will mean that more oxygen is consumed in this process resulting in less oxygen available for the decomposition of organic matter which will eventually be expressed as higher BOD_5 values. This would not be wanted since the simulated BOD_5 values are already close to the observed values and any increasing of the BOD may mean that the simulated values become unacceptably high. This effect can be partially overcome by slightly increasing the value of the coefficient parameter governing the "decomposition rate of organic matter" (OC).

A series of simulations were run with modified coefficient parameter values using a "trial and error" approach to determine which modifications provided the best overall simulations. The "trial and error" approach determined that the following parameter modification provided the best results. Table E-7 lists the parameters changed and the final values chosen.

Table E-7: Coefficient parameters for the calibration of SubWet 2.0 to the Baker Lake wetland data

Rate coefficent parameter	Abbreviation	Initial Value	Final Chosen Value	Units
Max. nitrification rate	DC	3.5	5.0	1/24 h
Half saturation constant for denitrification	MN	0.1	0.01	mg N/L
Temperature coefficient of denitrification	TD	1.07	1.05	unitless
Max. nitrification rate	NC	0.9	1.7	unitless
Max. decompositon rate of organic nitrogen	AC	0.9	1.2	unitless
Max. decomposition rate of organic matter	OC	0.2	0.22	1/24h

The calibration efforts significantly improved the nitrification of ammonium as shown in Figure E-33. The simulation of nitrate did improve (e.g., down from a simulated concentration of 5.5 mg/L to 3.5 mg/L) but did not reach the observed value of 0.52 mg/L. However, the overall denitrification rate as shown in Table E-8 did improve significantly. The data shown in Table E-8 indicates that the overall observed loss of nitrogen from the waste stream was 75.5 mg/L and the simulated loss calculated by SubWet after calibration was 70.9 mg/L; a significant improvement from the 44 mg/L (see Table E-6) predicted by SubWet prior to calibration.

It is generally advisable to assess the success of the calibration effort by monitoring the rate of denitrification, nitrification and ammonification rather than the concentrations of individual wastewater parameters. A comparison of the rate values between observed and simulated results is a more robust way to assess the success of the calibrations. For example, in the Baker Lake data, the final calibration values chosen indicated that the overall removal of nitrogenous compounds from the waste stream was between 4 to 6 % of the observed values (see Table E-9). This is well within the acceptable limit for models, despite still having relatively high dissimilarity between the simulated and observed values for nitrate. Although the difference for nitrate does appear unacceptably great, the overall proportional contribution of nitrate is small in comparison to the improved removal of ammonium which was a larger component of the overall loss of the total nitrogenous compounds. It should be noted that these efforts did lower the simulated value for BOD_5, however, even with the lowering of this value, the simulated BOD_5 result was still within 7% of the observed value and thus an acceptable estimate.

Table E-8: A comparison of observed (measured) and simulated removal rates for nitrogen compounds within Bake Lake (Nunavut) effluent after wetland treatment (after calibration of the cold climate default parameters).

	Org N	*Ammonification* →	Ammonium	*Nitrification* →	NO_2^- / NO_3^-	*Denitrification* →	N_2 (gas)
Obs Δ (mg/L)	57.4 to 0		81 to 62		0.55 to 0.52		
Obs Mass Δ (mg/L)	(+57.4)		(+19)		(+0.03)		
Total Obs loss from **Ammonification** (mg/L)		**57.4**					
Total Obs loss from **Nitrification** (mg/L)				(57.4 + 19) **= 76.4**			
Total Obs loss from **Denitrification** (mg/L)						(57 + 19 + 0.03) - 0.52 = **75.5**	
Sim Δ (mg/L)	57.4 to 3.1		81 to 61.5		0.55 to 3.45		
Obs - Sim Mass Δ (mg/L)	(+54.3)		(+19.5)		(-2.9)		
Total Sim loss from **Ammonification** (mg/L)		**54.3**					
Total Sim loss from **Nitrification** (mg/L)				(54.3 + 19.5) = **73.8**			
Total Sim loss from **Denitrification** (mg/L)						(54.3 + 19.5) - 2.9 = **70.9**	

Table E-9: Comparison of simulated and observed concentrations (mg/L) and rates (mg N / L)

Item	Observed value	Simulated value	Deviation %
BOD5	247	230	7
Ammonium	61.9	61.5	0.6
Nitrate	0.52	3.5	-
Organic nitrogen	0.0	3.1	-
Phosphorus	9.4	8.3	13
Ammonification	57.4	54.3	6
Nitrification	76.4	73.8	4
Denitrification	75.5	70.9	6

