Developing an Understanding for Wastewater Treatment in Remote Communities in Nunavut, Canada

Investigating the Performance, Planning Practice and Function of Tundra and Constructed Treatment Wetlands

by

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Author’s Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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ABSTRACT: Since humans began to permanently settle locations for extended periods of time there has been the challenge to safely dispose of, or treat human effluent. In specific to the communities of Nunavut and Arctic Canada, the treatment of wastewater has been particularly challenging. The harsh climate, remote nature and socio-economic factors are a few of the aspects which make the treatment of wastewater problematic in Canadian Arctic communities.

In the past several decades a number of conventional and alternative wastewater treatment systems (e.g. lagoons and tundra wetlands) have been proposed and implemented in Nunavut and other remote Arctic communities. Knowledge of performance of these systems is limited, as little research has been conducted and regulatory monitoring has been poorly documented or not observed at all. Also, in the past, the rational design process of treatment systems in Arctic communities has not acknowledged cultural and socio-economic aspects, which are important for the long-term management and performance of the treatment facilities in Arctic communities.

From 2008 to 2010 I characterized and studied the performance of several tundra wastewater treatment wetlands in the Kivalliq Region of Nunavut, as well as two in the Inuvaliat Region of the Northwest Territories. Performance testing occurred weekly throughout the summer of 2008. Characterization included surveys of plant communities in the tundra wetlands, specifically analyzing the relationship between *Carex aquatilis* and various nutrient contaminants in wastewater. Through their characterization I was able to provide greater insight into primary treatment zones within the wetland, and identify the main potential mechanisms for the treatment wastewater in the Arctic. I also studied the performance of a horizontal subsurface flow (HSSF) constructed wetland in Baker Lake Nunavut; the first system of its kind in the Canadian Arctic.

The weekly performance study showed average weekly percent reduction in all parameters, with small deviations immediately after snow-melt and at the beginning of freeze-up. For the six parameters monitored I observed reductions of 47-94% $cBOD_5$, 57-96% COD, 39-98% TSS, >99% TC, >99% *E. coli*, 84-99% NH_3-Nand 80-99% TP for the six tundra treatment wetlands. Whereas, the wetland characterization study through the use of spatial interpolations on each of the wetlands and their water quality showed that concentrations of the wastewater parameters decreased the most in the first 100m of the wetland in all three treatment wetlands used in this portion of the analysis (Chesterfield Inlet, Paulatuk and Ulukhaktok). Areas of greatest concentration where shown to follow preferential flow paths with concentrations decreasing in a latitudinal and longitudinal direction away from the wastewater source. The Paulatuk and Ulukhaktok treatment wetlands were observed to effectively polish pre-treated wastewater from the facultative lake and engineered lagoon, with removals of key wastewater constituents of $cBOD_5$, TSS and NH_3-N to near background concentrations. And despite the absence of pre-treatment in Chesterfield Inlet, the wetland was also observed to effectively treat wastewater to near background concentrations. Further characterization on the composition of the sedge *C. aquatilis*, showed a high percent cover of the species corresponded with areas of high concentration of NH_3-N in the wastewater. A principal components analysis verified the spatial results showing correlation between *C. aquatilis* cover and NH_3-N concentrations. Analysis also showed strong positive relationship between sites closer to the source of wastewater and *C. aquatilis*. No correlation was found between the other parameters analyzed and *C. aquatilis*.

The first year of study of the HSSF constructed wetland showed promising mean removals in $cBOD_5$, COD, TSS, *E. coli*, Total Coliforms, and TP throughout the summer of

2009; removals of 25%, 31%, 52%, 99.3%, 99.3%, and 5% were observed respectively. However, the second year of study in 2010 the system did not perform as expected, and concentrations of effluent actually increased. I concluded that a high organic loading during the first year of study saturated the system with organics.

Finally, a review of planning process and regulatory measures for wastewater in Arctic communities and the impending municipal wastewater standards effluent resulted in the following recommendations; i) wastewater effluent standards should reflect the diverse arctic climate, and socio-economic environment of the northern communities, ii) effluent standards should be region or even community specific in the Arctic, and iii) for planning and management of wastewater incorporation of Inuit understanding of planning and consultation needs to be incorporated in the future.

This research has several major implications for wastewater treatment and planning for Nunavut and other Arctic Regions. The performance and characterization of tundra treatment wetlands fills significant gaps in our understanding of their performance and potential mechanisms of treatment, and treatment period in the Kivalliq Region. Although the HSSF constructed wetland failed, further research into engineered/augmented treatment wetlands should be considered as they provide low-cost low maintenance solutions for remote communities. Finally, the data collected in this study will provide significant insight into the development of new municipal wastewater effluent standards for northern communities, which will be reflected in the *Fisheries Act*.

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INTRODUCTION

The congregation of human individuals in a single permanent location for extended periods of time has demanded the need for methods to dispose of, or treat wastes, particularly those of human origin. There has been evidence of such activity throughout various periods of human history and development, and it was even well documented during the time of ancient Athens (Tchobanoglous, 1979). Public health concerns related to sanitation have led to numerous epidemics, such as cholera, which occurred throughout Europe and has been recorded since the 14^{th} Century. During the early to mid-19^{th} Century, scientists of the day such as Philip Carpenter linked unsanitary conditions in both European and North American cities to high death rates (Bellhouse & Genest, 2005). A British Medical Journal poll listed sanitation as the single most important medical advance since 1840 (Ferriman, 2007).

Approximately a century after Carpenter's writings, similar unsanitary conditions were arising in aboriginal communities of the Canadian north (sub-Arctic and Arctic). Changes in settlement patterns similar to those in the early North America and European settlements led to unsanitary conditions and outbreaks of disease (Chabot & Duhaime, 1998). Then and now, several factors compound the problem of sanitation in Arctic communities including the climate, their remote localities and in some cases the physiographic features. Experts in sanitation and wastewater treatment have proposed and implemented conventional techniques in the Canadian Arctic with varying degrees of success, in terms of i) performance of the technology and ii) acceptance or understanding by the community (Dawson & Grainge, 1969; Grainge, 1969; Miyamoto & Heinke, 1979). However, there remains a great deal of uncertainty with regards to which approaches are most suitable for Canadian Arctic communities. This uncertainty is because there is limited knowledge on how Arctic environments respond to increased loads of nutrients and water, and how conventional systems respond to Arctic conditions (Johnson & Wilson, 1999). Also, socio-economic issues are an ever present issue; related to a lack resources and trained personal as well as other factors (Johnson, 2010). Further, there is distrust caused by a lack of communication and discussion between Inuit groups in the Canadian Arctic and the government agencies over treatment approaches, and more recently concerns over compliancy to regulatory standards (Johnson, 2008).

Planning/Regulation of Wastewater in the Arctic

The current uncertainty over appropriate wastewater treatment methods in Nunavut and the lack of Inuit participation in the planning process demands the need for a redirection of the wastewater management planning approach (Johnson, 2008; Johnson, 2010). One interpretation is that there is a fundamental difference between Inuit and southern perception of planning. Bates (2007) described the Inuit understanding of planning to be largely based on necessity and first-hand knowledge. Inuit may prefer adaptive methods rather than predictive, and eliminate uncertainty and risk through practical applications (Suluk & Blakney, 2008; CAID, 2011). The use of technologically pragmatic and non-cumbersome treatment systems conforms to adaptive methods of wastewater planning.

Consultation conducted for new wastewater regulatory standards on behalf of Environment Canada further revealed significantly different perceptions of what is considered adequate consultation by Inuit and First Nations groups (Environment Canada, 2009). Inuit wish to have the flexibility to determine their own future. Top down approaches of wastewater planning, which aboriginal organizations suggest has been primarily used throughout the *Canada-wide Strategy for the Management of Municipal Wastewater Effluent* document, are an example of this (Johnson, 2008). Aboriginal groups requested that the definition of adequate consultation with aboriginals be re-worked to best reflect their definition of consultation. Despite this request, and resulting new consultation guidelines (Department of Indian Affairs and Northern Development, 2011), this process may or may not be reflected in the consultation process in the design of new treatment facilities by industry who will be responsible for the guiding communities towards selecting appropriate technologies.

Current Practice of Wastewater Treatment in the Canadian Arctic

The management and treatment of wastewater is regulated in Nunavut, by the Nunavut Water Board with inspection by Department of Indian and Northern Affairs Canada. Despite this little is known in regards to the performance of the current wastewater treatment systems because of community/region capacity issues to monitor wastewater effluent into the receiving environment. Wastewater treatment in the Arctic is largely done through the use of basic and less expensive technologies, such as engineered lagoons and land treatment (tundra treatment wetlands). Engineered lagoons can be defined as engineered or earthen ponds which are used to stabilize wastewater through a combination aerobic, and anaerobic processes or those processes individually (Crites & Tchobanoglous, 1998),whereas land treatment involves the treatment of wastewater through its application on land using methods of overland flow, rapid-infiltration or irrigation systems making use of the soil surface, plants and soil matrix to help treat the wastewater. Treatment wetlands are one example of land treatment.

Currently in the Inuit regions of the Canadian Arctic there are only a few mechanical systems in use (See Chapter 1). Facultative lakes, lagoons and wetlands are among the most common technologies employed across the Arctic communities; e.g. Annak Lake; Sanikiluaq, Nunavut. Facultative lakes are natural lakes which are used to dispose wastewater in. Treatment occurs in a similar manner as to engineered facultative lagoons, where there is an aerobic zones near the surface, caused by surface mixing and an anaerobic treatment zone at the bottom of the lake (Tchobanoglous, 1979). Tundra treatment wetlands are tundra landscapes designated to receive and treat municipal wastewater through natural processes of biological action, absorption and sedimentation in the landscape before discharging into a body of water; most commonly the ocean in Inuit communities.

Current Understanding of Wastewater Planning and Treatment in the Canadian Arctic

In the Canadian Arctic wastewater treatment facilities such as lagoons and wetlands are largely designed and managed using southern engineering standards, adopting design models to reflect Arctic temperature (Heinke et al., 1991; Kadlec & Johnson, 2008; Prince et al, 1995). Since the 1970's our knowledge of wastewater treatment in remote Canadian Arctic communities has grown very little despite a half-century of operation. Much of our understanding has been developed from site specific consultant and government reports [see Dillon Consulting Limited (2009) and Environment Canada (1985)], and only a few peer reviewed articles, as well as conference proceedings [see Miyamoto & Heinke (1979) and Johnson & Wilson (1999)].

The articles I have listed above primarily address performance of lagoon treatment systems. Only Doku & Heinke (1995) discuss the potential for greater use of natural and constructed wetlands to treat wastewater in Northern Canada in detail. Dubuc et al. (1986) represents the very few studies to investigate long-term performance of wetlands in Northern Canada, with a study in a hydro-construction camp along the 55th parallel in Quebec. To date no long-term monitoring of treatment wetlands has occurred in Nunavut. Nor has there been any extensive discussion or study of mechanistic functions of tundra wetlands to treat wastewater in peer-reviewed literature. Currently the closest approximation for mechanistic functionality in Arctic treatment wetlands is drawn from cold temperate climate regions of southern Canada, Scandinavia and northern United States; examples from extensively studied locations being from Minot Wetland in North Dakota and Houghton Lake wetland in Michigan (Hammer & Burckhard, 2002; Kadlec, 2009). Only an article by Kadlec & Johnson (2008) addresses some mechanistic function in a Nunavut treatment wetland, but does not provide significant background data. Further, much of the current knowledge on plant and microbial influence on wastewater treatment in the Arctic derives from smaller-scale fertilizations and carbon cycling studies in different Arctic environments [see works by Shaver & Chapin (1995), Arens et al. (2008), and Edwards & Jefferies (2010)].

Little attention has also been given to the planning practice of wastewater treatment in the Canadian North, let alone Nunavut. Ritter (2007) and Johnson (2010) only briefly touch upon the issue of planning and wastewater management in remote northern aboriginal communities. The remainder of current thought on the subject relies on contributions from indirect sources on waste management and contamination in the Arctic [see Berkes et al. (2007) and Environment Canada (2009)].

There is a clear absence of seasonal and long-term performance of tundra treatment wetlands. Therefore, unsurprisingly we know even less with respect to treatment mechanisms in tundra treatment wetlands. There are also apparent gaps in our understanding of how to approach planning and management of wastewater in remote northern communities. Finally, some attention also needs to be given to testing alternative technologies for wastewater treatment, such as constructed wetlands in these remote communities.

Potential for Constructed Wetlands in Arctic Communities

Constructed (engineered) wetlands (CWs) have been applied around world in numerous climates (Vymazal, 2005; Vymazal, 2011; Wittgren & Maehlum, 1997). Most definitions of CWs simply acknowledge a CW as a man-made structure that emphasizes the natural characteristics of wetlands to transform and absorb contaminants (Kadlec & Wallace, 2009). Vymazal (2005) provides a similar definition: "CWs are engineered systems that have been designed and constructed to utilize natural processes involving wetland vegetation, soils and the associated microbial assemblages to assist in treating wastewaters." Throughout this paper I define CWs in the following manner: CWs are engineered systems which are lined to prevent significant exfiltration of wastewater into the underlying ground prior to passing through the system, and maintain mechanisms to control influent and effluent flow. Wetland systems which do have some engineered structures, such as berms, inflow/outflow pipes or make use of natural liners such as bedrock are not described in this thesis as CWs, but rather as augmented natural wetlands.

CWs have shown great promise as alternative low-cost technologies to treat wastewater in remote, economically compromised regions and small communities even in challenging climatic conditions (Kivaisi, 2001; Merlin et al., 2002; O'Hogain, 2008). However, despite their extensive successful use in cold-temperate climates around the world (Jenssen et al., 2005;

Wallace et al., 2001; Wittgren & Maehlum, 1997), they have yet to be tested in extreme cold climate conditions, like the Canadian Arctic. Communities in the Canadian Arctic in theory make excellent candidates for alternative wastewater treatment technologies, because of limited economic resources, physiographic characteristics and trained personnel to operate and maintain more conventional mechanical treatment facilities (Johnson, 2010). Also, for a number of decades communities in the Canadian Arctic have been using tundra wetlands to treat their wastewater (Kadlec & Johnson, 2008; Wootton & Yates, 2010). Although our knowledge is growing or understanding of treatment performance and mechanisms of the tundra wetlands is limited, some evidence have shown excellent (sometimes orders of magnitude below regulatory standards) removals for regulated wastewater effluent parameters during the summer months (Kadlec & Johnson, 2008; Yates et al., 2008; Yates et al., 2010). Because of the socio-economic conditions and the extensive use of tundra wetlands in the Canadian Arctic, constructed wetlands warrant experimentation in this region. However, testing of these systems will require consideration of various designs to account for low soil/water temperatures, small frost free period, slow rate of decomposition of organic matter and therefore mineralization rates of various nutrients. Engineered designs to optimize existing tundra wetlands, augmented natural wetlands to increase hydraulic residency time (HRT), and increase active treatment zones (decrease areal loading rates) has been adopted in a few instances in the Arctic; Cambridge Bay, Nunavut is an example of one such system (Kadlec & Johnson, 2008). However, on the other hand, the arctic does provide environmental factors which in theory provide optimal treatment conditions; namely the twenty-four hour sunlight, plants and bacteria which have evolved in nutrient limited environment, which will readily take up excess nutrients.

OBJECTIVES

Given the evidence I presented earlier describing our current lack of knowledge of wastewater treatment with wetlands in the Canadian Arctic, my research objectives were developed to shed light on several areas of wastewater treatment and management in the region. Therefore, my goal was to provide a platform from which further studies could begin to answer narrower questions, as well as inform the regulatory process. In order to achieve this goal, my research was largely a descriptive exercise dedicated to developing a baseline understanding of wetland wastewater treatment, its primary treatment mechanisms, in both a natural and constructed Arctic environment. Further, I wished to prompt discussion on wastewater treatment with respect to planning practice and the regulatory framework in Nunavut.
My research objectives reflect developing this baseline of understanding by;

1. Contributing to the understanding of wastewater treatment in Arctic Canada, and future treatment and effluent standards for Arctic Canada.
2. Assessing the performance of the existing natural wetlands to treat wastewater in the Arctic summer.
3. Characterising existing treatment wetlands to identify potential key treatment processes.
4. Evaluating the potential of constructed wetlands to act as a wastewater treatment technology for Arctic communities through performance studies with a pilot scale constructed wetland.
5. Identifying the role/relationship of specific plants in wastewater treatment.
6. Make recommendations on appropriate technologies for remote Arctic communities and pending municipal wastewater effluent standards based on a review of the literature and personal observations.

SITE DESCRIPTIONS

My research was largely conducted in the Kivalliq Region of the Nunavut. This region lies along the western shores of Hudson Bay (Figure 1). The region contains the only inland community in Nunavut, Baker Lake. Many studies included in this thesis occurred in this community, specifically the pilot constructed treatment wetland study. The communities of Paulatuk and Uluhaktuk, both in the Inuvialuit Region of the Northwest Territories were also included in this thesis. Descriptions of the communities studied are provided. Site pictures for each of the wetlands can be observed in Appendix A.

Whale Cove (Tikirarjuaq) Treatment Wetland (62°11'N, 92°35'W)

Whale Cove is located on the western shores of Hudson Bay. Its population has been increasing since 2001, and in the 2006 census it was recorded as 353 (Statistics Canada, 2006). Climate normals are not maintained for this community. Its closest neighbour community where weather data is maintained is Rankin Inlet, which has a yearly average temperature of -11^{o}C (sd 1.3) (Environment Canada, 2010). The annual rainfall is 181.5 mm and annual snowfall is 120 cm (Environment Canada, 2010).

Wastewater is collected by the hamlet's trucks from short-term holding tanks at individual residences and other serviced buildings. The sewage is dumped into a 15,000 m^3 facultative lake, located 0.7 km SW of the community. The effluent continuously discharges into a tundra wetland before discharging into Hudson Bay. The water license for Whale Cove states that effluent from the treatment facilities is not to exceed 120 mg/L for BOD_5, 180 mg/L for TSS and $1x10^6$ cfu/100ml for fecal coliforms (Nunavut Water Board, 2009).