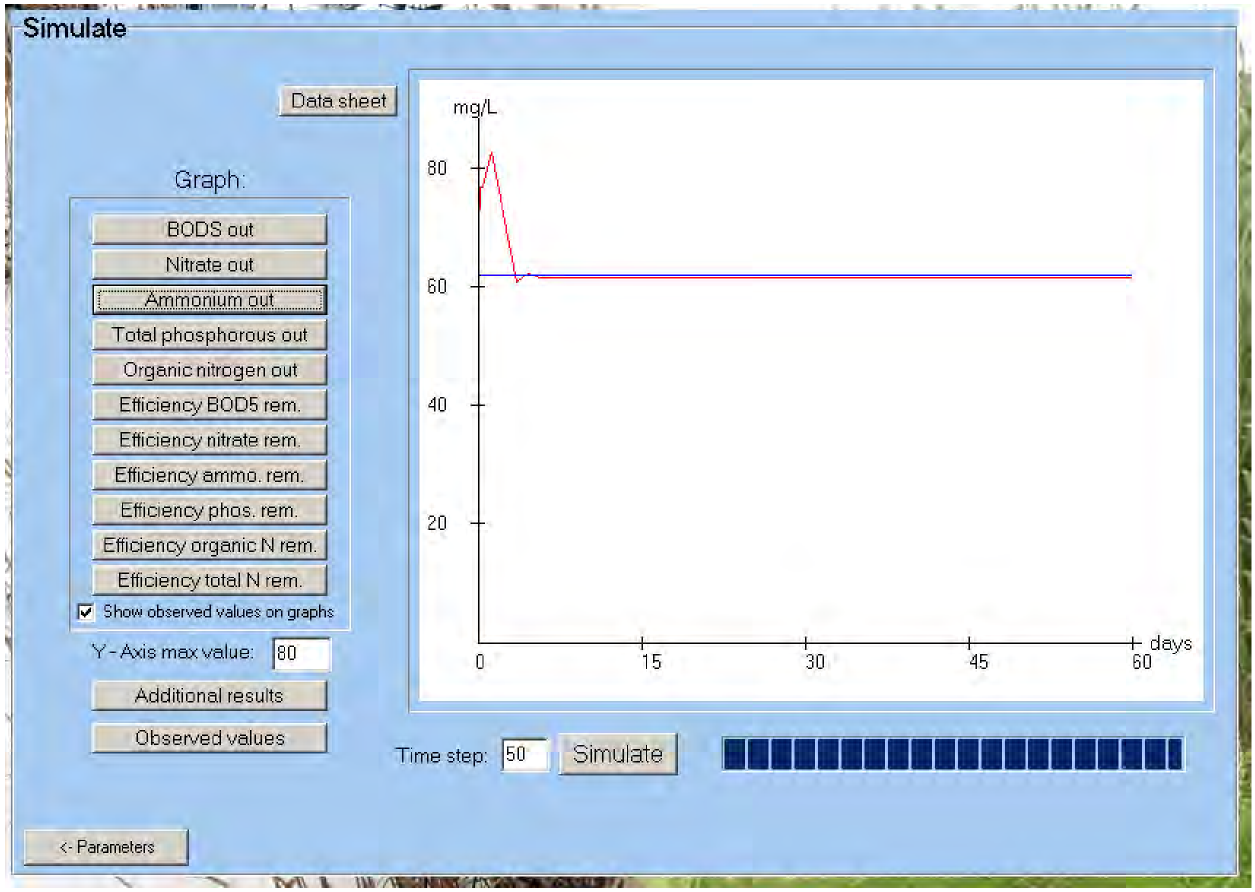


Figure E-33: Simulated ammonium values (red) in comparison to the observed values (blue) after calibration. A comparison to the simulated results generated prior to calibration (see Figure E-31) illustrates that the calibration efforts significantly improved the predictive accuracy of the SubWet model for ammonium.

In summary, the Baker Lake data set provided an example of a more challenging calibration exercise. However, despite the unusually high waste stream strength, the calibration of SubWet demonstrated that this model can provide a reasonable approximation of treatment efficiencies.

SubWet (version 2.0): modelling software for subsurface wetlands

Frequently Asked Questions (FAQs)

1. **Why does SubWet 2.0 have both a cold climate and warm climate entrance?**

   A: SubWet 2.0 has been designed to model the treatment of municipal effluents under two different climatic regimes; both a cold climate and warm climate. The default values determined for the coefficient parameters of the different biochemical processes are temperature dependent and thus these values are different in a cold climate verses a warm climate. The user has the option to choose the default parameters that best represent the climate conditions of the treatment wetland.

2. **What defines a cold climate or a warm climate condition?**

   A: For the purpose of this model, cold climate is defined as sites with temperatures varying between 0°C and up to 22°C in summer; subsurface water temperatures is always above freezing in winter (except in extremely high latitudes where wetlands may freeze in winter, e.g., above 60 degrees North). Warm climate areas are those which typically range in temperatures between 26°C to 34°C.

3. **Can SubWet 2.0 be used to model treatment efficiencies in both natural and constructed wetlands?**

   A: Yes, SubWet 2.0 has been designed to model the treatment in both natural and constructed wetlands. There are some key differences in how SubWet 2.0 manipulates the input data for either natural or constructed wetlands. Some examples include how it determines the number of flow paths, and how it determines the "Recommended horizontal flow".

4. **What are the key differences between natural wetlands and constructed wetlands? How do I know which category to use?**

   A: The SubWet model considers **constructed wetlands** to be man-made features designed with specific dimensions and often filled with crushed stone, gravel or sand as the wetland's subsurface matrix and vegetated with either cattails (*Typha*) or reeds (*Phragmites*), however a variety of species besides the two listed can be used. Because of the artificial substrate, SubWet makes the assumption that the percent particulate matter (AP) within the effluent entering the wetland will be the controlling factor regulating the speed which the effluent travels through the subsurface matrix. SubWet refers to this rate as the "Recommended Horizontal Flow (HF)". To determine the HF, SubWet uses the empirical formula HF = 25 – (8*AP). So for example, if the percent particulate matter is 3% then the HF would equal 1 m / 24h [e.g., 25 – (8*3) = 1 m / 24h].

SubWet defines **natural wetlands** as depressions or lowlands vegetated with water tolerant plant species; most often grasses, sedges and cattails. Natural wetlands do not have well defined boarders and often have soil matrixes of varying depths with variable hydraulic conductivities. Although flow volume and flow paths and flow speeds through the natural wetlands are often difficult to estimate, SubWet still requires an estimate of the hydraulic conductivity of the soil matrix. An estimate of the hydraulic conductivity (HC) is particularly important for operation of the SubWet model since the model assumes that HC will be the factor that limits the rate at which the effluent travels through the subsurface matrix of natural wetlands. Therefore, in the design window (Figure 2 above), SubWet always makes the Recommended Horizontal Flow (HF) automatically equal to the Hydraulic Conductivity (HC) and does not utilize the empirical formula employed when using the constructed wetland mode.

5. **How does SubWet 2.0 take into account the differences between natural and constructed wetlands?**

   A: The design equations are different, considering that the hydraulic conductivity of natural wetlands sometimes is limiting the capacity of the wetland and the gravity and a suitable slope is applied, while constructed wetlands have use gravel with a high hydraulic conductivity and even in some cases use pumping.

6. **How does SubWet define the term "Input Values"?**

   A: Input values are entered into the "Design" window of SubWet. The input values identify key features of the wetland that SubWet will need in order to model treatment of the effluent. Key features include items such as the length, width and depth of the wetland and key factors about the effluent such as volume, and organic content.

7. **Is the Recommended Horizontal Flow (HF) calculated differently for natural wetlands in comparison to how it is calculated for constructed wetlands?**

   A: The hydraulic conductivity of natural wetlands is low and thus SubWet sets the recommended horizontal flow rate equal to the hydraulic conductivity of the subsurface medium of the natural wetland. The subsurface medium chosen for use in constructed wetlands is often chosen to have a high hydraulic conductivity. The horizontal flow rate in constructed wetland is often limited by the percent organic matter within the effluent. The higher the percent organic content is the greater the chance that this matter will begin to plug the interstitial spaces of the medium. Thus SubWet determines the recommended horizontal flow rate by the empirical formula: (25-8*AP) m/24h when the percent particulate matter is greater than 2.5%.

8. **SubWet sets the number of paths (in the Design window) to a value of one for natural wetlands, and a number greater than one for constructed wetlands. What does the number of paths refer to and why does SubWet use a default of one for natural wetlands, but a variable number greater than one for constructed wetlands?**

   A: Constructed wetlands are purposely designed to contain media (e.g., gravel) that has a high hydraulic conductivity. For example it is possible with certain gravels or crushed stone to obtain relatively high horizontal flow rates approaching several metres within a 24 hour period. Typically, the higher the horizontal flow rate, the better the effluent flow will diffuse throughout the entire wetland, meaning that there will be relatively few to any locations within the wetland where the effluent is not flowing (note: no flow areas are typically referred to as “dead zones”). In other words, the effluent will come into contact with all portions of the wetland and the edge effect (e.g., low utilization at the edge of the wetland) will be very low. Greater utilization of the entire subsurface section of the wetland often means that the effluent is taking more than one path through the wetland. Typically, the higher the horizontal flow rates, the greater number of paths are being utilized (e.g., 2, 3, 4 or more paths).

In natural wetlands, the hydraulic conductivity of these natural soils is often very low and therefore it is often not possible to have more than one flow path. For natural wetlands the hydraulic conductivity is often the factor that limits the capacity of the wetland.

9. **How does SubWet define the term "Forcing Functions"?**

   A: The forcing functions are entered into the "Forcing Functions" window. For the most part, these values represent the concentration of wastewater constituents within the effluent entering the wetland prior to treatment. Other values refer to the volume of effluent, the porosity of the subsurface matrix, the length of the simulation to be undertaken, subsurface oxygen concentrations, etc. SubWet uses these values to define the operating conditions.

10. **What values are used for the concentration of oxygen within the five oxygen boxes in the forcing function's window?**

    A: A measured oxygen concentration can be placed into these boxes that correspond to each of the five sections of the wetland's length. If measured concentrations are used, then the measurement should be taken at a point mid-way in the depth of the root zone (e.g., 0.5 * DE). If measured values are not available, then a general rule of thumb is to assume the oxygen concentration is between 70 to 90 percent saturation unless the BOD and concentration of ammonium are particularly high and it is anticipated that the dissolved oxygen levels would be significantly depressed.