The wetland length is approximately 860 m with a width ranging between 30 and 55 m. The slope was estimated at approximately 3% with steeper and lower elevation changes between.

The Whale Cove wetland is located between two granite ridges formed from glacial scour. The wetland sits on a shallow well-drained mineral soil relief created from the surrounding ridges. The soil depth is variable and can reach approximately 0.30 m in depth. Soils at the start of the wetland (e.g., site of influent) are composed of saturated sand overlain with an organic layer. The organic soil depth ranges from 0.02-0.12 m in depth in the upper portion of the wetland. Much of the wetland located downstream consists of a homogenous mineral relief soil that changes to a gravel-cobble mix at the bottom of the wetland. Occasional granite outcrops emerge throughout the wetland complex. The wetland itself is very heterogeneous in relation to flow pattern, with areas of apparent subsurface water movement, and other areas with distinct and indistinct preferential surface flow movement. Therefore, water pooling occurs throughout the wetland complex. There are also two small bodies of water near the outflow (effluence) of the wetland where preferential flow channel into and out of before reaching the final exit point. There are also numerous flows originating from the surrounding ridges adding to the volume of the water passing through the system and thus providing some dilution to the effluent.

The Whale Cove wetland is composed of various low growth shrubs, grasses, sedges, bryophytes and perennials. The wetland is estimated to have a species richness of approximately twenty-nine. Observations by Yates *et al.* (unpublished observations) suggest that species community compositions is influenced by gradients in the degree of treatment in a cross sectional pattern down the wetland. *Carex aquatilis*, mastodon flower (*Senecio congestus*), pygmy buttercup (*Ranunculus pygmaeus*) are often observed near the point of influence to wetland from the lagoon. The lower part of the wetland is a wet tundra meadow, with felt-leaved willow (*Salix arctophila*), *Carex saxatilis*, and *Festuca rubra*. Various bryophytes are common throughout the lower portion of the wetland. Overall plant height and relative density was found to be greater closer to the lagoon than in the lower part of the wetland.

Baker Lake (Qamani'tuaq) Treatment Wetland (64°19'N, 96°02'W)

The Hamlet of Baker Lake is the only inland community in Nunavut, located on the north shore of Baker Lake. Its population has also been rapidly growing because of extensive mineral resources extraction nearby the community. In 2006 the population was recorded as 1,728 a 14.7% increase from the 2001 census (Statistics Canada, 2006)

The mean January temperature is -32.3°C and the mean July temperature is 11.4°C, with an average annual temperature of -11.8^{o}C (sd 1.3). The annual rainfall is 156.7 mm while the annual snowfall is 130.7 cm (Environment Canada, 2010).

Sewage is collected by the hamlet's sewage trucks and hauled to the dumpsite located 1.4 km N of the community. A new multi-celled holding lagoon system was built to replace the inadequate single-celled system in 2010. Plans also included the installation of berms between Lagoon Lake and Finger Lake (Garbage Lake) to increase residency time. The wetland is estimated to be 3.3 km in length, varying 14-80 m in width and a slope of approximately 1-2%. The communities water permit states that the treatment facilities should not discharge effluent which is greater than 80 mg/L for BOD_5, 100 mg/L for TSS and $1x10^4$ cfu/100ml for fecal coliforms (Nunavut Water Board, 2010b).

The treatment wetland of this community is a sub-basin of a larger watershed draining into Baker Lake. The wetland is defined by a granite ridge to the north, and moraine to the south. Two large lakes at the head of the sub-basin drain into the wetland from the north-west. These lakes then drain into Lagoon Lake, Finger Lake (also known as Garbage Lake), Airplane Lake and finally into Baker Lake. Sewage influent flows into Lagoon Lake from the holding cell through the first or upper section of the treatment wetland. The upper section is primary a preferential flow channel. Gravels from glacial till are dominant through this portion of the wetland. Large mats of settled solids from the influent cover the area outside the holding cell. Soil depth is 0.12-0.30 m, with depth increasing towards Lagoon Lake.

The mid portion of the wetland which lies between Lagoon and Finger Lake is largely composed of organic soils (~0.30 m) with underlying mineral soil. The wetland becomes more heterogeneous in the middle section and the preferential flow channel is less distinct than what is found above Lagoon Lake. Following Finger Lake the wetland changes into a low order stream and flows to Airplane Lake. Soil is largely mineral, with some underlying cobble/bedrock. The remaining sub-basin is composed of a low-Arctic tundra stream complex.

The Baker Lake wetland is composed primarily of sedges and grasses. *Carex aqualitis* Wahlenb. subsp. *stans* (Drejer) Hultén is dominant throughout the majority of wetland, particularly the middle and upper sections. *Arctophila fulva* (Trin.) N.J. Andersson is also common through the upper portion of the wetland. The wetland has an overall species richness of 19. In areas of pooling water *Equisetum arvense* Linnaeus is found along the edges. Other notable species in the upper portion of the wetland are *Senecio congestus* (R.Br.), *Ranunculus pygmaeus* Wahlenb, *and Stellaria crassifolia* Ehrh.

The lower portion of the wetland forms a distinct stream channel after Finger Lake and the surrounding wetland becomes a wet tundra with a dominate shrub cover of dwarf birch (*Betula glandulosa* Michx.), *Salix arctophila* Cock. ex Heller, and *Poa arctica* R. Br. subsp. *arctica* . Other species such as dwarf blueberry (*Vaccinium uliginosum* L.) and

Puccinellia species are also present. The remainder of the basin is a low-Arctic tundra stream with dwarf shrub (*Betula* and *Salix*) lining the shores along with various sedges and grasses.

Chesterfield Inlet (Igluligaarjuk) Treatment Wetland (63°20'N, 90°42'W)

Chesterfield Inlet is located on the western shore of Hudson Bay. From 2001 its population has been decreasing. In 2006, a census recorded a population of 332, a decrease of 3.8% from 2001. Climate normals are not maintained for this community. Its closest neighbour community where weather data is maintained is Rankin Inlet, which has a yearly average temperature of -11^{o}C (sd 1.3) (Environment Canada, 2010). The annual rainfall is 181.5 mm and annual snowfall is 120 cm (Environment Canada, 2010).

The wetland is estimated to be 720 m long, 58-225 m wide with a slope of 1%. Originally wastewater was dumped directly into a natural hollow and drained into the wetland. In 2010 this was replaced with a new engineered lagoon. The community's water license states that the treatment facilities should not discharge effluent which is greater than 80 mg/L for BOD_5, 100 mg/L for TSS and $1x10^4$ cfu/100ml for fecal coliforms (Nunavut Water Board, 2010a).

The treatment wetland for the Hamlet of Chesterfield Inlet is located in a shallow depression which eventually flows into Chesterfield Inlet. The area is characterized by low lying bedrock (granite) which slopes to southwest and east, thus defining the wetland boundaries. A natural depression acted as a shallow holding cell for disposed sewage which drains through two preferential flow channels. One channel flowing to the north of the wetland leads to a small pond, and the other channel on the southern portion of the wetland leads to a larger pond which drains towards the Chesterfield Inlet.

Field investigations revealed that the Chesterfield Inlet wetland is largely contained and receives little to no overland flow from adjacent water bodies. Much of the surrounding landscape is dominated by un-vegetated surfaces.

The soil of the upper portion of the wetland is a mixture of silts and fine sand over top of bedrock. Organic soil overlays the sands and silts in this portion of the wetland. The organic overlay comprises approximately 50% of soil profile. The lower portion of the wetland transitions towards a high shrub-tundra with large cobble intermixed with silts and sands. The soil in this portion of the wetland is very shallow with an approximate depth of 0.10m. The organic material on the surface is largely composed of bryophytes on top of rock. Near the designated effluence point, the bedrock emerges again and soil (mineral or organic) is limited and the coarseness of gravels varies.

The Chesterfield Inlet wetland is a mixture of mineral soil, wet meadow, and high shrub tundra. The wet meadow is dominated by *Carex aquatilis, Stellaria crassifolia,* and *Arctophila fulva*. Occasional stands of *Salix arctophila* boarder preferential flow channels. *Hippuris vulgaris* is also common in areas of standing water. The upper portion of the wetland transitions into sedge-grass meadow into high shrubs dominated by *Salix arctophila*, bryophytes, *Dryas integrafolia* Vahl. and *Carex rariflora* (Wahlenb.) Sm. Near the designated effluence point of the wetland, the following tundra species are prevalent; *Saxifraga cernua* L., *Dryas integrafolia, Cassiope tetragonal* (L.) D. Don, and *Betula glandulosa*.

Repulse Bay (Naujat) Treatment Wetland (66°31'N, 86°14'W)

The community is located on the northern shore of Repulse Bay, which is situated on the southern shore of the Rae Isthmus. The community has a total population of 748—an increase of 22.2% from the 2001 census (Statistics Canada, 2006). The annual precipitation is 150 mm rainfall, 58.2 cm snowfall (Environment Canada, 2010). The mean high in July is 15.7°C and the mean low is 5.8°C. In January, the mean high is -29.4°C and the mean low is -36.4°C (Environment Canada, 2010).

Sewage collection is by the hamlet's sewage trucks. The sewage dumpsite is located 1 km E of the community. The sewage is treated by passing through natural wetlands along a 1400 m flow path before the effluent enters Hudson Bay. The width of the wetland ranges between 50-90 m, with a total wetland area of 95,000 m^2, and a slope of approximately 2%. No lagoon currently exists at the site. Wastewater is discharged into a shallow natural depression. The community's water license states that the treatment facilities should not discharge effluent which is greater than 120 mg/L for BOD_5, 180 mg/L for TSS and $1x10^4$ cfu/100ml for fecal coliforms (Nunavut Water Board, 2009b).

The Repulse Bay treatment wetland is contained within a valley surrounded by high granite hillsides and ridges. The wetland is composed of a series of natural perennial ponds and interconnecting channels surrounded by wet-sedge tundra. Wastewater flows into the natural channels and exits into Repulse Bay (Arctic Ocean). The upper portion of the wetland is composed of organic soil layers on top of coarse sand and gravel. The lower portions of the wetland, which is closer to the discharge point into the ocean, contained more silts. Organic soil layers are generally less than 0.05 m in depth except in the upper portions of the wetland where organics matter has accumulated from the discharged sewage.

The Repulse Bay treatment wetland is dominated by wet-sedge tundra species, particularly *Carex aquatilis, Ranunculus pygmeaus*, and in the upper portions of the wetland by *Stellaria crassifolia*. In the lower portion of the wetland complex, *Poa artica* and *Plantago juncoides* Lam. var. *glauca* are common. However, *Carex aquatilis* was prevalent throughout, specifically on the banks of the channels and ponds.

Coral Harbour (Salliq) Treatment Wetland (64°08'N, 83°10'W)

The Hamlet of Coral Harbour is located on Southampton Island in the northern portion of Hudson Bay. The community has total population of 769—an increase of 8.0% from the 2001 census (Statistics Canada, 2006).

The climate of Coral Harbour has a mean January temperature is -30°C, mean July temperature is 9.3°C. Annual rainfall is 155.2 mm, annual snowfall is 133.5 cm.
Sewage is collected by the Hamlet's sewage trucks. The sewage dumpsite is located 3.6 km north of the community. Wastewater is dumped into an engineered lagoon, which continuously flows into a natural wetland with a 650 m flow path before entering a small shallow lake during the frost free period. The area of the wetlands is approximately 100,000 m^2. The wetland width ranges from 100-160 m, on very gradual slope (<1%). The 2008 water license stipulated that the water quality of the discharge from the wetland should remain at or below 30 mg/L for BOD_5 and total suspended solids and 1×10^4 cfu/100ml for fecal coliforms (Nunavut Water Board, 2008).

The Coral Harbour treatment wetland was located on a sand-silt plain. Very little organic soils are present throughout the site. This is the only wetland observed in the Kivalliq Region where effluent did not appear to enter the ocean or any other large body of water once it exited the wetland complex. Water was observed to be percolating through the sand-silt soil layers and emerging again down slope around bedrock protrusions. The wetland discharges into a small shallow lake.

The wetland consists primarily of bare soil with prostrate shrubs acting as the primary cover. In the upper portion of the wetland, *Salix arctophila* and *Salix alaxensis* (Andersson) are common. *Senecio congestus* is also a prevalent species in the upper portion of the wetland. Mosses and small sedges are common in the lower portions of the wetland.

Arviat Treatment Wetland (61°05'N, 94°00'W)

The Hamlet of Arviat is located on the northern shore of a peninsula on the west coast of Hudson Bay. The community has a Total population of 2,060—an 8.5% increase from the 2001 census (Statistics Canada, 2001). The community is the most southern in the Kivalliq Region. Annual precipitation is 160 mm rainfall and 118 cm snowfall. The mean high in July is 13.1°C and mean low is 4.5°C. In January, the mean high is -27.9°C and mean low is -35.0°C (Environment Canada, 2010).

Collection is by Hamlet sewage trucks. The trucks dump into a 55,000 m^3, single cell exfiltration lagoon, located 2.8 km from the center of the community. Sewage exfiltrating from the lagoon flows into the adjacent wetland. The wetland is approximately 480 m in length and 120-160 m in width with varying flow paths throughout (slope 1%). The total wetland area is estimated at 78000 m^2. The wetland effluent is currently permitted to have an effluent quality of 80 mg/L of BOD_5, 100 mg/L total suspended solids and 1 x 10^4 cfu/100ml for fecal coliforms (Nunavut Water Board, 2010c).

The Arviat treatment wetland is located on the relic coastal shoreline of Hudson Bay. It is composed of very fine sands. Sand berms have been constructed to direct wastewater flow parallel to the coast before discharging into Hudson Bay. Very little organic soil is present on top of the sand. The existing organic matter has been deposited due to sewage discharge from the facultative lagoon. The sand layer is greater than 1.0m in depth throughout most of the wetland.

The Arviat wetland complex is composed primarily of *Senecio congestus* throughout the entire system. However, *Hippuris vulgaris* and *Stellaria crassifolia* are also common throughout the wetland.

Paulatuk Treatment Wetland (69° 21′ 5″ N, 124° 4′ 10″ W)

The Paulatuk facultative lake (Dead Lake) and wetland treatment system serves 294 residents (Statistics Canada, 2006). Wastewater from households and businesses is trucked to a facultative lake.

The designated wastewater treatment area drains into Darnley Bay of Amundsen Gulf from Dead Lake. In 2007 it was estimated approximately 11,200 m^3 of wastewater was being discharged into Dead Lake. Dead Lake is estimated to have a volume of 103,000 m^3. The wetland is characterized as wet-sedge tundra, dominated by *Carex* and *Poa* spp. In drier upland areas along the wetland boundaries, *Salix* spp. were observed to be dominant. Low lying hills, from relic ocean bottoms surround the treatment area. Mineral soils underlie the wetland, composed of various coarse sands and gravels.

A single preferential flow path proceeds through the middle of the wetland, with smaller indiscreet channels and pools also being common throughout the wetland. Wastewater flows out of the continuously discharging facultative lake. The wetland ranges from 40m to 80m in width. The wetland extends approximately 350 m from the facultative lake to the ocean. The wetland effluent drains over a ledge (formed from soil slumping along beach front) into the ocean.

Climate normals gathered by Environment Canada for the Hamlet of Paulatuk has a summer average of approximately 10^oC (Environment Canada, 2010). Freezing temperatures are persistent from October onwards through May. The highest daily maximum is 15^{o}C for July (Environment Canada, 2010).

Uluhaktuk (Holman) Treatment Wetland (70°44′11″N 117°46′05″W)

The Hamlet of Uluhaktuk is located on Victoria Island, in the Inuvialuit Region of the Northwest Territories. The community has approximately 400 residents. The hamlet discharges sewage into a single-celled facultative lagoon. It is estimated that the community discharges 40 m^3/day, into a 14,000 m^3 lagoon. Lagoon effluent continuously permeates through lagoon berm wall into the adjacent wetland complex. The wetland is approximately 73,960 m^2; with a length of the wetland was estimated at approximately 480 m and the width 120 m. The average summer temperature from June through September is 8.3^{o}C and the daily average temperature for the community is 11.7^{o}C, with 162 mm of precipitation per year (Environment Canada, 2010).

Soils were found to be primarily composed of clay fines allowing for a slow percolation of wastewater through the soil. Hydrologic surveys found a perched water table throughout the wetland. Therefore wastewater primarily moved through the wetland as surface flow.

The wetland is primarily wet-sedge tundra with low-shrubs. Common species were *Senecio congestus*, *Salix arctophila*, *Carex aquatilis*, *Cereastium ceratoides, Stellaria crassifolia* and *Poa glauca*.

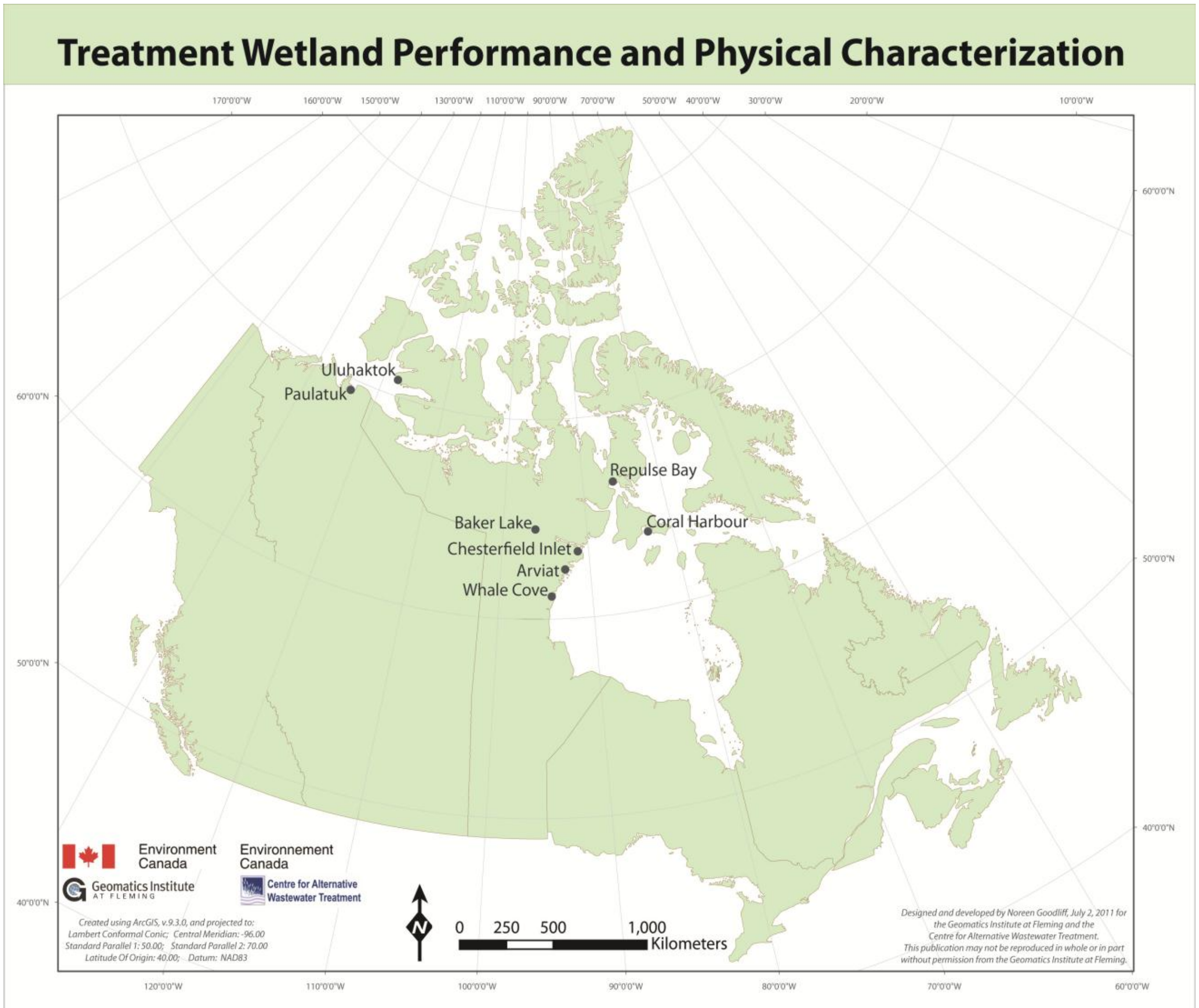

Figure 1. Map of Nunavut, its regions and surrounding territories. Locations of each of the communities where treatment wetlands were studied are located in Kivalliq Region of Nunavut and Northwest Territories (Created by: Noreen Goodlif).

CHAPTER 1

A REVIEW OF WASTEWATER TREATMENT AND PLANNING IN THE CANADIAN ARCTIC: COMMENTS AND RECOMMENDATIONS FOR NEW MUNICIPAL EFFLUENT PERFORMANCE STANDARDS

Summary: The planning and treatment of wastewater in remote Canadian Arctic communities is complex; climate, culture as well as an array of socio-economic factors, result in the need for varied approaches to wastewater planning and treatment than in southern Canada or other temperate less remote regions of the world. The impending performance standards for municipal wastewater effluent as proposed in the *Canada-wide Strategy for the Management of Municipal Wastewater Effluent* will alter the regulatory framework for wastewater again for Nunavut as well as for the Far North as a whole. I review wastewater management from pre to post Arctic settlement, as well as the current wastewater technologies being adopted in the Arctic. Based on this review, I comment on the implications of new performance standards for municipal wastewater effluent and how they should address the complex nature of treating wastewater in the Far North, specifically Nunavut. I recommend that performance standards should, i) reflect the diverse climate, and socio-economic environment of the northern communities. ii) The effluent standards should remain adaptive as more knowledge is gained. iii) Consultation between government, scientists and aboriginal groups should be meaningful and fulfill each group's expectations/definition of consultation.

Keywords: Canadian Arctic, effluent standards, management, municipal wastewater, review

INTRODUCTION

The Arctic climate, geography, and remote nature are the most significant influences on wastewater management and treatment in Arctic regions of Canada. In Nunavut as well as other territories in the Canadian Arctic, wastewater planning has only been in practice since the mid-20th century, and will have to meet growing challenges in the coming decades because of rapid population growth, expansion of industry and climate change.

Although wastewater management is a relatively new practice in the Arctic, it is complicated by a hierarchy of governmental institutions, aboriginal land claim agreements, and various socio-economic issues which directly or indirectly influence wastewater management in Canadian Arctic communities (Suluk & Blakney, 2008; Johnson, 2010). Aboriginal organizations as well as a few practitioners have acknowledged the need to review the current status of wastewater management in the Canadian Arctic, including a look at the diverse socio-economic factors that influence wastewater treatment in the remote communities of the Canadian Arctic (Johnson, 2010).

In this paper I review a brief history of wastewater treatment and planning in Arctic Canada, the current technologies used to treat wastewater, as well as the current legislative process governing the treatment and disposal of wastewater in Nunavut. I will place this review in the context of the new wastewater effluent standards that will be legislated in the Department of Fisheries and Oceans Canada *Fisheries Act* for municipalities in the Canadian Arctic in 2013; drawing light to how the impending standards will affect future community wastewater planning, and treatment technologies used in the Canadian Arctic. I also make a number of recommendations based on wastewater planning, management as well as treatment for communities in Nunavut based on data collected from several systems within the region and recommendations made in other documents.

METHODS

For this review I gathered information and made personal observations in numerous Arctic communities between 2008 and 2010. Throughout the extent of the study, I visited twelve communities, encompassing the western and eastern Arctic and sub-Arctic. For this study I reviewed pertinent independent and government reports, statutes, and manuscripts related to wastewater treatment in the Canadian Arctic. Because of the current lack of peer-reviewed publications on wastewater management in the Canadian Arctic, I drew much of the review on current government documents and various available consultant reports to aid in highlighting the current state of wastewater management in the Canadian Arctic. I then intertwined my personal observations of Arctic wastewater treatment systems and my scientific understanding of their performance to drive a critical evaluation of their current function and the regulatory frameworks which currently govern them and those which will be in the near future.

I define sub-Arctic and Arctic communities in Nunavut as localities found above 60^{o} N – with the caveat that some communities below this latitude are included because of their remoteness (e.g. Sanikiluaq, Nunavut). Above $60\,^{o}$ N includes the continuous permafrost zone and the northern portions of discontinuous permafrost zone in Canada (Grainge, 1969), and is the southern border of Nunavut, again with the exception of Sanikiluaq. I categorize these communities from sub-Arctic and Arctic Canada, Nunavut (NU), Yukon Territory (YT), Northwest Territories (NT), Quebec (Nunavik) and Labrador (Nunatsiavut) together as they will all be influenced by the same regulatory process for determining new municipal wastewater standards in the Canadian Arctic. However, I acknowledge that the different regions and even communities within them have distinct climates, socio-economic and political variables which are unique, but cannot all be taken into consideration within the scope of this paper.

REVIEW

Evolution of Wastewater Management: Pre to Post Arctic Settlement

Permanent settlement in the Canadian Arctic and portions of sub-Arctic has been very recent, i.e. about 50-60 years ago in some portions of Nunavut. Municipal planning of any type did not commence in the Arctic until the mid-20th Century and master plans for communities in the Canadian far north only were introduced in the 1970s (Rees & Fenge, 1987). Prior to this time, residents were primarily aboriginal Inuit with small populations temporarily located near trading posts, the only non-aboriginal populations and the majority of population remaining nomadic and removed from these locations. Nomadic Inuit groups were small and most often formed from family members amounting to six to ten individuals, with some groups up to fifty members (Douglas et al., 2004). Larger groups would only form for short periods throughout the year at meeting places timed for migrations of fish or caribou (Chabot & Duhaime, 1998). In this context, prior to the 1960s, Arctic and sub-Arctic community settlements were haphazard. More permanent dwellings were established around these locations following tuberculosis epidemics, and when some Inuit began to seek government assistance during the 1940s (Chabot & Duhaime, 1998). In some regions of the Canadian Arctic, such as Nunavik, villages did not exist until as late as 1959 (Chabot & Duhaime, 1998). At this time prefabricated ("matchbox") homes were provided to residents, although running water and sanitation services were not provided, initially (Chabot & Duhaime 1998). Residents were removing waste from dwellings and disposing of it close to buildings with pails (with plastic-bag liners or "honey bags") or into pit privies or latrines (Grainge 1969). Because of frozen or impervious substrates, wastes would wash into nearby bodies of water, which would often be drinking water sources for the community. Such conditions were common throughout the Canadian Arctic and native communities of Alaska (Riznyk et al., 1993; Ikehata & Pui, 2008). Prior to the introduction of piping, or haulage water distribution systems, it was estimated that water use was 6 gal/person/day (20 L/day/person), and carried to individual residences with a pail (Johnson & Wilson, 1999). Roads were uncommon in early Arctic settlements, making disposal of waste away from residences and the distribution of drinking water, problematic. Grainge (1969) also describes an early utilidor (piped) system that was in use Inuvik, NT during the late 1960s. However, the management of wastewater during on this time was largely focused on disposal rather than treatment.

With the introduction of haulage services for drinking water, water usage in the towns increased dramatically, which also led to greater volumes of wastewater to be disposed. The wastewater treatment technologies used in the Canadian Arctic and specifically Nunavut today have for the most part, been in practice since the 1960-1970s. Specific facilities in this region have only been upgraded as needed with population growth, often using the same technology at a larger scale but such technology is not truly 'scalable'. The most common conventional treatment techniques used throughout Nunavut and other Northern areas are various forms of long and short-term lagoon systems (stabilization ponds or facultative lakes) (Heinke et al., 1991; Michelutti et al., 2007; Wootton et al., 2008) (Table 1). These systems were adopted as early as the 1940s in Alaska, and various parts of the Northwest Territories (Dawson & Grainge, 1969; Douglas et al., 2004). However, their effectiveness has not been systematically reviewed save for the few government documents and peer-reviewed articles listed; Miyamoto & Heinke (1979), Environment Canada (1985) and Prince et al. (1995).

Some larger communities directly discharge into nearby bodies of water; often Hudson Bay, the McKenzie River or the Arctic Ocean received the waste, because of their large assimilative capacities. Dawson & Grainge (1969) recommended this as an appropriate practice for sewage disposal, especially during ice breakup. Today these communities make use of varying degrees of primary treatment prior to discharge (Johnson, 2008; Sikumiut Environmental Management Ltd., 2008; Wootton et al., 2008a, 2008b, 2008c). Land treatment is also commonly used in present day Nunavut, often in combination with various continuous and discontinuous discharge engineered lagoons or makeshift holding cells. Many of these systems can be described as tundra wetlands. Table 1 shows the type of wastewater treatment facilities currently used in Inuit communities of Nunavut. Data from communities in the Yukon Territory, NT. and northern Quebec/Labrador is included to demonstrate consistency of current technologies employed throughout the Canadian Arctic and sub-Arctic.

Table 1. Treatment systems currently in use in a set of remote communities in Canada (Sikumiut Environmental Management Ltd., 2008; Wootton et al., 2008a, 2008b, 2008c)

Region	Facultative Lake	Engineered Lagoon	Lagoon and Wetland	Wetland (Land disposal)	Direct Discharge (Ocean)	Mechanical
Nunavut	2	7	8	3	1	3
Northern Quebec & Labrador (Nunavik & Nunatsiavut)	5	8	1	0	1	0
NT & Yukon (Inuvulait)	2	1	3	0	0	0

Despite proposals to use piped systems as a means of collecting wastewater from residences and service buildings in Nunavut, wastewater and drinking water are primarily hauled to and from dwellings by pumper trucks (Johnson & Wilson, 1999). These trucks remove wastewater from small holding tanks contained under each residence, or fill water tanks located in the residence or commercial buildings for drinking water (Johnson, 2008; Wootton et al., 2008a). Trucked (haulage) services were put in place despite early recommendations by Grainge (1969), who suggested that a piped (utilidor) system would have higher operation and maintenance costs and longer periods of inactivity because of blizzards which frequently last five days. A review by Ritter (2007) disagreed and suggests that a haulage system has lower operation and maintenance costs. Ritter (2007) argued that piping systems have expensive capital costs, which outweigh the expense of operation and maintenance costs with haulage systems. Haulage systems also provide a means of local employment.

There are a few exceptions to the extensive use of haulage systems in Nunavut (e.g. Rankin Inlet), and throughout the rest of the Canadian Arctic (e.g. Inuvik, NT) where municipal piping systems serve residents and other buildings in those communities (Wootton et al., 2008a, 2008c). However, communities like Rankin Inlet still have a portion (5%) of their wastewater collected by trucks (Wootton et al., 2008a).

Current Wastewater Treatment Technologies in the Arctic

Long and short-term holding (discontinuous and continuous discharge) lagoons are the most common treatment system in Nunavut and other Canadian Arctic communities (Heinke et al., 1991). These 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. Lakes receiving direct discharge of wastewater are referred to as facultative lakes or ponds. Annak Lake (Sanikiluaq, NU) and Merritt Lake (Resolute Bay, NU) are both examples of facultative lakes (Douglas & Smol, 2000; Douglas et al., 2004; Michelutti et al., 2007). 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 (Pohl, 1970). Because lower bacteria and algae populations limit the metabolism of organic compounds, mechanical aeration has been recommended for northern regions (Dawson & Grainge, 1969; Pohl, 1970). Although mechanical aeration is a common solution in temperate regions, the availability of infrastructure to power those systems is not feasible in most Arctic communities.

Prince et al. (1995) recommended that a wastewater stabilization system consisting of four anaerobic ponds, one facultative pond, and one storage pond with intermittent (annual) discharge would provide optimal performance in cold climates. Each part of the system is described as having a retention time of two days, one to two months and twelve months respectively. Prince et al. (1995) also recommended that continuous discharge or discharge in the spring should not be designed for cold climate systems, as the receiving environment may not accommodate the loading of untreated waste; fall discharge for cold climate systems is best. One issue is that Prince et al. (1995) was based on an extrapolation from evidence collected in northern Alberta, hence it may not reflect the even more northern conditions in the Arctic.

Despite extensive use of lagoons in the Arctic, there remains little peer-reviewed literature on their performance (Wootton et al., 2008c). Heinke & Deans (1973), Heinke et al. (1991), Prince et al. (1995) and Heaven et al. (2003) all showed that lagoon systems can be an appropriate technology for wastewater treatment in the Canadian north. However, only Miyamoto & Heinke (1979) reported reductions of biological oxygen demand (BOD), and total suspended solids (TSS) in lagoon effluent in an Arctic community. They presented treatment of BOD, TSS and fecal coliforms during the summer and winter of 1971. Summer median influent was reported at 195+/-68 mg O_2/L and effluent 40+/-20 mg O_2/L and winter median lagoon effluent at 51+/-28 mg O_2/L, a percent reduction of 80% and 71% respectively. Similar reductions were observed for TSS. Johnson & Wilson (1999) examined NT and Nunavut lagoons and facultative lakes reporting percent reduction of BOD at 87% to 96%, and TSS in the range of 90% to 93%.

The use of mechanical and connected centrally serviced wastewater treatment facilities in Nunavut and the Canadian Arctic is minimal (Table 1). Some large communities, such as Rankin Inlet and Resolute Bay, Nunavut use Hudson Bay or the Arctic Ocean as a receiving environment, with preliminary 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 preliminary 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 Inuit 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), whereas Rankin Inlet and Iqaluit Nunavut both have proposals for the design of advanced treatment systems (Johnson, 2008). Currently Rankin Inlet has screening, only. Rankin Inlet is known to use 1 mm mesh drum screen and Resolute Bay has a basic macerator (Wootton et al. 2008a).

Most Nunavut and other Arctic communities remain without mechanical systems, because of the regular failure of these systems to produce effluent to regulatory standards, high operating costs, or the lack of a skilled labour pool to maintain them (Johnson &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 high-performance techniques in developing regions of the world, as suggested by Riznyk et al. (1993); Denny (1997) and Kivaisi (2001).

Land disposal or land treatment is another common method of wastewater treatment or disposal in Nunavut and the Arctic as a whole (Wootton et al., 2008a) (Table 1). Land application of sewage is one of the oldest forms of wastewater management, and dates back to ancient Athens (Tchobanoglous, 1979), when early civilizations were applying human waste to agricultural fields. Land treatment was also popular in mid-19th Century Europe and re-popularized in the 1960s as an economical alternative for small rural communities (Crites & Tchobanoglous, 1998). Land treatment and wetland systems make use of the natural biogeochemical cycles of plants, periphyton, and the soil for the transformation, and mineralization of organic matter in the wastewater (Knox et al., 2008). In temperate regions, land treatment was such a common technique through the 20th Century that overland flow design criteria were developed, and their general concepts were later adapted for free water surface constructed wetlands (Kadlec & Wallace, 2009). Crites & Tchobanoglous (1998) described land application techniques that are still used currently in temperate locations, and how wastewater flowing over the impermeable bed is treated by a biofilm matrix attached to the grass. These systems are often used as secondary treatment, and for organic nitrogen removal because of oxidation from turbulent flows through the grass (Kadlec & Wallace, 2009). Land treatment using overland flow has shown excellent results for the treatment of municipal wastewater in temperate locations in comparison to conventional mechanically engineered treatment systems (Wallace & Knight, 2006). Crites & Tchobanoglous (1998), reported results on a land application system for both the treatment of raw and primary treated wastewater, showing reductions of BOD of 95% and 89%, respectively. In Nunavut, 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 connected to the community water supply, as in Baker Lake (Wootton et al., 2008a). Although overland flow is present, e.g. in Coral Harbour NU, many of the land treatment locations are actually in wet-sedge tundra wetlands. 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 (Gough et al., 2002). This suggests that the wetlands may not have been present prior to sewage being disposed at the location.

Whether or not these landscapes have been altered, the use of wetlands is extensive for both primary and secondary treatment in Nunavut. It could be argued that some of the natural wetland complexes may be considered augmented natural wetlands or even constructed wetlands because of the use of berms and other engineered structures. Kadlec & Johnson (2008) and Wootton et al. (2008a) reported that engineered berms have been employed to designate a flow path through natural wetlands, such as in Arviat, and Cambridge Bay, Nunavut.