11. **How does SubWet define the term "Initial Values"?**

    A: The initial values are entered into the "Initial Values" window. These values provide the starting concentration needed for the 25 differential equations used by SubWet.

12. **How to select the initial values?**

    A: The value selected for Box A is generally slightly lower than for the untreated wastewater while the value for Box E is generally slightly greater than the desired concentration exiting the wetland or a value that is slightly greater than the observed (i.e., measured) concentration exiting the wetland. The values for the remaining three boxes are chosen in a manner that is reflective of intermediate values generally entered in a decreasing manner from Box B to D. Better estimates of these values can be obtained by selecting the values from the “Additional Results” data sheet using the values generated for the last day of the simulated run.

13. How does SubWet define the term “Parameters”?

A: The parameter values are entered into the “Parameter” window. These values are the coefficient parameters utilized by the differential equations. Note: SubWet has developed a set of default parameters for operation in the cold climate mode and another set of default parameters for the warm climate operation mode. Both sets of default parameters are within a common range for that parameter. Modification of these values can be used to calibrate SubWet to site specific conditions.

14. What is PF, the precipitation factor?

A: The precipitation factor accounts for the dilution of the treated effluent that is caused by precipitation and or snow melt.

15. How is the precipitation factor (PF) calculated?

A: The precipitation factor calculated on metrological information regarding precipitation and evapotranspiration rates. If the precipitation exceeds the evapotranspiration by “x” mm/24h and the hydraulic loading is HL m/24h = 1000*HL mm/24h. PF = (1000 HL + “x”) / 1000 HL.

An example: for Chesterfield HL = 0.0007 and if the precipitation per day is 1 mm and the evapotranspiration 0.5 mm. The PF = (0.7+ 1 - 0.5)/ 0.7 = 1.71.

16. How does precipitation factor (PF) change the recommended flow?

A: The flow rate is multiplied by PF to obtain the recommended flow, which should be used in the next screen image named “forcing functions” as the flow.

17. **How does SubWet use the PF value in the calculations?**

A: Each time the PF is applied, the concentration of the wastewater parameters of the effluent flowing into the wetland is divided by the PF value. NOTE: it is important to apply the PF only once, since repeated applications will repeatedly decrease the concentrations. The application of the PF does not alter the flow rate.

18. **Can the precipitation factor be used to factor in the dilution effect caused during spring freshet (melt)?**

A: in theory it should be possible to use the precipitation factor to account for the inflow of melt water into the wetland during spring melt. However, there are other factors that need to be considered when applying the PF in this manner, particularly in regards to natural wetlands used in the far north (i.e., Nunavut, Canada). It is true that many of the natural wetlands are physical depressions in the surrounding landscape and as such they will be a collection place for the melt waters originating from the melting snow pack. If the catchment area of the wetland was known and the water equivalents of the snow pack was determined then in principle one should be able to estimate the amount of new water coming into the wetland during the period of melt. Treatment wetlands used in the far north may also have frozen effluent that has accumulated during winter time conditions. Care should be taken to incorporate the volume of melting effluent into consideration when determining what precipitation factor to apply. In some ways it may be best to attempt to determine what the combined strength of snow melt waters plus frozen effluent would be and how this would impact not only the flow through entering the wetland, but also the strength of the effluent stream which now potentially contains new effluent, snow melt and the melt waters from frozen effluents that may have accumulated over the winter time but are now being released rapidly during spring freshet. In theory, the combined strength and volume of effluent entering the wetland could be determined, however, the logistics of doing this may be challenging.

19. Why is HC, the hydraulic conductivity important?

A: Because it may limit the capacity of the natural wetlands. If RF / (HC*S*DE) > LE then the wetland will not have a capacity sufficient (at least not by use of the gravity) to accommodate subsurface flow. Note, if the volume of wastewater to be treated is greater than the hydraulic capacity of the wetland for subsurface flow, then the excess wastewater volume will likely flow overland on the surface (not subsurface). Wetland treatment of the surface flowing wastewater can still occur, but most likely at a reduced efficiency (rate). In cases where a portion of the wastewater is flowing over the surface SubWet can still be used to model treatment since SubWet 2.0 has been previously used on surface wetlands with laminar flows. This will be accomplished by calibration of the model to the site conditions. SubWet 2.0 cannot be used where the surface flow are turbulent (not laminar).

20. Is the hydraulic conductivity important for constructed wetlands?

A: Usually not, because gravels with sufficiently high HC can be chosen.

21. What can we do if the capacity is not sufficient for a natural wetland to treat the wastewater?

A: The effluent entering a natural wetland may not preferentially flow to all parts of this natural wetland area with the result that only a portion of the natural wetland is actually involved in the treatment of the municipal effluent. In some cases, it may be possible to alter the flow of effluent so that it flows to all parts of the wetland. It might be possible to accomplish this through a variety of alterations to the wetland such as the digging of trenches or the erecting of berms to redirect flow to areas previously inactive in the treatment of the effluent.