Wetlands have shown excellent ability to treat wastewater in the past in more temperate locations (Mander & Jenssen, 2002; Kadlec & Wallace, 2009). However, similar to lagoon systems in Nunavut and in the remaining Canadian Arctic, there is very little data from peer-reviewed literature on wetland performance. Based on descriptions in Johnson & Wilson (1999), Wootton et al. (2008a), Wootton et al. (2008b), Wootton et al. (2008c) and personal observation, much of the assimilative capacity of these systems is through dilution along a series of small lakes or ponds connected by wetland streams as is the case in Repulse Bay and Baker Lake, Nunavut. However, there are examples of wetlands where dilution is not the primary mechanism of assimilating wastewater, such as Paulatuk NT, Uluhaktok NT and Chesterfield Inlet NU. Chesterfield Inlet has shown promising preliminary results on reduction of wastewater parameters such as $cBOD_5$, TSS and nutrients (Yates et al., 2010).

Current Wastewater Legislation

In Nunavut, the Nunavut Land Claims Agreement Act (NLCA) (1993) has the greatest influence on the management of wastewater in the territory. The Nunavut Waters and Surface Rights Tribunal Act (NWSRTA) (2002) provisions the NLCA for the management of water and deposit of waste into water, including municipal wastewater. Sections of the NWSRTA are pursuant to the Northwest Territories Waters Act, as a part of a transitional process during Nunavut’s formation, and will be eventually replaced under the Act. However, to date much of the regulations from the Northwest Territories Waters Regulations still apply.

Representative responsibility of the regulations mentioned above are led by the territorial Department of Environment, whose mandate is the promotion and protection of natural resources, including water. Their directive includes the protection of water and other natural resources from contamination from municipal wastewater. Under the NWSRTA the Nunavut Water Board (NWB) was created for hands-on approach to the management and regulation of inland water in the territory, by issuing water licenses to deposit waste, including wastewater into inland surface water, but do not have enforcement power (Nunavut Water and Surface Rights Tribunal Act, 2002). The NWB may also make recommendations for marine environments if it is believed that any decisions that the NWB makes may influence the marine environment. Individual municipalities must apply to the NWB for and to maintain water licenses to discharge municipal wastewater. The NWB acts at arm’s length from the territorial government to manage water, and is part of a larger tribunal of organizations who have jurisdiction over water resources; namely the Nunavut Impact Review Board, Nunavut Planning Commission and the Nunavut Wildlife Management Board. Jointly these organizations may make decisions over allocation of water licenses and deposition of wastewater into the environment. The Department of Indian and Northern Affairs Canada (INAC), the principal federal agency in Nunavut is responsible enforcement of compliance of water licenses issued by the NWB, through the employment of federal inspectors. Their power is provincial in nature, and overarches the responsibilities of the NWB. Monitoring of wastewater effluent water quality is the responsibility of the Hamlets (municipalities) and INAC. It is important to note that aboriginal communities' rights over water take priority in Canada. However, these rights are not explicitly identified in any provincial or federal legislation.

DISCUSSION

Planning of sustainable wastewater treatment systems in Nunavut and other remote communities in the Arctic faces numerous challenges from extreme climate and different perceptions/understanding of planning. Another major obstacle is the lack of understanding of treatment mechanisms in the Arctic and performance of existing systems as pointed out by Johnson (2008, 2010).

Performance assessments by my research group Wootton and Yates (2010) and Yates et al. (2010); Yates & Wootton (2011) have shown that many wetland treatment systems in Arctic perform very well during ice-free periods, often with effluent quality lower than the proposed southern effluent standards (Canadian Council of Ministers of the Environment, 2009). Performance for lagoons and facultative lakes has been shown to be inconsistent with very different performances across the Canadian Arctic (Miyamoto & Heinke, 1979; Johnson & Cucheran, 1994; Prince et al., 1995; Johnson &Wilson, 1999). And much of the research conducted in the past has largely discussed the design and application of technologies such as lagoons in Dawson & Grainge (1969) and Pohl (1970), while many other studies have lacked long-term data or non-site specific data (Johnson & Wilson, 1999). It is also difficult to draw conclusions on the adequacy of all current systems to perform to regulatory standards, despite the fact that communities are required to have regular monitoring/reporting on their wastewater effluent (Wootton et al. 2008a). Compliance monitoring by local and territorial governments of Arctic wastewater treatment systems is minimal, and limited by the availability of laboratory facilities capable of analyzing wastewater (Johnson, 2008; Wootton et al., 2008a). For many communities in Nunavut, the closest laboratories for wastewater sample analysis are located in Yellowknife, NT or Winnipeg, MB for the western Arctic; which in many cases is over a day's journey from many Arctic communities.

Consultation between Environment Canada and aboriginal participants on wastewater systems acknowledged the absence of a laboratory in Iqaluit (Environment Canada, 2008). Such a laboratory would be required to service the eastern portion of Nunavut. As I highlighted earlier, peer-reviewed research is limited on all wastewater treatment systems currently employed in Nunavut and the rest of the Canadian Arctic. Therefore, a great deal of uncertainty is present for appropriate design and performance standards. This requires the use of appropriate planning methods, incorporating risk analyses and management to accommodate for the uncertainty (Doer-MacEwen, 2007).

Further shortcomings in wastewater treatment in the Arctic and Nunavut may be found in the initial planning process, and implementation, more so than the available engineering technologies themselves. Chabot & Duhaime (1998) comment, that the early institutionalization of northern communities has had major consequences for planning process. Poorly planned wastewater treatment facilities may be considered one of those consequences. Currently the initial planning strategies for treatment systems follow southern planning frameworks which have in the past resulted in poorly conceived infrastructure (Johnson, 2008). Many of the facilities presently used in the Arctic are more common to southern regions where the technologies have demonstrated a high degree of performance and have met regulatory standards. Such as the use of valve boxes containing gate valves in engineered lagoons. Such mechanisms do not withstand the climatic conditions, and frost heaves characteristic of the Canadian Arctic. Pond Inlet, Nunavut is one example where decant valves are no longer functional, requiring the community to decant the lagoon with pumps (Yates & Wootton, 2010).

The weaknesses found in many of the systems may be because of socio-cultural and economic reasons as alluded to by Johnson (2008), and different perceptions (understanding) of planning and contamination (Bates, 2007; Cassady, 2007), rather than the technologies themselves. Johnson (2010) expands on early comments suggesting that the study of "social science" of wastewater management in the Arctic has been ignored. The complexity of the governmental structure, which includes several levels of local government representing the aboriginal community and other levels representing non-aboriginal interests, plus land claims and territorial government only add to the socio-cultural complexity of wastewater management.

In the next several paragraphs I will describe some of the complexity of government structure and the differences in perceptions of planning, particularly understanding of the definition of adequate consultation. In 1993, the Inuit again began to have control over their future after the signing of the Nunavut Land Claims Agreement, which was then realized with the opening of the Nunavut Legislative Assembly on April 1, 1999. However, it is still often argued that planning in Nunavut communities tends to reflect a top down rational effort directed from the Canadian federal government, with very little meaningful participation by the community (Suluk & Blakney, 2008). An absence of participation could be attributed to the lack of capacity within the young Government of Nunavut to act out its original goals as an Inuit government operating on traditional ecological principles (White, 2009), or *Inuit Qaujimajatuqangit* (IQ) as preferred by Inuit groups (Wenzel, 2004). Suluk & Blakney (2008) suggest that the Government of Nunavut is a "carbon copy" of the Government of NT, which is bound by federal red-tape, with mere adjustments in federal administration to account for a geographic change in name.

As briefly described earlier, currently in Nunavut, wastewater effluent discharge is governed by several pieces of federal legislation, and territorial acts, particularly the *Nunavut Waters and Surface Rights Tribunal Act.* Under this act communities are required to obtain a Water License from the Nunavut Water Board, and submit annual reports based on monitoring of their treatment facility (Wootton et al., 2008a). The current Nunavut legislation works on the same premise as it did when Nunavut was part of NT (Johnson & Wilson, 1999). Presently each community is allowed to discharge volumes of wastewater specific to the community, as outlined in their water license. The effluent of the wastewater passing through the treatment system also varies between communities and their water license.

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 lays out regulations to be upheld within the Canadian *Fisheries Act.* This strategy is to include specific national performance standards (NPS) for effluent of Canadian municipal wastewater treatment facilities at 25 mg/L for BOD, TSS, and 0.02 mg/L for total residual chlorine (TRC) (Canadian Council of Ministers of the Environment, 2009). These are new minimum standards replacing existing standards for Canadian municipalities. However, standards have not yet been recommended for northern Canada, including Nunavut. A five-year research period was granted to determine what standards (effluent concentration levels) would be appropriate in the Canadian north because of climatic conditions (Canadian Council of Ministers of the Environment, 2009). Immediately the ITK reported the dissatisfaction of the Nunavummiut over the CCME strategy, suggesting the strategy had not appropriately acknowledged the needs and concerns of northern communities (Johnson, 2008). An Environment Canada report provided some indication of this in initial consultations with aboriginal communities over wastewater. Aboriginal groups did not believe that consultations actually occurred on the proposed regulatory framework, but rather only a dialogue and discussion to communities (Environment Canada, 2009). In the *Evaluation of Environment Canada's Aboriginal Consultations on Wastewater: Management Response and Final Report* for the Canada-wide Strategy for Management of Municipal Wastewater Effluent suggested that aboriginal groups in the north did not feel that consultations allowed for appropriate feedback of their needs (Environment Canada, 2009). As the consultation commenced in 2007, this can be attributed to the negative response from the Inuit community over the process as described in the *National Inuit Position Paper regarding the CCME Canada-wide Strategy for the Management of Municipal Wastewater Effluent and Environment Canada's Proposed Regulatory Framework for Wastewater* (Johnson, 2008). Interpretation of the consultation process in both of these reports, contradict each other.

The Inuit position expressed dissatisfaction in the insufficient consultation timeframe, lack of representation and financial support for Inuit organizations to attend consultations (Johnson, 2008). The result was that the Inuit believed that the "consultation process had not fulfilled the Crown's duty to consult" (Johnson, 2008). Environment Canada reported they had representation from 4% of the Inuit communities, and 25-30% representation from First Nation communities (Environment Canada, 2009). From the perspective of Environment Canada they had successfully met their obligations in the consultation process, based on the Federal Government's definition of consultation and had delivered materials to the aboriginal communities. This definition is provided by the Treasury Board's 2007 *Guidelines for Effective Regulatory Consultations*. However, significant attention was given in the Environment Canada report, that from the perspective of the First Nations and ITK the consultation did not adequately address their concept of consultation. The Environment Canada report concluded and recommended that the Treasury Board modify its definition of consultations so it reflects both the federal government and Canada's Aboriginal Peoples. Despite this request, and resulting new consultation guidelines (Department of Indian Affairs and Northern Development, 2011), this process may or may not be reflected in the consultation process in the design of new treatment facilities by industry who will be responsible for the guiding communities towards selecting appropriate technologies.

In the consultation process and in the strategy laid out by the CCME, it is unclear whether the new regulations will be consistent for the entire north or based on settlement region or geography. The Inuit position paper acknowledges many of these unknowns (Johnson, 2008). One unknown was the argument over the importance of frost free days. Frost free days vary significantly throughout the North, and are as low as 40 days in Resolute Bay and as high as 126 days in Nain. Currently, standards for effluent are per Hamlet based on their water license guidelines and reflect the system in place or geographic location; as in Alert where the permit specifically indicates performance standards given the difficult location as 80 mg/L and 70 mg/L for BOD_5 and TSS respectively (NWB, 2010). In comparison, a community much further to the south of Alert, Coral Harbour, is required to meet 30 mg/L effluent concentration for both BOD_5 and TSS (NWB, 2008).

In 2013, the research period for determining appropriate performance standards is to be completed, with the new standards to be proposed in the regulations of the *Fisheries Act*. For the regulations to be pertinent to the North, the wastewater framework will have to address a number of other factors outside of performance; i. the impending rapid urbanization and growth in the Arctic, because of economic development through resource extraction, ii. the unknown influences that climate change will have on Arctic systems, iii. adaptive planning framework to accommodate for increased knowledge of wastewater treatment and the rapidly changing environment. Melting permafrost will have significant implications, especially for wetlands used for wastewater treatment, as well as lagoon systems (Nuttall and Callaghan, 2000). Warren et al. (2005) suggests that the impact of climate change on Arctic infrastructure may have significant implications on public health. Although climate change may improve treatment of wastewater itself, but containment will become an increasing challenge of lack of permafrost, resulting soil seeps. Contamination and environmental degradation of this sort are not simply public health issues, but also cultural issues in the Arctic (Nuttall and Callaghan, 2000).

Although there is evidence emerging that shows that the performance of the current treatment systems in the Canadian north are achieving current regulatory standards during the summer months set by the Nunavut Water Board see [Yates et al. (2008); Wootton & Yates (2010); Yates et al. (2010)], it would be unwise to suggest that current methods will be adequate into the future with population growth and unknown implications of climate change. Geographic or community specific performance standards would be best suited for such a large geographic diverse area. Therefore maintaining the current regulatory practice, but under the new framework is likely still the best practice.

Again, the current absence of monitoring of effluent is a major obstacle for remote northern communities. The financial constraints, retaining trained personnel will remain an endemic problem for remote communities throughout Nunavut and the rest of the Canadian north. It is also likely that despite changes in the regulatory framework and performance standards, that monitoring and compliance issues will not disappear, unless significant investment is placed into the establishment of laboratories and securing personnel in the north (Johnson, 2008). Further, by 2013, although much study will have been conducted on Arctic wastewater treatment, it cannot be expected that the knowledge obtained in that short period of time will be sufficient to guide decision making into the future. Research will have to continue and several iterations of performance standards be made for various regions in the north. This will become especially important with continued growth and development, as well as climate change. As current wastewater treatment systems used, particularly wetlands may no longer be able to accommodate the load of wastewater without impacting the receiving environment. Examples of impending change can be seen through various statistics. Nunavut represented Canada's largest population growth at 3.2% in 2010 (Statistics Canada, 2010). And in 2010, the Minister Economic Development & Transportation for Nunavut put forth estimates of 13% in economic growth (Taptuna, 2010).

Inuit and First Nations perception of planning can be at variance from more urban and southern concepts. Inuit planning is largely based on necessity and first-hand knowledge, andtherefore Inuit prefer adaptive rather than predictive methods, and to eliminate uncertainty and risk through flexibility (Bates, 2007). This method would work within the Inuit definition of consultation. Therefore, performance standards may need to change with increased knowledge of wastewater treatment in extreme cold climates will be important to adjust for growth in Arctic communities, changing environment as well as maintaining meaningful consultation with aboriginal groups.

Finally, this review poses implications and parallels to other remote Arctic communities in Alaska, Greenland northern Scandinavia and Russia. Many of these communities also face challenges with aboriginal land rights, socio-economic issues, such as under employment, remoteness and extreme cold climates. Ritter (2007) described how Alaska and parts of Arctic Canada have similar challenges in regards to the management and treatment of wastewater. At the 2011 Alaska Health Summit Jenssen (2011) presented on wastewater management issues also comparable to those reviewed in this paper. The comments and recommendations I have made within could be used to address issues in these regions as well.

CONCLUSIONS

The management planning and treatment of wastewater will continue to be difficult for communities in Canada's Arctic. These challenges clearly extend beyond the extreme climate, impending unknowns resulting from climate change, and absence of performance data of existing systems. Socio-cultural and political differences and varying understanding of the concepts of planning between Inuit and federal government will have the greatest, although indirect influence on wastewater treatment in the future. The impending performance standards should take into consideration the diverse climate, and socio-economic environment of the northern communities, focusing on maintaining a similar method of determining effluent quality for specific communities as the Nunavut Water Board currently, or by delineating specific geographic boundaries which are representative of climate regimes. Most importantly the performance standards should remain adaptive, allowing for meaningful consultation between aboriginal groups and scientists to change standards as more experience and knowledge is obtained. This review is pertinent to other remote cold climate communities globally; particularly those in Alaska who have similar climate and socio-economic structure as Arctic Canada.

CHAPTER 2

PERFORMANCE ASSESSMENT OF ARCTIC TUNDRA MUNICIPAL WASTEWATER TREATMENT WETLANDS THROUGH THE ARCTIC SUMMER

Summary: The treatment of municipal wastewater can be problematic in the remote cold climate environment of the Canadian Arctic, because of a variety of operational, financial, and technical and bureaucratic reasons. As a result, treatment facilities for many communities are thought to only achieve preliminary to primary treatment of municipal wastewater, wastewater often being discharged directly into wetlands. In this study I provide the first season-long study of tundra wetland systems in the Canadian Arctic. In 2008, I studied the performance of six natural wetland system used for wastewater treatment in the Kivalliq Region of Nunavut, Canada. The wetland systems studied services communities of approximately 320 to 2300 residents, including commercial and government buildings, but generally minimal industry. In total, the systems receive a flow rate of approximately 28-163 m^3/day of wastewater. I observed average weekly percent reduction in all parameters, with small deviations immediately after snow-melt and at the beginning of freeze-up. For the six parameters monitored I observed reductions of 47-94% $cBOD_5$, 57-96% COD, 39-98% TSS, >99% TC, >99% *E. coli*, 84-99% NH_3-Nand 80-99% TP. In three of the systems, the water discharged from the wetlands and into the receiving environment maintained similar concentrations, and significant similarities in NH_3-N and TP as observed in the natural background concentrations of nearby wetlands. The performance of tundra wetlands to treat the wastewater demonstrates that they are an appropriate technology for remote Canadian Arctic communities. This study also exemplifies the ability of natural wetlands to act as sinks and transformers, acknowledging that mechanistic assessments will be required to identify primary processes involved in the treatment of Arctic wastewater.