22. What is the load capacity limitations for wetlands?

A: HL = 0.16 m/24h or 160 l / 24h m^2 can be considered the capacity limit. This is generally considered to be a general rule of thumb determined from case studies of other wetlands treating municipal waste. However, it may be possible to obtain a higher capacity if the wastewater was more dilute that typical municipal wastewater.

23. How to select the depth (DE) of the wetland in put value?

A: DE should correspond to the root zone. For tundra it is generally in the range of 0.3-0.5 m and for tropical wetland with Phragmites it is approximately 0.8-1.2 m. For temperate wetland with Phragmites the approximation is closer to 0.7 – 1.0 m.

24. What is the retention time in one box “RTB”?

The SubWet program divides all wetlands into five (5) boxes of equal size. The program assumes the effluent will travel sequentially from the first to the second and ultimately to the fifth box of the wetland. SubWet employs a modified “Tank in Series dispersion Model” to reflect that the effluent does not travel through the wetland as plug flow. SubWet has assumed that a total of five tanks in series best reflect the conditions within wetlands (both natural and constructed). SubWet sets the number of boxes (tanks) to “5” for pragmatic reasons. A higher number of boxes would require a more sophisticated modeling approach that currently offered by SubWet, and yet a lower value would yield less accurate results. Thus setting SubWet to run with 5 boxes is a tradeoff between the requirements for greater model complexity ease of use, while maintaining acceptable accuracy. The value for the “water flow” (see above) needs to be filled in before the RTB can be calculated. SubWet determines the retention time for each of the boxes in the following manner: In the Chesterfield Inlet example, the void volume of the wetland is 4122.36 m3, the daily inflow is 36 m3/d meaning that the hydraulic retention time is 4122.36 m3 / 36 m3/d = 114.5 days. One fifth of this time is 114.5 d / 5 = 22.9 days.

25. How is RTB calculated?

A: The water volume/RF = VO*porosity/RF

26. What is the importance of RTB?

A: It is important that the retention time in the wetland (= 5* RTB) is sufficient to ensure the required treatment results. RTB is used in the calculations to find the treatment result in one box (tank), which determines the water quality (the water analyses) of the water flowing out of the tank (box) to the next tank.

27. What does the warning given in red "Simulation length too small" mean?

A: This message means that the simulation length is too small to ensure that the results reach steady state. The observation of fluctuating quality in the beginning of the simulation means that the initial values inputted into SubWet did not reflect the steady state conditions (predicted by SubWet). The closer the chosen initial values are to the values predicted by SubWet to reflect a steady state condition, the less the fluctuations will be. If the initial values are chosen precisely, it may even be possible to ensure no fluctuations, meaning that the model would reach a steady state in a very short period of time (e.g., simulated days). It should be noted that reaching steady state within SubWet has no correlation with reaching steady state within the wetland (natural or constructed).

28. When should SubWet be calibrated and how is this done?

A: An attempt should be made to calibrate SubWet if the simulated values for BOD_5, Nitrate, Ammonium, Total Phosphorus, and Organic Nitrogen are significantly different (e.g., >20%) from the measured values. Calibration is accomplished by altering the default coefficient parameters on the Parameters" window. The choice of which parameters to alter depends on which simulated wastewater parameters are not in agreement with measured values. The following outline the list of coefficient parameters and the overall effect resulting from the lowering or raising of these values. The value in parenthesis represents the cold climate default value.

- AC = 0.05- 2.0 [default value 0.9 (1/24h)] *increase value = increased reaction rate*

- NC = 0.1- 2.5 [default value 0.9 (1/24h)] *increase value = increased reaction rate*
- OC = 0.05- 2.0 [default value 0.25 (1/24h)] *increase value = increased reaction rate*
- DC = 0.00-5 [default value 3.5 (1/24h)] *increase value = increased reaction rate*
- TA = 1.02- 1.06 [default value 1.05 (no unit)] *increase value = increased temperature sensitivity*
- TN = 1.02- 1.09 [default value 1.07 (no unit)] *increase value = increased temperature sensitivity*
- TO = 1.02- 1.06 [default value 1.04 (no unit)] *increase value = increased temperature sensitivity*
- TD = 1.05- 1.12 [default value 1.07 (no unit)] *increase value = increased temperature sensitivity*
- KO = 0.1-2 [default value 0.01 (mg/l)] *increase value = slightly decreased reaction rate*
- OO = 0.1-2 [default value 0.05 (mg/l)] *increase value = slightly decreased reaction rate*
- MA = 0.05-2 [default value 0.1 (mg/l)] *increase value = slightly decreased reaction rate*
- MN= 0.01-1 [default value 0.1 (mg/l)] *increase value = slightly decreased reaction rate*
- PA= 0.00-1 [default value 0.01 (1/24h)] *increase value = increased reaction rate*
- PN=0.00-1 [default value 0.001 (1/24h)] *increase value = increased reaction rate*
- PP= 0.00-1 [default value 0.001 (1/24h)] *increase value = increased reaction rate*
- AF= 0-100 [default value 0.36] *increase value = increased reaction rate*

29. Are the ranges of parameter values limited?

A: Yes. The ranges are summarized in the SubWet manual and also within the SubWet 2.0 program file. To view in the program file, go to the "Parameter" window and move the cursor over top of the abbreviation for the parameter of interest. Once done, the range will be shown. When modifying the parameter values, all modifications should remain within the established range and only in very rare conditions should attempts be made to choose values outside of that range.

30. Which time step should be chosen for the simulations?

A: It is recommended that a time step of 100 be used (meaning that the integration time step is 1/100 of 24 hours). This value should be more than sufficient to ensure an acceptable level of accuracy. SubWet can perform all computations quickly and thus there is generally no need to reduce this step value for the sake of speed.

31. Is it possible to see the calculated concentrations day by day in the five boxes?

A: Yes, go to additional results and there the concentrations of the five state variables are shown day by day for all five boxes.

32. What are the major factors limiting the use of SubWet 2.0.

A: In general, SubWet 2.0 cannot be used if the wetland is overloaded, corresponding to a HL > 0.16 m/24h. In terms of its application to natural wetlands, there are several factors that could impact its overall effectiveness. These refer primarily to:

a) a lack of site specific knowledge concerning the hydrology and overall movement of the effluent through the wetland. Natural wetlands often have preferential flow paths that can be seen on the surface of the wetland; however, it is often difficult to determine flow rates and volumes of these paths. It is even more difficult to determine preferential flow paths occurring subsurface. These factors make it difficult to determine averaged hydraulic conductivity times (contact times).

b) the fact that it is often difficult to determine the influence of water inflow (either in the form of ground water intrusion or surface inflow) and thus it is difficult to determine the proportion of treatment that could be attributed to dilution.

c) The irregular shape of wetlands and changes in elevation together with changing substrate make modeling sometimes difficult.

33. Which waste water constituents are the most difficult to reduce?

A: BOD_5 and ammonium, and sometimes phosphorus. However the decomposition of organic matter (BOD_5 and organic nitrogen) is generally efficient in wetlands. Nitrate removal is also generally efficient since most subsurface flow wetlands have anaerobic zones where denitrification can take place. However, in some subsurface flow wetlands the presents of aerobic zones can be limited meaning that nitrification is limited and therefore the removal of ammonia is correspondingly low. If the phosphorus adsorption capacity of the soil is limited, it may also be a problem to obtain sufficient removal efficiency for phosphorus.

34. If it is found that the BOD_5 results are not acceptable what can be done to improve the removal of BOD_5?

A: In most cases, an insufficient reduction in BOD_5 is related to the wetland area being too small. SubWet can be used to determine what size of wetland would be needed to achieve the desired results.

35. If it is found that the ammonium results are not acceptable what can be done to improve the removal of ammonium?

A: Nitrification may often be insufficient, while the other results are acceptable. It is difficult in most cases aeratethe wetland and thereby enhance the nitrification. On occasion increased nitrification can be achieved if the wastewater is well oxygenated prior to its inflow into the wetland. , This can be accomplished by pre-treatment in an aerated lagoon.

36. It is found that the organic nitrogen results are not acceptable what can be done to improve the results?

A: Decomposition of organic nitrogen may be insufficient, while the other results are acceptable. In this case it is sometimes necessary to oxidize the wastewater before the treatment on the wetland to get a better decomposition of the organic nitrogen before treatment by the wetland.

37. Is removal of nitrate- nitrogen an important problem for wetlands?

A: Denitrification is generally not a problem in wetlands. However, if it is anticipated to be a problem for a constructed wetland, then during the design phase, the depth of the constructed wetland could be increased to ensure an increase in the anaerobic zone needed for denitrification.

38. What can be done if the phosphorus removal in the wetland is insufficient?

A: Little can generally be done for natural wetlands since removal rates are governed by *in situ* adsorption processes and plant uptake/release mechanisms. Within constructed wetlands there is always the option to choose the substrate media to be one that has a high phosphorus adsorption capacity. Additives to the effluent entering the wetland or to the wetland media such as iron sulfate, iron chloride or aluminum sulfate can be applied to cause precipitation of the phosphorus from solution. However, care should be taken since the precipitated material could plug inter-gravel spaces and thus significantly decrease the hydraulic conductivity of the subsurface medium. Phosphorus and nitrogen may be transferred to the tissue of the wetland vegetation; however, if plant tissue is not harvested before the plant dies, then the decay of the plant may cause a release of the phosphorous back into the wetland. The plants should be harvested when they have the highest concentration of nitrogen and phosphorus. This time is dependent on the climate, however, in temperate zone (latitude 40-55) the highest concentrations of nitrogen and phosphorus in the plants is generally found between September 15^{th} to 30^{th}. By harvest in this period it is possible to remove up to 200-250 kg nitrogen and 25-30 kg phosphorus per ha.