Keywords: Canadian Arctic; cold climate; natural tundra wetland; wastewater treatment

INTRODUCTION

During the 1950s and 1960s permanent (rather than nomadic) communities formed in the Arctic and in the last few decades rapid population growth has prompted a need to determine if current wastewater management strategies are appropriate given the remoteness and cold, dry climate unique to Arctic settlements (Chabot & Duhaime, 1998; Ritter, 2007). Many communities in Nunavut use natural wetlands to treat wastewater either continuously discharging from detention lagoons or facultative lakes (Wootton et al., 2008; Yates et al., 2010).

Tundra treatment wetlands in the Arctic are often located in naturally occurring wet depressions on the tundra, and have variable physio-geographic features, which influence plant communities and water retention which in turn influence the treatment of wastewater discharged into the systems. Their pre-treatment counterparts, facultative lakes, are natural lakes or ponds where wastewater is directly discharged into for preliminary and primary treatment. These systems act similarly to engineered facultative lagoons, which are also common throughout the Canadian Arctic (Johnson & Cucheran, 1994; Wootton et al., 2008). Annak Lake in Sanikiluaq is a well-documented facultative lake in Nunavut (Douglas and Smol, 2000; Douglas et al., 2004; Michelutti et al., 2007). Arctic treatment wetlands generally treat continuously discharging wastewater from retention lagoons or raw wastewater discharged directly into the wetland, although seasonally decanted systems are also present. Wetlands are a common and preferred approach in the Canadian Arctic because the high capital investment, operation costs, and the requirement of a specialized labour pool to maintain mechanical systems are beyond the capacity of most Nunavut communities (Johnson and Wilson, 1999). In communities in Nunavut, wastewater disposed into wetlands is done so at some distance away from the community and drinking water sources, although there are examples where the receiving environment is connected to the community water supply – e.g. Baker Lake (Wootton et al., 2008).

Natural wetlands have also been extensively used in the past to treat wastewater in temperate locations (Mander & Jenssen, 2002; Kadlec & Wallace, 2009). Treatment wetlands make use of the natural biogeochemical cycles of plants, periphyton, and the soil for the transformation, and mineralization of organic matter in the wastewater (Knox et al., 2008). Treatment wetlands have been shown to perform very well in temperate to cold temperate regions for polishing primary and secondary wastewater effluents (Wittgren & Maehlum, 1997; Wallace et al., 2001), many of which are engineered natural systems (e.g. Oxelosund, Sweden). In the cold temperate climate of Scandinavian countries, these systems have been used extensively (Kallner & Wittgren, 2001; Andersson et al., 2005). This is the case in Sweden where NH_3-N levels in effluent are now required to be reduced by at least 50% in all wastewater treatment, including natural wetlands (Andersson et al., 2002). Despite the successful use of natural wetlands to treat wastewater, in developed countries their use has declined. Kadlec and Wallace (2009) and Hammer and Bastian (1989) both recommended that natural wetlands for wastewater treatment stop because of their value in the landscape. Protection of wetlands in the United States in 1991 and parts of Canada now prevent this activity in most cases.

There is also evidence of the use of augmented or engineered natural wetlands in Nunavut. Cambridge Bay, Nunavut makes use of a lagoon-tundra wetland system. The natural wetland has been engineered to redirect and control flows (Kadlec and Johnson, 2008). The community of Arviat, Nunavut also uses berms and channels to direct wastewater flow away from the ocean and to keep a longer residency time in the wetland (Wootton et al., 2008).

Despite the presence of engineered wetland and lagoon systems compliance monitoring by local and territorial governments of Arctic wastewater treatment systems is known to be minimal, and is further limited by the unavailability of accredited laboratory facilities capable of analyzing wastewater (Johnson, 2008; Wootton et al., 2008). New regulatory standards for wastewater effluent that are to be implemented in Canada require that wastewater facilities in the Arctic be assessed for performance (Johnson, 2008; Canadian Council of Ministers of the Environment, 2009). Because of the climate of Canada's Arctic, wastewater effluent standards may be set higher than southern Canada, where 25 mg/L for $cBOD_5$, 25 mg/L for total suspended solids and 1.25 mg/L for NH_3-N has been set as a benchmark (Canadian Council of Ministers of the Environment, 2009; Government of Canada, 2010). All facilities in southern Canada are required to commence monitoring within three years, whereas a five year research period was granted for the northern territories (Northwest Territories, Nunavut, Yukon and regions above the 54^{th} parallel in Quebec and Newfoundland-Labrador) (Government of Canada, 2010). This research period will determine appropriate performance standards for treatment facilities in the extreme cold climate regions of Canada. Standards for the Far North are to be determined by 2013 (Canadian Council of Ministers of the Environment, 2009).

Given the remoteness and cold climate of the region, long term seasonal study of natural wetland treatment systems in Nunavut have not been extensively monitored until this study. The objective of this study was to assess the performance of six natural or augmented natural tundra wetlands treating municipal wastewater in a region of Nunavut during the Arctic summer. This study will help determine whether the current systems can remove wastewater contaminants to proposed regulatory standards for Canadian municipal wastewater. This study also provides the first season-long study of Arctic tundra wastewater treatment wetlands.

METHODS

Site Descriptions

Six natural treatment wetlands were studied in the Kivalliq Region of the Nunavut Territory, Canada. I studied systems in the Hamlets of Arviat, Baker Lake, Chesterfield Inlet, Coral Harbour, Repulse Bay and Whale Cove. The wetlands in these communities varied in size, geographic orientation, substrate (type and depth) and vegetation community. Some systems were characterized as wet-sedge tundra wetlands, wet-sedge tundra with defined stream channels, and low to prostrate shrub tundra. Some wetland systems were combined with facultative lagoons or lakes (Arviat, Coral Harbour, Whale Cove), while others received wastewater directly or with minimal pre-treatment (Baker Lake, Chesterfield Inlet and Repulse Bay). These communities were selected for study because of their proximity to a major transportation hub in the Arctic (Rankin Inlet) where samples could be quickly shipped within 24 hours for analysis in a portable laboratory by a staff of Centre of Alterative Wastewater Treatment technicians. Also, the majority of communities in Kivalliq Region used wetlands to treat wastewater, allowing for a greater sample of wetlands.

The community input of wastewater volume and concentration also varied, largely because of population size (320 to 2300 residents). Wastewater disposed of in the system is estimated by the volume of water used by the community; in 2006 it was estimated that the six communities ranged in water use at 55-96 L $person^{-1}d^{-1}$ (MTO, 2004). The estimated input into the systems was 28-163 m^3/day (Nunavut Water Board, 2008; 2009a; 2009b; 2010a; 2010b; 2010c).

All communities with the exception of Baker Lake were located on the coast of Hudson Bay. The average temperature for the region between June and October is 6.4^{o}C (sd 1.7), and a yearly average of -11.5^{o}C (sd 1.4). The average precipitation for this time period is 162 mm; a yearly average of 284 mm (Environment Canada, 2010).

Data Collection

I collected weekly samples from six treatment wetlands between June 21st and September 24th, 2008 which approximates the historical ice-free period of the year; June 10-15 to September 5-20 (Maxwell, 1981). Samples were transported in coolers to a laboratory in Rankin Inlet and analyzed within twenty-four hours of collection for time sensitive analysis of parameter (e.g. $cBOD_5$, and pathogens) following Standard Methods for Wastewater.

At each of the six wetlands samples (500 mL each) from the point of influence and effluence were collected with the help of local people acting as samplers. Additional sample points were used in Baker Lake because of the length of the system. These were located between the influence and effluence. The weekly samples gathered were used to evaluate the temporal variation associated with treatment efficacy of the tundra wetlands. Biological, chemical and physical water quality parameters were assessed; particularly $cBOD_5$, TSS, and NH_3-N which are regulatory parameters of the new *Fishery Act* regulations (Table 1) (Government of Canada, 2010). Temperature was recorded continuously over the ice-free period, with Onset Temperature logging tidbits situated in the surface w\ater of the influent and effluent streams; obtaining readings at 0.5 hour intervals.

Sampling at the influent and effluent is considered the minimum required sampling for wastewater treatment facilities (Kadlec & Wallace, 2009). Sampling more than once per week was not logistically possible, given restrictions of flight schedules in the Arctic to transport samples within a twenty-four hour period.

Adjacent tundra wetlands not receiving wastewater were sampled one time during the summer of 2008 to determine local background concentrations for the parameters of interest. These sites were selected based on proximity to the treatment wetland, and were not known to receive wastewater.

Table 2. Water quality parameters for the characterization of tundra wetlands and baseline study.

Water Quality Parameters	
Ammonia-nitrogen (NH_3-N)	Total Phosphorus
Dissolved Oxygen	COD
Total Coliforms	$cBOD_5$
E. coli	Total Suspended Solids

All parameters were analyzed using Standard Methods for the Examination of Water and Wastewater (Eaton & Franson, 2005). Hach DR 2700

Although heavy metals and persistent organic pollutants were not measured in this study, they would be parameters of interest for future studies.

I used a paired t-test (Type I; $p < 0.05$) to determine significant difference of the mean effluent to influent values in each of the wetlands. A paired t-test is a commonly used measure of significance when determining changes in concentration of wastewater through a treatment system (Bulc, 2006; Ling et al., 2009). A second season of data were collected in 2009 for Baker Lake only (Appendix B).

RESULTS

Raw wastewater was directly discharged into the wetlands or lagoons via tanker trucks. I observed a range of 550-1000 mg/L of $cBOD_5$ in raw wastewater entering these systems. Influent wastewater entering wetlands following pretreatment in facultative lakes or lagoons was significantly less than that of direct discharge into the wetland, as observed in influent values in Whale Cove (facultative lake pretreatment) as compared to Chesterfield Inlet (direct discharge) (Table 3).

The performance of each community varied for different wastewater parameters; some wetlands having much better performance on either TP or NH_3-N or both, than other wetlands. TSS was especially variable. In systems where wastewater was diluted in stream and small water bodies, TSS removals were very high because of sedimentation because of gravitational settlement of particulate matter. This was especially true in Repulse Bay and Baker Lake. $cBOD_5$ and COD removal was observed to be 47-94% and 57-96% respectively. In cases where percent removal was low for COD and $cBOD_5$, actual concentration of influent into the wetland was low, due to pre-treatment in either a facultative lake or lagoon. Whale Cove and Coral Harbour both exhibited this trend; the community of Whale Cove utilizing a facultative lake before continual discharging into the adjacent wetland and Coral Harbor making use of an engineered lagoon which continuously exfiltrates into the adjacent wetland. This was also the case for TSS in the Whale Cove and Arviat wetlands; Arviat also makes use of an engineered lagoon. However, in each case wetland effluent was below 25 mg/L for TSS; the new effluent standards for municipal wastewater facility effluent for $cBOD_5$ and TSS in southern Canada.

At the time of study treatment facilities with minimal holding capacity during the winter months, such as Chesterfield Inlet observed increases in $cBOD_5$ effluent concentrations during the spring freshet (Figure 2).

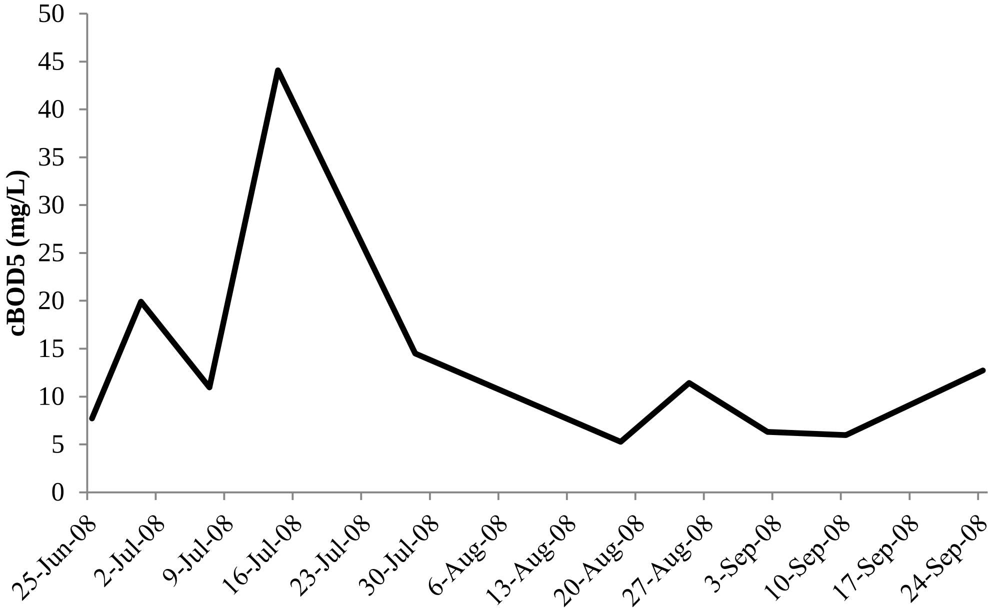

Figure 2. Chesterfield Inlet cBOD5 effluent increases during the spring freshet.

Baker Lake was resampled weekly again in 2009 where the effluent demonstrated consistency between the two years as demonstrated by $cBOD_5$ (Figure 4) (Appendix B).

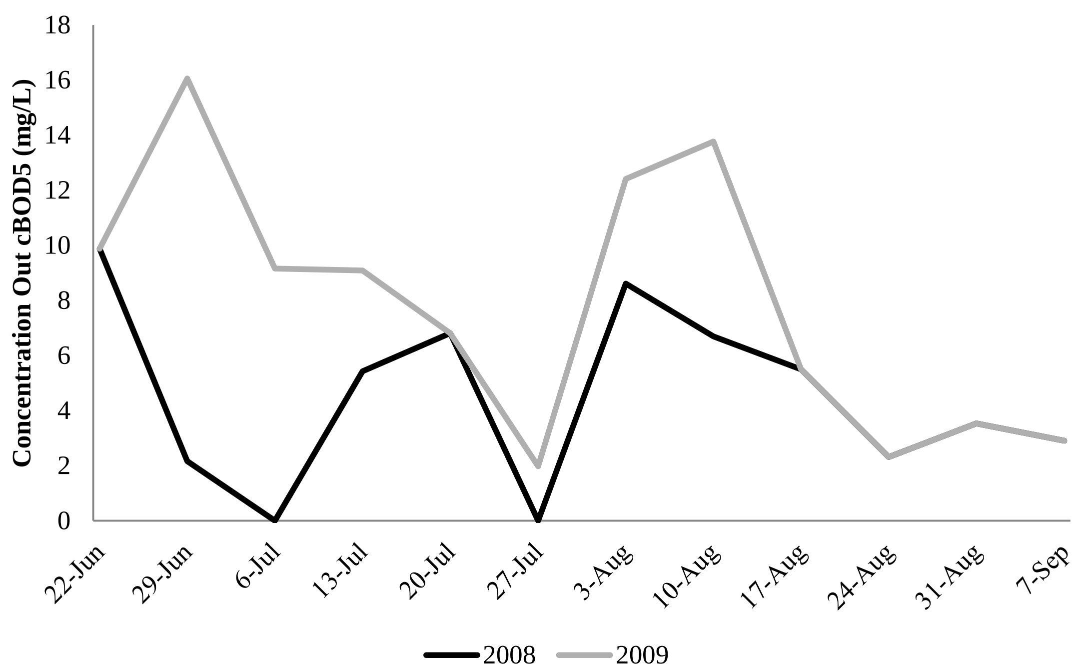

Figure 3. cBOD5 weekly effluent comparison in Baker Lake treatment wetland between 2008-2009.

Table 3. Mean influent and effluent data from six Kivalliq natural treatment wetlands. Bacteria parameters of total coliforms (TC) and *E.coli* were recorded in cfu/100ml.