39. Which Arrhenius Constants are applied for the different processes in the SubWet 2.0 model?

A: Nitrification and denitrification are relatively more sensitive to temperature changes (particularly the nitrification process) and because of this the Arrhenius Constant applied is generally higher – 1.07, 1.08 and even 1.09 in some situations. For the decomposition of organic matter and organic nitrogen compounds an Arrhenius Constant of 1.05 is generally applied.

40. What is the connection between the denitrification process and the decomposition of organic matter?

A: Denitrification is a reaction where nitrate is oxidizing organic matter: Organic matter + nitrate are converted to CO2 + H_2O + N_2. The organic matter decomposed by the denitrification process is of course included in the calculation of the resulting BOD_5.

41. How is the coupling established in the model between the BOD_5 reduction and denitrification?

A: For 1 mg nitrate – N removed by denitrification, 1.97 mg organic matter expressed as BOD_5 is decomposed, corresponding to the chemical equations for the oxidation of organic matter.

42. Can SubWet be used in natural wetlands that exhibit both subsurface flow and overland flow?

A: SubWet was developed to model biochemical processes associated with the treatment of effluent flowing subsurface. As mentioned in Q19, SubWet 2.0 can also be applied for surface wetlands, provided that the flow is laminar and not turbulent. The parameters are different for the two types of flow, indicating that the subsurface flow is more effectively per ha than the surface wetland.

43. **Can SubWet be operated and expected to perform correctly if the initial concentrations of all wastewater constituents are not available for inputting into the Forcing Function window?**

A: The more information SubWet has to work with the better the simulation. There are key constituents concentrations that are needed since these are the core of what SubWet is trying to model and as such it needs an initial concentration or starting point. For example, SubWet requires an initial concentration for both BOD_5 and Ammonium and most often Organic nitrogen. BOD_5 and Ammonium are particularly important since the oxidation of organic matter and the nitrification of ammonium both consume oxygen and therefore these two processes are interlinked within the SubWet program. Other constituents like phosphorous are removed through adsorption processes are modeled independently and thus the absence of this value would not impact the simulation of BOD or Ammonium. In practice if effluents are pretreated in sewage lagoons, the ammonification of organic nitrogen may have already taken place before the effluent reaches the wetland and in situations where this is expected to have occurred, then a value for organic nitrogen may not be available. Likewise, if the sewage lagoon is aerated, the nitrification of ammonium to nitrate may have also taken place prior to the effluent entering the wetland. In situations where the concentrations of organic nitrogen or nitrate are unknown, a standard lower detection limit for that constituent can be substituted instead. This value is often placed at 0.0001 mg/L and it is necessary to apply this value rather than zero which will cause SubWet to malfunction.

The constituents POM%, PON% and POP% are generally not routinely monitored and as such are often not available unless specifically analyzed for. Once again, if values for these constituents are not available then the default value of 0.0001 mg/L should be applied. Low values of POM, PON and POP are considered to be values less than 0.1%. At these low levels SubWet is not very sensitive to these constituents. In wetlands, values are rarely observed above 0.1%.

44. What value for BOD_5 should be used if you only have $cBOD_5$?

A: The biochemical oxygen demand (calculated after a 5 day incubation period) measures the concentration of oxygen consumed (mg/L) from both the carbonaceous oxygen demand and the nitrogenous oxygen demand. The parameter $cBOD_5$ measures only the carbonaceous oxygen demand. The value $cBOD_5$ should be applied in SubWet 2.0 because the decomposition of BOD_5 and organic nitrogen are considered as two separate processes within this model. Thus SubWet already treats both of these processes separately in its calculations. In most cases, BOD_5 and $cBOD_5$ can be used interchangeably with little influence on the simulated results. In other words, the values for BOD_5 and $cBOD_5$ are generally considered similar for modeling purposes.

45. Does SubWet require values for the concentration of ammonia – nitrogen (NH_3 – N) or only the ammonium ion - nitrogen (NH_4^+ - N)?

A: Subwet models the ammonium ion since the pH of most wetlands is near neutral and not basic enough to shift the equilibrium to the ammonia – nitrogen form.

46. How important is it for the simulation to reach a steady state condition?

A: the simulated values generated by SubWet can be variable and fluctuate widely before the program has reached a steady state condition. Therefore the best results from the simulation will be obtained after the model reaches steady state. The steady state condition will be identified once the simulated values become more or less stable. There will always be fluctuations in the simulated values; however, the magnitude of the fluctuations will be relatively small and stable in size.

47. Is there a relationship between the number of days for the SubWet program to reach a steady state and the number of days for the wetland to reach steady state?

A: The time for SubWet 2.0 to reach steady state is very dependent on the initial values for the five boxes. In the real situation the initial values are dependent on the water that has been treated before it enters the wetland and the length of time since the last addition of the effluent to the wetland took place. Generally, it would take 2-5 times the retention time of the entire wetland (= 5 tanks) to achieve steady state but it will ultimately dependent on the initial conditions of the effluent entering the wetland or the analytical values for the five boxes for the simulated results.