Arviat

Volume Discharged (235 m^3/day)	Influent Concentration				Effluent Concentration					
	Mean	Standard Deviation	Max	Min	Mean	Standard Deviation	Max	Min	% Change	t-test (paired) n=11
$cBOD_5$ (mg/L)	103	50	193	33	16	6	24	6	85	0.000
COD (mg/L)	236	63.2	334	63.2	100	47.7	171	42.7	58	0.000
TSS (mg/L)	55.7	38.7	145	5.0	19.1	22.8	74.0	0.0	66	0.005
TP (mg/L)	11.3	7.8	34.7	6.3	2.3	2.2	9.0	1.0	80	0.002
NH_3 -N (mg/L)	73.2	43.3	209	43.3	11.0	10.4	40.4	0.4	85	0.000
E. coli	29500	18600	60000	10000	898	1350	4510	4	97	0.000
TC	633000	543000	162000	110000	4720	6790	24200	4	99	0.002
DO	1.9	1.1	3.9	0.3	9.1	1.8	11.8	1.8	79	0.000
Temp.(^{o}C)	9.2	4.6	19.5	0.6	6.3	3.6	14.3	0.2	-	-

Baker Lake

Volume Discharged (167 m^3/day)	Influent Concentration				Effluent Concentration					
	Mean	Standard Deviation	Max	Min	Mean	Standard Deviation	Max	Min	% Change	t-test (paired) n=13
$cBOD_5$ (mg/L)	466	228	962	246	6	4	17	0	99	0.000
COD (mg/L)	798	676	2920	366	24.0	27.9	109.0	1.4	97	0.001
TSS (mg/L)	314	521	1770	7.0	3.2	3.9	13.0	0.0	99	0.027
TP (mg/L)	13.9	3.7	25.7	11.1	0.2	0.2	0.9	0.0	99	0.000
NH_3 -N (mg/L)	82.5	16.4	133	67.4	0.1	0.1	0.2	0.0	>99	0.000
E. coli	16400000	1670000	68500000	3200000	14	14	52	3	>99	0.002
TC	30600000	26200000	96900000	2420000	1100	1500	4850	17	>99	0.001
DO	0.7	0.3	1.1	0.2	8.9	1.6	11.5	6.4	92	0.000
Temp.(^{o}C)	14.2	4.8	25.9	4.4	3.2	1.9	8	0	-	-

Chesterfield Inlet

Volume Discharged (36 m^3/day)	Influent Concentration Mean	Standard Deviation	Max	Min	Effluent Concentration Mean	Standard Deviation	Max	Min	% Change	t-test (paired) n=12
$cBOD_5$ (mg/L)	221	117	379	70	14	11	44	5	94	0.000
COD (mg/L)	300	134	569	99.4	64.3	38.8	138	26.2	79	0.000
TSS (mg/L)	74.9	44.9	153	15.0	10.3	16.1	50.0	0.0	86	0.003
TP (mg/L)	5.6	1.6	9.1	1.6	0.4	0.3	0.9	0.0	92	0.000
NH_3-N (mg/L)	39.6	18.4	90.4	18.4	0.1	0.1	0.4	0.0	>99	0.000
E. coli	1390000	2670000	9400000	60000	87	182	600	3	>99	0.064
TC	57100000	74500000	242400000	300000	771	1240	3800	11	>99	0.016
DO	1.7	1.4	4.2	0.2	11.0	0.8	12.0	0.8	84	0.000
Temp.(^{o}C)	6.6	2.7	16.3	0.5	6.2	2.9	13	0.5	-	-

Coral Harbour

Discharge Volume (96 m^3/day)	Influent Concentration Mean	Standard Deviation	Max	Min	Effluent Concentration Mean	Standard Deviation	Max	Min	% Change	t-test (paired) n=14
$cBOD_5$ (mg/L)	181	180	649	33	14	14	54	5	92	0.005
COD (mg/L)	308	158	738	147	66.3	64.6	198	10.1	79	0.000
TSS (mg/L)	93.2	146	560	6.0	10.5	10.0	27.5	0.0	88	0.387
TP (mg/L)	5.5	2.5	12.7	2.0	0.8	0.8	2.2	0.1	86	0.000
NH_3-N (mg/L)	21.8	11.2	41.0	6.1	2.8	5.5	16.0	0.0	87	0.000
E. coli	37000	55600	150000	600	168	339	1200	3	100	0.029
TC	4950000	9860000	27400000	9500	6960	21800	79400	21	100	0.072
DO	3.3	3.4	11.9	0.6	10.6	0.9	12.4	9.4	68	0.000
Temp.(^{o}C)	11.7	5.6	24.8	3.2	9.7	6.7	24.9	0.5	-	-

Repulse Bay

Discharge Volume (66 m^3/day)	Influent Concentration Mean	Standard Deviation	Max	Min	Effluent Concentration Mean	Standard Deviation	Max	Min	% Change	t-test (paired) n=11
$cBOD_5$ (mg/L)	385	237	1020	164	25	18	77	12	93	0.000
COD (mg/L)	450	165	653	174	64.4	46.6	171.0	18.9	86	0.000
TSS (mg/L)	197	321	920	6.0	34.8	27.8	84.0	6.0	82	0.071
TP (mg/L)	9.2	2.4	11.4	3.8	1.4	1.0	3.4	0.1	85	0.000
NH_3-N(mg/L)	70.0	34.3	142.8	3.2	2.8	2.6	9.0	0.1	96	0.000
E. coli	14100000	15100000	53400000	300000	165	310	800	3	100	0.008
TC	2130000000	204000000	678000000	1600000	1940	3420	10600	22	100	0.006
DO	1.3	1.6	6.0	0.2	10.1	2.4	15.7	6.9	87	0.000
Temp.(^{o}C)	6.1	4.3	23.1	0.1	6.2	4.3	17.2	-0.3	-	-

Whale Cove

Discharge Volume (82 m^3/day)	Influent Concentration Mean	Standard Deviation	Max	Min	Effluent Concentration Mean	Standard Deviation	Max	Min	% Change	t-test (paired) n=13
$cBOD_5$ (mg/L)	40.3	73	271	14	21	48	174	3.0	47	0.015
COD (mg/L)	133	34.1	199	95.8	39.5	36.7	146	13.7	70	0.000
TSS (mg/L)	29.4	34.3	88.0	0.0	18.0	34.9	126	0.0	39	0.000
TP (mg/L)	4.1	1.4	6.9	1.3	0.1	0.1	0.3	0.0	97	0.000
NH_3-N (mg/L)	9.0	3.3	13.5	3.8	0.0	0.0	0.0	0.0	100	0.000
E. coli	7590	9500	35000	300	36	39	123	3	100	0.009
TC	126000	149000	484800	1300	205	221	694	13	100	0.007
DO	10.0	1.2	12.3	7.9	10.9	0.6	11.9	10.2	8	0.004
Temp.(^{o}C)	8.2	6.6	24.9	0.5	10.7	6.1	22.2	0.3	-	-

Table 4. Reference water quality values for adjacent nearby natural wetlands. Bacteria parameters of total coliforms (TC) and *E.coli* were recorded in cfu/100ml.

	Wetlands					
	Arviat		Baker Lake		Chesterfield Inlet	
Parameters	Background	Effluent	Background	Effluent	Background	Effluent
$cBOD_5$	6.3	15.6	1.8	5.6	2.7	13.9
COD	31.8	100	66.6	24	14.5	64.3
TSS	6	19.1	2	3.2	3	10.3
TP	0.15	2.3	0.07	0.2	0.02	0.4
NH_3-N	0.14	11	0.18	0.1	0.08	0.1
E. coli	40	898	6	14	20	87
TC	615	4720	44	1100	1360	771
DO	11.2	9.1	9.6	8.9	10.8	11
	Coral Harbour		Repulse Bay		Whale Cove	
Parameters	Background	Effluent	Background	Effluent	Background	Effluent
$cBOD_5$	3.8	13.9	24.1	25.3	0	21.4
COD	30.5	66.3	91	64.4	21	39.5
TSS	103	10.5	0	34.8	0.3	18
TP	ND	0.08	0.2	1.4	0.18	0.1
NH_3-N	0	2.8	0.012	2.8	0.02	0
E. coli	6	168	80	165	6	36
TC	10	6960	12100	1940	56	205
DO	9.9	10.6	10.9	10.1	6.6	10.9

DISCUSSION

The performance of each community's treatment wetland varied for different wastewater parameters, some wetlands having much better performance on either TP or NH_3-N or both, than other wetlands. TSS was especially variable. In systems where wastewater was diluted in stream and small water bodies, TSS removals were very high because of sedimentation because of gravitational settlement of particulates (Wallace and Knight, 2006). This was especially true in Repulse Bay and Baker Lake. $cBOD_5$ and COD removal was observed to be 47-94% and 57-96% respectively for all the wetlands. In cases where percent removal was low for COD and $cBOD_5$, actual concentration of influent into the wetland was low, due to pre-treatment in either a facultative lake or lagoon. Whale Cove and Coral Harbour both exhibited this trend; the community of Whale Cove utilizing a facultative lake before continual discharging into the adjacent wetland and Coral Harbor making use of an engineered lagoon which continuously exfiltrates into the adjacent wetland. This was also the case for TSS in the Whale Cove and Arviat wetlands; Arviat also makes use of an engineered lagoon. However, in each case wetland effluent was below 25 mg/L for TSS; the new effluent standards for municipal wastewater facility effluent for $cBOD_5$ and TSS for southern Canada.

Natural background concentrations of parameters were also observed from an adjacent, discrete reference wetland. For nutrient parameters of TP and NH_3-N, the treatment wetland effluent was observed to be similar in concentration to reference levels: TP 0.02-0.2 mg/L and NH_3-N 0-0.18 mg/L (with the exception of Repulse Bay and Arviat for TP). Only Baker Lake and Whale Cove achieved background levels in treated effluent for both TP and NH_3-N. Chesterfield Inlet achieved background levels for NH_3-N and Coral Harbour achieved background levels for TP.

Pathogen concentrations were reduced to background concentrations in some instances, although this was variable and may reflect different natural sources of pathogens, such as snow geese (*Chen caerulescens* L.) which were commonly present throughout some of the wetlands. Other studies have also reported high background concentrations of pathogens and other parameters due to waterfowl (Kadlec & Wallace, 2009; Kadlec et al., 2010). The organic concentrations, denoted by $cBOD_5$ and COD, at the effluence still remained higher in the treatment wetland in comparison to the reference wetland concentrations for most communities. Only Baker Lake and Repulse Bay achieved effluent levels below background levels for COD. Although effluent was dissimilar from background concentrations in most cases it was found to be on average for the summer to be below proposed regulatory standards for $cBOD_5$ in all the communities.

It is not clearly understood which mechanisms and environmental factors play the greatest role of treating or influencing treatment of wastewater in the Arctic. By examining processes of nutrient and organic matter mineralization in Arctic environments, I suggest how wastewater treatment may be influenced in such a climate. Air temperature and soil temperature plays the largest, although indirect, role in the treatment of wastewater in the Arctic. Chapin (1983), Chapin & Shaver (1985) and Hobbie (2007) showed how temperature influences nutrient availability, organic matter mineralization which rely on the same microbial communities as wastewater treatment would. Because of extreme low temperatures during the winter (e.g. -17^{o}C to -32^{o}C between November and May) no significant treatment would occur during the winter months. Also, wastewater treatment would be minimal during the spring freshet, with the release of thawing waste accumulated during the winter in the communities that do not have the capacity of long term storage. The sampling I conducted captured a portion of the spring freshet, which likely accounted for variation or large standard deviation in effluent concentration of many of the parameters I tested; deviations being the most prominent the end of June during final snow melt and the end of September following senescence and short periods of freezing temperatures. In similar treatment wetlands throughout the Canadian Arctic, such as Arviat and Cambridge Bay, wastewater preferential flow has been minimized and residency time increased through the use of berms and other structures (Kadlec & Johnson, 2008). This was done to increase treatment periods and to allow for microbial uptake/transformation of nutrients in the wastewater in the far north.

Soil temperature relating to microbial activity and plant growth would significantly influence the treatment of wastewater in Arctic wetlands. Most Arctic wetlands, particular wet-sedge tundra have been found to be very nutrient poor, particularly limiting in P (Shaver et al., 1998). However, the greatest responses in plant communities in all Arctic environments, was observed when the addition of N and P were combined (Arens et al., 2008). In Arctic systems many nutrients become locked and unavailable to plant and microbial communities in frozen or partially frozen soils (Mack et al., 2004). In wet-sedge tundra where soils were supplemented with additional nutrients, particularly N and P, plant communities quickly uptake the nutrients, promoting growth and often demonstrated changes in community structure (Gough et al., 2002). Also, some species have adapted to utilize organic forms of N, such as in amino acids (Chapin et al., 1993). 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. Vegetation surveys of the wetland show predominantly nitrophilous species present in areas of highly concentrated wastewater, which agrees with Gough et al. (2002) observations of changes in community structure in response to sources of nutrients. It was recently observed by Edwards (2009) that Arctic microorganisms become active at temperatures as low as -5^{o}C. Hobbie & Chapin (1996) also suggested that microbial activity may be able to uptake nutrients in soils at temperatures as low as -5^{o}C. These observations may contribute to the rapid increase in wetland performance from late June to early July due to increases in microbial populations as a result of additional nutrient availability in still semi-frozen soils.

Filtration and sedimentation of suspended solids and adsorption of nutrients within the soil and water column also plays a significant role in some systems with more open water, as mineralization rates in the water column of wetlands would be low. Whereas, in systems where flows go into the soil profile, sedimentation would be minimal, as soil depths are often shallow (less than 0.30 m in depth), leaving only minimal media for sedimentation and filtration to occur. Personal observations show accumulations of organic matter in many of the wetlands surveyed throughout the Arctic. Chapin et al. (1993) observed that mineralization of organic material is slow in relation to more temperate locations because of low soil temperatures.

The high percentage change of wastewater concentration in many of the wetlands I studied also corresponds well with observations made on other natural and augmented treatment wetlands used in more southern or temperate locations. However, many examples of natural wetlands in temperate locations are used to polish wastewater from lagoons or mechanical treatment facilities. Therefore, influent concentrations are much lower than the raw wastewater received in many Arctic wetlands. Andersson et al. (2002) studied a Swedish wetland with mechanically pre-treated wastewater for five years. Influent levels for BOD and nitrogen were low; a maximum average of 29.5 mg/L and 18 mg/L for BOD_7 and NH_4^+-N respectively. They observed removals for these species in the range of 73-85% for BOD and 23-39% for NH_4^+-N (Andersson et al., 2002).

The Houghton Lake, Michigan wetland system has been studied extensively since the 1970s and was one of the first natural wetlands to receive pre-treated wastewater in North America (Kadlec et al., 2010). This system has also successfully met treatment objectives in a cold climate setting. The natural system was shown to effectively treat the secondary wastewater entering the system

Data from a treatment wetland in Minot, North Dakota, further exemplifies excellent treatment following extended periods of freezing temperatures as low as -45^{o}C (Hammer & Burckhard, 2002). Again this system experienced extensive pre-treatment through facultative ponds in comparison with influent for the wetland averaging 13.1 mg/L for BOD_5 and 4.2 mg/L for NH_3-N. For temperatures <5^{o}C BOD removal rate was 27.2% and 46.8% for NH_3-N (Hammer & Burckhard, 2002). Although the Minot wetland system is a constructed surface flow wetland, the importance of sustaining removals through extreme temperature fluctuations is important for future considerations in more northern locations. Systems like the one in Minot function at approximately 10^{o}C and can provide some comparison to average Canadian Arctic summer temperatures. However, other environmental factors such as photoperiod and cooler soil temperatures cannot be as easily compared between the Minot wetland and the other examples provided with Arctic systems.

Kadlec and Johnson (2008) modeled expected removals of TSS, cBOD, N and P using rate coefficients appropriate for Arctic conditions to show how a wetland system in Cambridge Bay, Nunavut could successfully treat municipal wastewater. The models they used showed removal rates that are expected to drive $cBOD_5$ under 9 mg/L, and down to 10 mg/L for total suspended solids following pre-treatment in continuous flow facultative lakes. Very low rate coefficients were used for more temperature sensitive nitrogen species. The expected effluent values that Kadlec & Johnson (2008) calculated (BOD-9 mg/L and TSS 13 mg/L), are comparable to what I observed in the Chesterfield Inlet wetland. These results were comparable even though Chesterfield Inlet did not yet have a pre-treatment system.

However, although the modeling briefly discussed above and the data presented show Arctic wetlands can successfully treat municipal wastewater during a single Arctic summer, temporal performance will likely be more variable, because of yearly variation in weather, and in light of climate change. This is especially true in the Arctic where climate change is expected, and already is experiencing the most drastic changes (Lashof & Ahuja, 1990; Johannessen et al., 2004). Given estimates of increases in mineralization rates of organic matter and nutrients (Jonasson et al., 1993; Chapin et al., 1995), increases in plant biomass (Cornelissen et al., 2001), treatment periods would likely become longer, performance would only improve. But such changes would also require changes in the management strategies, because of changes in the hydrological regime, eutrophication downstream and prolonged increases in pathogens may have human and ecosystem consequences given the current management of treatment systems (Rouse et al., 1997; Smol & Douglas, 2007).

CONCLUSIONS

This study exemplifies the ability of natural wetlands to act as sinks and transformers of nutrients, organic material and pathogens even in the very harsh climatic conditions and low biomass producing ecosystems of the Canadian Arctic. The exact mechanisms and processes of transformation and removal have not been identified in this study and should be examined further. Despite our lack of knowledge in processes, 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 suspended solids removal. Removals for $cBOD_5$ were even below regulatory standards for effluent in southern Canada in all cases (Canadian Council of Ministers of the Environment, 2009). TSS was also found to be 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.

Natural wetlands to treat wastewater are an appropriate technology for Canadian Arctic communities where other technologies are not economically or technologically feasible. Large lagoons or facultative lakes to store wastewater over the winter period would be an appropriate management strategy to prevent spring freshet containing large volumes of frozen wastewater. Continuous flow lagoons, which slowly decant throughout the summer months, would likely be preferential. Since the time of study, Chesterfield Inlet and Baker Lake have both received larger lagoons as part of their wetland system.

CHAPTER 3

EXPLORATORY PERFORMANCE TESTING OF A PILOT SCALE HORIZONTAL SUBSURFACE FLOW WETLAND IN BAKER LAKE, NUNAVUT

Summary: Arctic Canada presents a unique environment to study the climatic limitations of constructed wetlands. Despite constructed wetland's increasing use in other cold climate and developing regions of the world, they have not been studied in the Canadian Arctic. In 2008, I designed and built a 4-celled gravity fed horizontal sub-surface flow constructed wetland (total area ~15m^2) in Baker Lake, Nunavut, Canada; the first experimental, engineered system with a liner in the Arctic. The wetland received municipal wastewater from the community. In June 2009, I began monitoring the performance of the HSSF wetland for key wastewater quality parameters (cBOD$_5$, COD, TSS, *E. coli,* Total Coliforms, and TP) from middle June through August. I again sampled the system in 2010, reducing the load on the system from 66 kg BOD ha^{-1} d^{-1} to approximately 23 kg BOD ha^{-1} d^{-1} with diluted wastewater. During both years, samples were collected from each cell and from the inlet and outlet three times per week. In both years, hydraulic retention time was maintained at a mean HRT = ~9d. Despite slow start-up in 2009, I observed some promising mean removals in cBOD$_5$, COD, TSS, *E. coli,* Total Coliforms, and TP; removals of 25%, 31%, 52%, 99.3%, 99.3%, and 5% were observed respectively. With a reduced loading rate in 2010 the system did not perform as expected, and concentration of effluent increased. I hypothesized that a high organic loading during the first year of study saturated the system with organics, stratification in the media, coupled with the fact that the use of predominately anaerobic technology in a temperature limited environment caused mineralization of organics to be even slower were among the reasons for the results.

Keywords: Arctic, constructed wetland, municipal wastewater, HSSF, cold climate

INTRODUCTION

In the context of ecological engineering and restoration (Mitsch and Jørgensen, 2004), constructed wetlands (CWs) have become a popular low-cost, high efficiency technology for the treatment of many different types of wastewater (Campbell & Ogden, 1999; Kadlec & Wallace, 2009), and have been applied widely around the world; including, tropical, temperate and cold temperate environments (Greenway & Simpson, 1996; Wallace et al., 2001; Wittgren & Maehlum, 1997). However, what Spieles and Mitsch (2000) stated is still true today – their long term effectiveness and sustainability requires study and this is especially true in the Arctic regions of Canada where they have yet to be experimentally tested.

In the cold temperate regions of North America continental Europe and Scandinavia, performance of constructed wetlands has been well documented (Wittgren & Maehlum, 1997). Free water surface wetlands (FWS), horizontal sub-surface flow (HSSF) and vertical flow (VF) have all been adopted throughout these regions. Mander & Jenssen (2003) describe these treatment wetlands as facing two main operating challenges in cold climates: (1) failure of system hydraulics, due to a change in viscosity or a freezing of the wastewater, and (2) the low temperatures leading to inadequate purification.

With respect to temperature in cold climate environments chemical oxygen demand (COD) and biological oxygen demand (BOD) removals have been shown to be un-influenced down to 5^{o}C. Greenway & Woolley (1999) and Vymazal (2002) have shown that organic matter removal in wastewater through anaerobic and aerobic bacteria can remain active to 5^{o}C. However, prolonged temperatures below 5^{o}C have many limitations for treatment of wastewater in wetlands; environmental variables that may indirectly or directly affect performance include freezing (ice), reduction in microbial community biomass, plant dynamics and mineralization of organics. Resulting heat loss in temperate environments generally occurs in late winter (Kadlec & Wallace, 2009), whereas in an Arctic environment this would be expected to occur much more rapidly. Even though substantial attention has been paid in finding effective measures to limit the effect of temperature on constructed wetlands systems very little is known about these technologies when employed in regions where mean annual temperature is well below 0^{o}C.

Natural tundra wetland systems have been extensively used for the treatment of wastewater in remote communities of the Canadian Arctic. Wootton et al. (2008) noted that eleven such wetland treatment systems are currently being used in Nunavut. These wetlands are often used to polish continuous discharge from lagoons and facultative lakes, as well as decanted lagoon wastewater and to treat raw wastewater. Kadlec & Johnson (2008) described a natural wetland in Cambridge Bay, Nunavut that was augmented or engineered to enhance treatment through the use of berms to channel wastewater and improve residency time. Preliminary observations from tundra treatment wetlands in the Canadian Arctic showed that during the summer months (July to mid-September) treatment of wastewater is high. Yates et al. (2010) observed 94%, 67%, 52%, 92%, 99%, 99.99%, 99.99%, removal of $cBOD_5$, COD, TSS, TP, NH_3-N, *E. coli*, and total coliforms respectively for a natural wetland system in Chesterfield Inlet, Nunavut. Treatment during the winter months using treatment wetlands is not feasible due to the climate. However, the successful use of natural wetlands in the Canadian far north, suggests that CWs may be a viable alternative technology for remote Arctic communities during summer months. CWs have also been shown to be an economical and a resource conservative technology appropriate for developing countries, rural areas, and in other small communities in cold temperate climates which have limited ability for large capital investments (Kivaisi, 2001; Wallace & Knight, 2006; Werker et al., 2002). I identified Arctic communities as localities that may potentially benefit from the technology and to test CWs effectiveness in an extreme cold climate environment. My objectives were, i) to conduct exploratory studies on the treatment efficacy of a small scale pilot HSSF constructed wetland during the short Arctic summer; a first in the Canadian Arctic. And, ii) to determine how a CWs system would respond in one of the most extreme cold climate wastewater treatment environments.

METHODS

The Hamlet of Baker Lake (64^{o}N, 96^{o}W) is the only inland community of Nunavut. Baker Lake has average summer (June-August) temperatures between 5^{o}C-12^{o}C, and mid-winter (December-March) -27^{o}C to -32.3^{o}C. The yearly average temperature for the community is -11.8^{o}C (Environment Canada, 2010). The landscape is dominated by low granite ridges and a glacial till moraine, with underlying mineral soils. The current treatment facility is composed of a small detention pond (~60 m^2), which drains overland through a sedge wetland into a series of small natural lakes with riparian wetland complexes between. The sub-basin drains into Airplane Lake and finally into Baker Lake; the source of drinking water for the community. Currently, the community discharges 167 m^3/day (167,000 L/ day) into the holding pond (Hamlet of Baker Lake, 2009).

The system consists of four in-line cells, with a total treatment area of 15 m^2 (Table 5). The cells were built with recycled insulated fibreglass holding tanks, and connected with 0.025 m (1 inch) diameter polyvinyl (PVC) piping. The piping was installed through the berm side of the pre-treatment holding pond and sunk below the surface. Piping was shallow buried to minimize late and early season freezing.

Table 5. Pilot constructed wetland dimensions in Baker Lake.

Cell #	Length (m)	Width (m)	Area (m^2)	Depth of Water (m)	Depth of Gravel (m)	Total Saturated Water Volume (m^3)	Water Only Volume (0.40 Porosity) (m^3)
1	2.26	1.98	4.47	0.33	0.36	1.48	0.27
2	2.16	1.73	3.74	0.37	0.51	1.38	0.25
3	2.16	1.73	3.74	0.3	0.51	1.12	0.20
4	2.13	1.55	3.30	0.38	0.46	1.25	0.23
Total			15.25	$\bar{x}$=0.345	$\bar{x}$=0.46	5.23	0.94

Local screened aggregate was used as the bed media, with a porosity of 0.40. Perforated sampling ports were installed in the media at the influent and effluent of each wetland cell. Each of the cells were planted with approximately 10 (dependent on plug size) *Carex aquatilis* (Stans), and *Poa glauca* (Vahl) plugs, two species which are indigenous to the adjacent natural treatment wetland. These species were selected as they have been commonly found in areas of high wastewater loading, are known to be nitrophilic and demonstrate phenotypic plasticity (Aiken, 2007). Additional plugs were planted in 2009, to increase vegetation cover in the cells. In 2008, the system was fed wastewater through the system to establish the plant community, and biofilm. Wastewater flow (m^3/day) was measured with a collection tank, which was emptied daily. I sampled the system in the summer of 2009 (June 21 to August 10) and again in 2010 (June 21 to

August 13) corresponding with the frost free season in the community. Samples were collected from the holding tank and from the effluent of the system three times per week. In 2009 the system was fed minimally pre-treated wastewater from the community of Baker Lake, and in 2010 the wastewater was diluted to reduce the organic load. In 2010 the organic load was reduced from 66 kg BOD ha^{-1} d^{-1} to approximately 23 kg BOD ha^{-1} d^{-1}. I maintained an average theoretical hydraulic residency time (HRT) of ~9d for both years. Longer residency times of 8-14d have been shown to be more effective in temperatures below 15^{o}C (Akratos & Tsihrintzis, 2007). Through both summer field seasons I sampled for COD, $cBOD_5$, TSS, *E.coli*, total coliforms, total phosphorus (TP), ammonia-nitrogen (NH_3-N) and temperature. Additional parameters of nitrate (NO_3^--N), and phosphate (PO_4^{3-} -P) were more extensively monitored in 2010. Parameters were analyzed according to Standard Methods for Water and Wastewater (Eaton & Franson, 2005).

I calculated expected effluent concentrations using the first-order kinetic model (P-*k*-C*) in order to compare observed effluent values for $cBOD_5$, and TSS (2-3). I re-calculated the rate constant for the P-*k*-C* model at 10^{o}C using the van't Hoff-Arrhenius equation as described in Crites & Tchobanoglous (1998) (1):

$$\frac{d(\ln k)}{dT} = E/RT^2 \qquad (1)$$

The P-*k*-C* model is described in Campbell & Ogden (1999) as:

$$As = \frac{Q(lnCo - lnCe)}{k_t * d * n} \qquad (2)$$

The k_t value for the P-*k*-C* model was determined by using a k_{10} value of 1.0; the Ɵ-factor used was 1.14. A high Ɵ-factor was deemed appropriate for extreme temperature cases as determined for a Minnesota HSSF wetland with a temperature range from 1-17^{o}C, as outlined in Kadlec and Wallace (2009).

The equation for TSS removal also described in Campbell & Ogden (1999) as:

$$TSS_{eff} = TSS_{inf} * (0.0158 + 0.0011 * HLR) \qquad (3)$$

RESULTS/DISCUSSION

$cBOD_5$ in the Baker Lake holding cell was observed to be an average of 421 mg/L for the summer of 2009 (Table 6). In 2010, the diluted wastewater I fed the system with maintained an average $cBOD_5$ concentration of 164 mg/L (Table 7).

Average removal of wastewater constituents was observed to be greatest during last week of July, 2009 (Table 6). Performance of the wetland would be expected to be highest during this time in Baker Lake CW as this would correspond with the season's highest average mean daily air temperature (11.4^{o}C in July) (Environment Canada, 2010). I observed an average temperature of wetland effluent of 11.8^{o}C and influent wastewater temperature was an average of 17.1^{o}C for the summer.

In 2009, I observed promising performance in the HSSF system, despite the high organic load from minimally pre-treated wastewater. $cBOD_5$ and COD averaged approximately 25% to 32% change in concentration respectively. Organic solids and total solids removal were observed to be 33% and 53% respectively. Pathogen parameters of *E.coli* and total coliforms also showed promising changes in concentration by two orders of magnitude. Only NH_3-N and TP concentrations changed very little from the influent to effluent throughout the study period, as would be expected in a HSSF system fed with minimally pre-treated wastewater in cold climates.

In response to our findings in 2009, I replicated the experiment in 2010 but reduced the organic loading rate by diluting the wastewater entering the system. This was done to accommodate for the low BOD removal values from 2009. Average loading for 2010 was calculated as 23 kg BOD ha^{-1} d^{-1} compared to 66 kg BOD ha^{-1} d^{-1} in 2009. Despite the reduction in loading in 2010, I observed no observable decrease in concentration of wastewater parameters from the influent to the effluent of the system as I had expected. In most cases increases in BOD, COD, TP and TSS were observed (Table 6). Only pathogens, *E. coli* and total coliforms were observed to decrease in concentration in the "treated" effluent (Table 6). Also concentrations of NO_3^--N were observed to increase in the wetland effluent, despite large increases of NH_3-N.

Table 6. Average weekly loading and % change of wastewater contaminant concentrations for July 1st to August 10th, 2009. All parameters in mg/L, and cfu/100ml for bacterial parameters unless otherwise stated.

Wk.	Parameter	Flow (L/day)	Loading (kg/ha/day)	Influent Concentration	Obs.Effluent Concentration	Expected Effluent	% Change
1	COD	387	253	998	773		23
	$cBOD_5$		118	464	212	66	54
	DO		0.15	0.6	1.5		-60
	TSS		43	168	36	11	79
	VSS		13	52	20		62
	E.coli		-	6.61	5.78		0.83[a]
	Total Coliforms		-	8.83	6.93		1.90[a]
	NH_3-N		28	110	62		44
	TP		3.8	15	15		0
	Temp. (^oC)		-	19.1	12.3		36
2	COD	383	158	628	476		24
	$cBOD_5$		97	384	380	53	1
	DO		-	ND	4.4		ND
	TSS		47	189	56	11	70
	VSS		37	149	31		79
	E.coli		-	8.45	5.48		2.97[a]
	Total Coliforms		-	9.29	6.61		2.68[a]
	NH_3-N		20	80	96		-20
	TP		3.4	13.4	14.5		-8
	Temp. (^oC)		-	18.2	12.9		29
3	COD	240	150	952	567		40
	$cBOD_5$		78	493	434	21	12
	DO		0.09	0.4	3.5		-89
	TSS		22	141	17	10	88
	VSS		20	128	16		88
	E.coli		-	6.60	5.47		1.13[a]
	Total Coliforms		-	8.21	6.79		1.42[a]

	NH_3-N		17	110	101		8
	TP		2.7	17	17.9		-5
	Temp. (^oC)		-	15	9.5		37
4	COD	167	90	824	565		31
	$cBOD_5$		36	333	256	4	23
	DO		0.03	0.3	4.8		-94
	TSS		12	108	23	10	79
	VSS		11	98	21		65
	E.coli		-	6.60	5.47		1.13[a]
	Total Coliforms		-	8.11	6.51		1.60[a]
	NH_3-N		12	110	107		3
	TP		1.6	14.4	14.6		-2
	Temp. (^oC)		-	16.9	12.4		26
5	COD	101	63	956	454		53
	$cBOD_5$		30	460	145	0.3	69
	DO		0.02	0.3	1.8		-83
	TSS		13	200	37	11	82
	VSS		12	185	31		83
	E.coli		-	6.38	5.48		0.90[a]
	Total Coliforms		-	8.36	6.37		1.99[a]
	NH_3-N		4.0	60	80		-33
	TP		1.1	17	12.1		29
	Temp. (^oC)		-	17.3	12.5		28
6	COD	149	77	792	691		13
	$cBOD_5$		38	393	459	2	-17
	DO		0.02	0.16	3.2		-95
	TSS		21	211	39	11	82
	VSS		19	193	34		82
	E.coli		-	6.60	5.48		1.12[a]
	Total Coliforms		-	8.84	6.38		2.46[a]
	NH_3-N		6.8	70	92		-31
	TP		ND	ND	13.1		ND
	Temp. (^oC)		-	16.3	10.9		33
Avg	COD	238	134	858	588		32
	$cBOD_5$		66	421	314	17	25
	DO		0.062	0.4	3.2		-88
	TSS		26	169	80	11	53
	VSS		20	134	90		33
	E.coli		-	7.70	5.54		2.16[a]
	Total Coliforms		-	8.80	6.65		2.15[a]
	NH_3-N		14	90	90		0
	TP		2.4	15.1	14.34		5
	Temp. (^oC)		-	17.1	11.8		31

[a] Log units. *E.coli* and total coliforms in log_{10} CFU/100ml.

After two seasons of operation, the HSSF system appeared to fail in 2010; observing increases in concentration of parameters in the wetland effluent. I hypothesize a number of factors as influencing these results. First, a likely primary cause of the failure was because of saturation of the bed media with organics because of overloading the system with concentrated wastewater in 2009. The increased values of COD, $cBOD_5$ and TSS in the effluent in 2010, point towards this hypothesis, as dissolved organic and particulate matter may have been re-suspended. The higher effluent values observed in 2010 suggests that the background concentration of organic matter, particulate solids and nutrients in the bed media were higher than the wastewater fed into the system. I calculated that through the study period in 2009 that approximately 1 kg of TSS remained in system, which 0.5 kg was accounted for as volatile solids. Kadlec & Wallace (2009) and Knowles et al. (2011) both suggest that in HSSF wetlands, water velocity is not enough to cause shear which would lead to re-suspension or disassociation of particles. Rather than picking up particles, surfacing of water on top the media would likely be the result of complete clogging of pore space with solids (Maloszewski et al., 2006). As I did not observe surfacing of wastewater in the system, it would suggest that significant clogging of the pore space was not occurring. This observation indicates that particle retention on the media surfaces was poor due to over-saturation, poor electro-static interaction between the particles and the bed media and/or a difference in ionic strength of incoming wastewater. Hermansson (1999) states that adhesion of particles to a surface is dependent on the media, bulk fluid and charge on the particle. If attachment was poor, Knowles et al. (2011) suggest that in SSF wetlands, particles could be released back into solution by peptization. This would result in the release of any number of particles back in solution, including phosphorus, solids and dissolved organics which I observed in 2010.

Table 7. Average percent change in concentration of wastewater parameters observed in 2010 and compared to modeled expected effluent concentrations. Concentrations are in mg/L unless otherwise stated.

Parameter	Flow (L/day)	Loading (kg/ha/day)	Influent Concentration	Obs. Effluent Concentration	Expected Effluent	% Change
COD	210	35.8	260	369		-30
$cBOD_5$		22.7	164	200	4.5	-18
DO		0.94	6.8	1.9		-72
TSS		3	21.7	25	9	-13
VSS		0.68	4.9	1.6		68
E.coli		-	4.51	3.95		0.56[a]
Total Coliforms		-	6.91	6.40		0.51[a]
NH_3-N		0.66	4.8	25.5		-431
TP		0.3	2.2	5.5		-60
NO_3^--N		0.1	0.51	0.56		-9
PO_4^{3-}		0.5	3.8	10.6		-64
Temp. (^oC)		-	12.7	10.8		15

[a] Log units. *E.coli* and total coliforms in log_{10} CFU/100ml.

Second, low mineralization rates as a result of low temperatures and an anaerobic environment, led to incomplete mineralization of organic matter, thus leaving an additional organic load exerted on the wetland in 2010. This event could have occurred regardless of overloading. The additional load was observed in 2010 as unrespired forms of organic C, N, and P remaining in the media accounting for the elevated $cBOD_5$, TP and NH_3-N in the wetland effluent. These results suggest that the system's primary treatment mechanism of the system was sedimentation, rather than the decomposition and transformation of organics and nutrients as initially thought may be occurring after the 2009 trial. When comparing these findings to decomposition and mineralization of nutrients in Arctic tundra soils it would be expected that decomposition of organic matter and respiration of C would be very slow, especially in an anaerobic system (Sullivan et al., 2008). As waterlogging, cold temperatures, and soil quality can work to stabilize C, P and N in the soil in arctic environments. Furthermore buried soil organic matter has been shown to have significantly reduced mineralization rates in arctic soils (Kaiser et al., 2007). Despite a rest period following the 2009 sampling, when the system was turned off during the freezing months accumulated organic material in the system was still not mineralized, as suggested could happen in southern conditions (Platzer & Mauch, 1997). This process could explain why in 2010 I observed increases in PO_4^{3-}-P concentration through each consecutive cell despite the decrease in oxygen and yet no decrease in BOD or COD. The only evidence I observed which refutes this hypothesis was the mean decrease in concentration of volatile suspended solids (VSS) in 2010. This result conflicts with the increase in TSS, $cBOD_5$ and COD in 2010. The mean increase in TSS would suggest a mineral fraction was responsible for the increase in concentration, rather than released particulate organics. Whereas, the increase in $cBOD_5$ and COD suggest dissolved organics were in excess in the system.

An analysis of the soil media extracted from the cells following the completion of the studies provides further indication that the bed was saturated, and releasing excess nutrients in 2010. Analysis of nutrients showed soil solution concentrations orders of magnitude in greater concentration than influent water (Table 8).

Table 8. Soil solution concentrations observed from each treatment cell following study period. All concentrations were recorded in mg/L.