48. **How many data sets were used to develop and calibrate SubWet to a warm climate mode of operation?**

    A: SubWet was developed to model the performance of constructed wetlands in Tanzania, eastern Africa. The model was calibrated using the data from 9 wetlands.

49. **How many data sets were used to develop and calibrate SubWet to a cold climate mode of operation?**

    A: SubWet was calibrated for operation in a cold climate mode using the data from five natural tundra wetlands of Nunavut, Canada.

50. **When entering a value for POM, PON or POP it is entered as a percent or a fraction? For example in the Baker Lake data, the value for POM% is 0.003. Does this mean the percent value is actually 0.3% or 0.003%?**

    A: the value is to be interpreted as a percentage. Thus 0.003 is actually 0.003%.

51. **Could the SubWet program ever be modified to model other wastewater constituents?**

    A: Yes but it would require that the additional constituents are included in the equations of the software. It would require some time but it could be done fairly easily.

52. **Once SubWet has been calibrated to a specific wetland, can the calibrated SubWet be used to determine a change in effluent volumes entering the wetland?**

    A. Yes, all calculations with SubWet 2.0 have a standard deviation in the order of 10 to 20% base on approximately 25 wetlands data sets.

Appendix F: Sample calculation of the percent deviation of concentration values for Whale Cove, NU data set

Table F-1: Sample calculation of the percent deviation of concentration values for Whale Cove, NU data set

Effluent observed values (mg/L)	Simulated effluent values before calibration (mg/L)	Model parameter default values	Parameter value after calibration	Effluent concentration values after calibration (mg/L)	% deviation of effluent values before calibration (mg/L)	% deviation of concentration values after calibration (mg/L)
BOD_5 = 21	BOD_5 = 8.6	OC = 0.25	OC = 0.05	BOD_5 = 20.89	64% *	0.52% **
TP = 0.1	TP = 1.46	AF = 0.36	AF = 0.2	TP = 0.23	34%	3.25%
NH_3-N = ok, no calibration						

* 40.3 mg/L (observed influent value) - 21 mg/L (observed effluent value) = 19.3 mg/L
40.3 mg/L - 8.6 mg/L (simulated value before calibration) = 31.7 mg/L
40.3 mg/L - 20.89 mg/L (simulated value after calibration) = 19.4 mg/L
Therefore: 31.7 mg/L - 19.3 mg/L = 12.4 mg/L
12.4 mg/L / 19.3 mg/L = 64%

** 19.4 mg/L - 19.3 mg/L = 0.1 mg/L
0.1 mg/L / 19.3 mg/L = 0.52%

Note: The observed influent and effluent values are used to calculate the % deviation of effluent values before and after calibration to actually see how the wetland is reducing each parameter (instead of simply calculating the difference in % between observed and simulated values).

Appendix G: Constructed wetland and engineered wetland systems classification derived from functional definitions coupled with brief descriptions as well as relevant references.

Table G-1: Functional Definitions of Types and Sub-Types of CW and EW Systems (Adapted from Mbuligwe *et al.*, (2011))

Wetland System Type: Main Types	Wetland System Type: Sub-Types		Wetland System Main Distinguishing Feature	Main/specific Applications	Relevant References
Surface flow (SF)			Wastewater flows horizontally through the system for treatment; the water surface is always above the wetland media top level	Secondary and tertiary level conventional wastewater treatment applications	(Kadlec & Wallace, 2009; Reed *et al*., 1995; Crites & Tchobanoglous, 1998; Kadlec & Knight, 1996; Mitsch & Gosselink, 2000; Kadlec *et al*., 2000; Metcalf & Eddy,1991; Patrick, 1994; Cooper *et al*., 1996; Cooper, 2001; Cooper *et al*., 1998; Campbell & Ogden, 1999; Suthersan, 1999; Cooper & Findlater, 1990)
Sub-surface flow (SSF)	Horizontal flow (HF) wetland system		Wastewater flows through the system for treatment horizontally, but the water surface is always below the wetland media top surface	Secondary and tertiary level conventional wastewater treatment applications	(Kadlec & Wallace, 2009; Reed *et al*., 1995; Kadlec & Knight, 1996; Mitsch & Gosselink, 2000; Kadlec *et al*., 2000; Metcalf & Eddy,1991; Patrick, 1994; Cooper *et al*., 1996; Cooper, 2001; Cooper *et al*., 1998; Campbell & Ogden, 1999; Suthersan, 1999; Cooper & Findlater, 1990)
	Vertical flow (VF) wetland system	Vertical downflow (VD)	Wastewater flows through the wetland system for treatment in the downward direction, flow is applied intermittently	Secondary and tertiary level conventional wastewater treatment applications	(Kadlec & Wallace, 2009; Mitsch & Gosselink, 2000; Cooper *et al*., 1996; Cooper, 2001; Cooper *et al*., 1998; Campbell & Ogden, 1999; Suthersan, 1999; Cooper & Findlater, 1990)
		Vertical upflow (VU)	Wastewater flows through the wetland system for treatment in the upward direction. The flow is applied continuously	Treatment of wastewater containing volatile substances such as VOCs	Kassenga, 2003

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