Parameter	Cell 1	Cell 2	Cell 3	Cell 4	Average
TP	1100	1010	964	1090	1041
PO_4^{3-}-P	1.8	3.9	7.2	4	4.2
NH_3-N	22.7	26.4	33.9	33.9	29.2

Higher concentration of nutrients in the soil solution would allow for dissociation from the soil into the lower concentration of the pore water, resulting in the higher concentrations of effluent observed. For, example the mean concentration of NH_3-N in the wetland effluent from 2010 (Table 7) is very similar in concentration to concentrations observed in the soil solution of the bed media (Table 8).

Finally, the presence of elevated NO_3^--N in the wetland effluent in 2010 may be explained by poor vertical mixing of water through the soil media, resulting in vertical stratification and preferential flows of varying temperatures and dissolved oxygen concentration. Warmer soil temperatures and higher dissolved oxygen in the upper layers of the soil media would result in an optimal environment for the nitrification of NH_3-N. Although, Kadlec &

Wallace (2009) suggest vertical stratification caused by temperature happens infrequently in HSSF systems, I believe it should not be discounted in an environment where soil temperatures are consistently below 5^{o}C. Also, porous media have been shown to be prone to stratification due to differences in electrical conductivity and that gravel media often prevents adequate mixing. Kadlec et al. (2003) observed such an event in a HSSF located in the cold temperate climate of northern Minnesota, where differences in conductivity of varying water sources fed into system resulted in a large vertical stratification and less treatment occurring in the deeper flow paths. Similarly, I observed high conductivity wastewater fed into the Baker Lake pilot system in 2009, on average 1210 µS, and in 2010 I observed conductivity of influent to be on average of 245 µS from the diluted wastewater. Had I observed concentrations of wastewater at different depths in the system as Kadlec et al. (2003) I may have also recorded less treatment with greater depth.

Having discussed the validity of potential hypotheses which may explain my results from this study I do not favour one hypothesis as a sole explanation for the results I observed. In fact, I believe part or all the hypotheses could be contributing and likely interrelated in some fashion. For example, the low conductivity wastewater fed into the system in 2010 would have favoured disassociation of ionic particles remaining in the system after the 2009 trials, while also causing vertical stratification in media leading to elevated NO_3^- -N observed in the wetland effluent. I suggest that further studies should be undertaken to work towards developing an understanding of CWs in extreme cold climate environments. Specifically, investigating optimal depth of media, and monitoring temperature at different depths, as well as studies to examine different organic loading and its corresponding mineralization rates in the Canadian Arctic.

CONCLUSIONS

Despite promising performance results of the pilot HSSF system in 2009, the pilot HSSF failed in 2010, even with a lower organic load on the system. Several factors potentially led to the systems failure. High organic loading prior to biofilm and plant establishment and high organic loading during the first year of study saturated the system with organics. This coupled with the fact that the use of predominately anaerobic technology in an extreme cold climate environment would cause mineralization of organics to be very slow. The result was an additional organic load being exerted on the system during 2010 study, which was observed in the increased concentrations of BOD in the effluent. Also, the use of dilute wastewater could have created vertical stratification of the pore water and/or providing a low electrical conductivity environment causing dissociation of weakly adhered particles to the media. This may explain the greater concentrations of N and P ions in the 2010 effluent compared to influent.

I suggest further studies examining the influence of soil depth on subsurface treatment, as well as continuing to investigate appropriate organic loading for constructed in extreme cold climates. In environments such as the Canadian Arctic deeper substrate mediums in subsurface flow systems may not be appropriate given the short frost free period.

CHAPTER 4

CHARACTERISATION OF TUNDRA WETLAND TREATMENT SYSTEMS IN THE CANADIAN FAR NORTH

Summary: Tundra wetlands have been extensively used in Canadian communities in the Far North to treat wastewater. However, little is known of these communities' municipal wastewater treatment wetlands performance or function. In 2009 and 2010, I characterised and assessed the performance of three natural wetland systems used for wastewater treatment; Chesterfield Inlet, NU; Paulatuk, NT and Uluhaktuk NT. Spatial interpolations of each of the wetlands and their water quality showed that concentrations of the wastewater parameters decreased the most in the first 50-100 m of the wetland in all three cases. Interpolative mapping showed that the effective treatment area to be much smaller than the originally delineated wetland size in each case. Areas of greatest concentration were shown to follow preferential flow paths with concentrations decreasing in a latitudinal and longitudinal direction away from the wastewater source. The Paulatuk and Uluhaktuk treatment wetlands were observed to effectively polish pre-treated wastewater from the facultative lake and engineered lagoon, with removals of key wastewater constituents of $cBOD_5$, TSS and NH_3-N to near background concentrations. It is assumed that this level of treatment is maintained throughout the summer months. And despite the absence of pre-treatment in Chesterfield Inlet, the wetland was also observed to effectively treat wastewater to near background concentrations. This study exemplifies the ability of natural wetlands to act as sinks and transformers of nutrients, organic material and pathogens even in the very harsh climatic conditions and low biomass producing ecosystems of the Canadian Arctic. For remote communities in the Canadian far North, natural wetlands likely will remain an effective method to treat municipal wastewater despite their decreasing use in temperate accessible locations where wetland conservation measures are a priority. The more rapid treatment observed in Uluhaktuk and Paulatuk wetlands demonstrate that some form of pre-treatment either in the form of a facultative lake or engineered lagoon should be used to further optimize performance of the wetlands, and manage wastewater during freezing periods.

Keywords: tundra wetlands, wastewater treatment, characterization, Arctic, municipal wastewater

INTRODUCTION

The remote nature and cold climate of small Canadian Arctic communities make the treatment of municipal wastewater problematic. Conventional mechanical systems are expensive, and difficult to maintain under Arctic climatic conditions (Johnson, 2010), and climate causes decomposition rates of organic material to be very low (Mack et al., 2004). Other factors which demand that the treatment facilities for these communities be simple are because of a lack of resources for hiring, training and retaining qualified personal as well as available capital for constructing conventional treatment facilities (Johnson, 2010; Wootton et al., 2008). As a result, wastewater often only receives preliminary to primary treatment before being discharged into natural/tundra wetlands or is discharged directly into wetlands without preliminary treatment. In economically developing regions of Canada's far North, the use of tundra wetlands as wastewater management strategy remains common (Wootton et al., 2008). I define tundra treatment wetlands are tundra landscapes designated to receive and treat municipal wastewater through natural processes of biological action, absorption and sedimentation in the landscape before discharging into a body of water; most commonly the ocean in Inuit communities.

Natural wetlands or constructed surface flow wetlands which most closely mimic natural wetlands have been used extensively to treat various wastewaters in more southern climates, and have been studied extensively (Kadlec, 2009; Kadlec & Wallace, 2009; Sartoris et al., 2000; Thullen et al., 2005). Surface flow or natural wetlands have been shown to be best applied to polish pre-treated wastewater from conventional sewage treatment plants or decant from facultative lagoons (Andersson et al., 2002; Hammer & Burckhard, 2002; Zachritz & Fuller, 1993). The Minot wetland (North Dakota) and one in Oxelosund Sweden are two examples of polishing wetland which have been used in cold climates with great success (Hammer & Burckhard, 2002; Kallner & Wittgren, 2001; Wittgren & Tobiason, 1995). The heterogeneous nature of natural or augmented natural wetlands makes it difficult to determine how and where treatment is occurring in these large systems. This is especially the case in systems which have not been engineered, because external influences on the wetlands are difficult to distinguish from controlled inputs. Sartoris et al. (2000) mapped internal distribution patterns of nitrogen species throughout a constructed surface flow system in California. Stober et al. (1997) used hydrologic and hydraulic assessments through surveying to determine flow directions, and estimated active treatment areas in a wetland created from a retired lagoon.

Augmented and natural wetlands have been used extensively in Nunavut to treat/polish pre-treated wastewater from lagoons and facultative lakes because of their simplicity to construct, and to operate in the remote communities of the Arctic. Kadlec & Johnson (2008) designed an augmented natural wetland with berms in Cambridge Bay, Nunavut. They expect that removal of $cBOD_5$ and TSS will be comparable to wetlands in other climatic regions, but the removal of nutrients, particularly NH_3-N would be less because of low temperatures. Berms have also been used in treatment wetlands in Alert and Arviat Nunavut to help treat wastewater by increasing hydraulic residency time in the system. Long-term summer baseline data from the Arviat wetland in 2008 showed high removals of $cBOD_5$, TSS and pathogens (Yates et al., 2008). Similar baseline data was gathered in Chesterfield Inlet in 2008 where concentration changes between 80-99% for $cBOD_5$, TSS, NH_3-N, TP and pathogens were observed between the end of June and mid-September (Yates et al., 2010). Because of the remoteness of many Arctic communities, regulatory monitoring of these systems has been minimal. Little is understood with respect to their performance and function in the wetlands as whole or how important pre-treatment of wastewater is in these extreme environments. Interpolation mapping and characterization of Arctic treatment wetlands, as discussed by Sartoris et al. (2000) has not been conducted.

In 2009, I characterised and assessed the performance of two natural wetland systems (Chesterfield Inlet, NU and Paulatuk, NT), used for wastewater treatment in the Canadian Far North. In 2010, I characterized Uluhaktuk (Holman), NT treatment wetland. At the time of study Chesterfield Inlet did not have any pre-treatment, while the Hamlet of Paulatuk makes use of a facultative lake as preliminary/primary treatment before it discharges into an adjacent natural wetland. The Hamlet of Uluhaktuk uses an engineered facultative lagoon as pre-treatment. These systems were chosen for comparison because of similar population sizes of the communities and similar annual wastewater discharge. My objectives were: i) to determine the effluent quality of the three treatment systems, as well as ii) to characterize the wetlands to determine effective treatment areas and identify potential primary mechanisms responsible treating wastewater in the remote wetlands.

SITE DESCRIPTIONS

The Hamlet of Chesterfield Inlet (63^{o}N, 90^{o}W) is located in the Kivalliq Region of Nunavut, Canada. The treatment wetland in this community services approximately 366 residents (Statistics Canada, 2006a). The wetland is located in a shallow depression in the landscape, with an approximate area of 5 ha (50,000 m^2) and a length of 720 m, with a minimum width of 58 m and a maximum width of 225m near the end of the wetland complex. It is estimated that approximately 36 m^3 is discharged directly into the wetland per day. Only a shallow natural depression slows the movement of wastewater before it enters the wetland. Wastewater flowed northwest into Chesterfield Inlet. The soil porosity of the site is 0.25. The wetland is dominated by *Carex aquatilis*, *Stellaria crassifolia*, and *Arctophila fulva*. Occasional stands of *Salix arctophila* line preferential flow channels. The average annual temperature is -11^{o}C, and mean summer temperature of 9.4^{o}C (Environment Canada, 2010).

Figure 4. Aerial view of Chesterfield Inlet treatment wetland delineating wetland boundaries and flow directions.

The Hamlet of Paulatuk is located in the Northwest Territories, Canada (69°N 124°W). The system is composed of a facultative lake (Dead Lake) and wetland serving approximately 294 residents (Statistics Canada, 2006b). Wastewater from households and businesses is trucked to the facultative lake. In 2007, it was estimated approximately 11,200 m^3 of wastewater was being discharged into Dead Lake (~31 m^3/day). Dead Lake is estimated to have a volume of 103,000 m^3 (Wootton et al., 2008). Basic estimates of effluent flow rate from a preferential flow channels as measured by Yates & Wootton (2010) showed a rate of 1.2 m^3/day. The wetland ranged from 40 m to 80 m in width. The wetland extends approximately 350 m from the facultative lake to the Arctic Ocean (Figure 5). The wetland was characterized as wet-sedge tundra, dominated by *Carex* and *Poa* spp. In drier upland areas along the wetland boundaries, *Salix* spp. were observed to be dominant. The highest daily maximum is 15^{o}C for July (Environment Canada, 2010). Paulatuk has an annual mean temperature of approximately -9.2^{o}C (Environment Canada, 2009).

Figure 5. Aerial view of Paulatuk treatment wetland delineating wetland boundaries and flow directions (see top right of photograph).

The Hamlet of Uluhaktuk is located on Victoria Island, in the Inuvialuit Region of the Northwest Territories. Average daily temperature for the community is -11.7^{o}C, with an annual average precipitation 162 mm (Environment Canada, 2010). Annual average summer temperature (June to September) is 6.9 ^{o}C. The community has approximately 400 residents, discharging an estimated 40 m^3/day of wastewater into a single celled facultative sewage lagoon. The lagoon is estimated to be 14,000 m^3 as calculated while on site conducting the characterization of the wetland. Lagoon effluent continuously permeates through lagoon berm wall into the adjacent wetland system (Figure 6). The wetland is approximately 74,000 m^2; with a length of the wetland was estimated at approximately 480 m and the width 120 m. The wetland is primarily wet-sedge tundra with low-shrubs. *Salix arctophila* was found to be the predominant shrub throughout the system, *Senecio congestus*, *Cereastium ceratoides*, *Carex aquatilis* were also prominent throughout the wetland.

Figure 6. Aerial view of Uluhaktuk treatment wetland delineating wetland boundaries and flow directions.

METHODS

Site assessments of the wetland were first undertaken to determine point(s) of influent and effluent of the wetland; major preferential flow pathways through the wetland complex were identified. A series of transects were established; commencing near the point of influence and completed near the point of effluence of each wetland. Transects expanded the latitudinal width of the expected effective treatment area. Groundwater sampling locations were established approximately every 15 m across a given transect. The number of sample locations on a given transect was dependent upon the width and the number of transects dependent on wetland length.

The collection of water samples from the treatment wetlands was conducted at a minimum of 35 sample points throughout the expected active treatment zone. Sampling for each wetland was completed in a single day. To accommodate for the logistical limitations imposed on shipping water samples from remote communities an n $\geq$35 was found to provide reasonable coverage of the wetlands studied. Surface water and groundwater samples were collected. A lysimeter (0.05m diameter) constructed from polyvinyl chloride (pvc) piping was placed into a bore hole of maximum depth of 0.30 m to collect groundwater. Water samples were analysed for key regulatory parameters in the Nunavut Water Board water licenses BOD_5 (I used $cBOD_5$ in its stead), TSS, *E.coli*, and NH_3-N as well as additional parameters: COD, TP and total coliforms (Government of Nunavut, 2002). Samples were processed according to *Standard Methods for the Examination of Water and Wastewater* (2005). Sampling was also conducted in a reference wetland nearby to the treatment wetlands to develop an understanding of background levels of measured parameters. However, reference sampling Uluhaktuk was not undertaken because of the absence of nearby accessible reference sites.

Topographic surveying using a TopCon Total Station® (TopLINK 7.2) was conducted to develop digital elevation models and areas of each of the wetlands. These data were used to generate a spatial interpolation of water quality throughout each wetland. This interpolation was used to show locations of high to low concentration of wastewater and potentially key treatment areas throughout each wetland. ESRI ArcMap was used to perform the interpolation analysis of the wetlands. From the survey data AutoCAD was used to create the wetland image. The drawing space was created with NAD27 projections. The blocks were created for the central GPS, boundary, and sample points. The primary sample station shapefile was joined with a .dbf file containing water quality data and exported as a shapefile that contained all water quality information. The inverse distance weighting (IDW) using Shepard's method of multivariate interpolation was used for all water quality analyses. This method is often used when data are not evenly spaced over a geographic area, and a continuous surface needs to be created to show a change in gradient (Shepard, 1968).

Expected effluent concentrations for the identified active portions of the wetlands were calculated using first-order kinetic model at 10^{o}C. I calculated expected effluent concentrations using P-*k*-C* in order to determine expected effluent values for $cBOD_5$, TSS. The van't Hoff-Arrhenius equation as described in Crites & Tchobanoglous (1998) was adopted:

$$\frac{d(\ln k)}{dT} = \frac{E}{RT^2}$$

The P-*k*-C* model is described in Campbell & Ogden (1999) as:

$$As = \frac{Q(lnCo - lnCe)}{k_t * d * n}$$

The k_t value for the P-*k*-C* model was determined by using a k_{10} value of 1.0; the Ө-factor used was 1.14. A high Ө-factor was deemed appropriate for extreme temperature cases as determined for a Minnesota HSSF wetland with a temperature range from 1-17^{o}C, as outlined in Kadlec & Wallace (2009).

The equation for TSS removal also described in Campbell & Ogden (1999) as:

$$TSSeff = TSSinf * (0.0158 + 0.0011 * HLR)$$

RESULTS/DISCUSSION

Wastewater discharged into the Chesterfield Inlet wetland was observed to have high concentrations of parameters at 181 mg/L, 146 mg/L, 5.5E4 cfu/100ml and 30 mg/L for $cBOD_5$, TSS, *E.coli* and NH_3-N respectively. In 2009, wetland effluent from Chesterfield Inlet was measured at 8 mg/L, 0.0 mg/L, 6 cfu/100ml, and 0.7 mg/L for $cBOD_5$, TSS, *E.coli* and NH_3-N respectively. $cBOD_5$ demonstrated expected trends in a decrease in concentration from the top of the wetland to the bottom, where COD was more variable (Figure 4). TSS was also observed to be variable throughout the wetland. Primary pathogen concentration change could be observed in the first approximate 100 m (50 m width) of the wetland. The effective treatment area was estimated to be approximately 5000 m^2 (0.5 ha). This was also observed to be the case for NH_3-N and TP. Wetland effluent in the Chesterfield Inlet treatment was found to be comparable to reference conditions (from a nearby wetland) (Table 9).

Table 9. Background concentrations for Chesterfield Inlet, NU and Paulatuk, NT. Data for Uluhaktuk was not available.

Parameter	Chesterfield Inlet Background Concentrations	Paulatuk Background Concentrations
$cBOD_5$ (mg/L)	4	2
TSS	3	ND
COD (mg/L)	13-15	4.4
NH_3-N(mg/L)	0-0.8	0.01
TP (mg/L)	ND	0.01
Total coliforms (cfu/100ml)	$1.4x10^3$	$1.25x10^2$
E. coli (cfu/100ml)	20	9

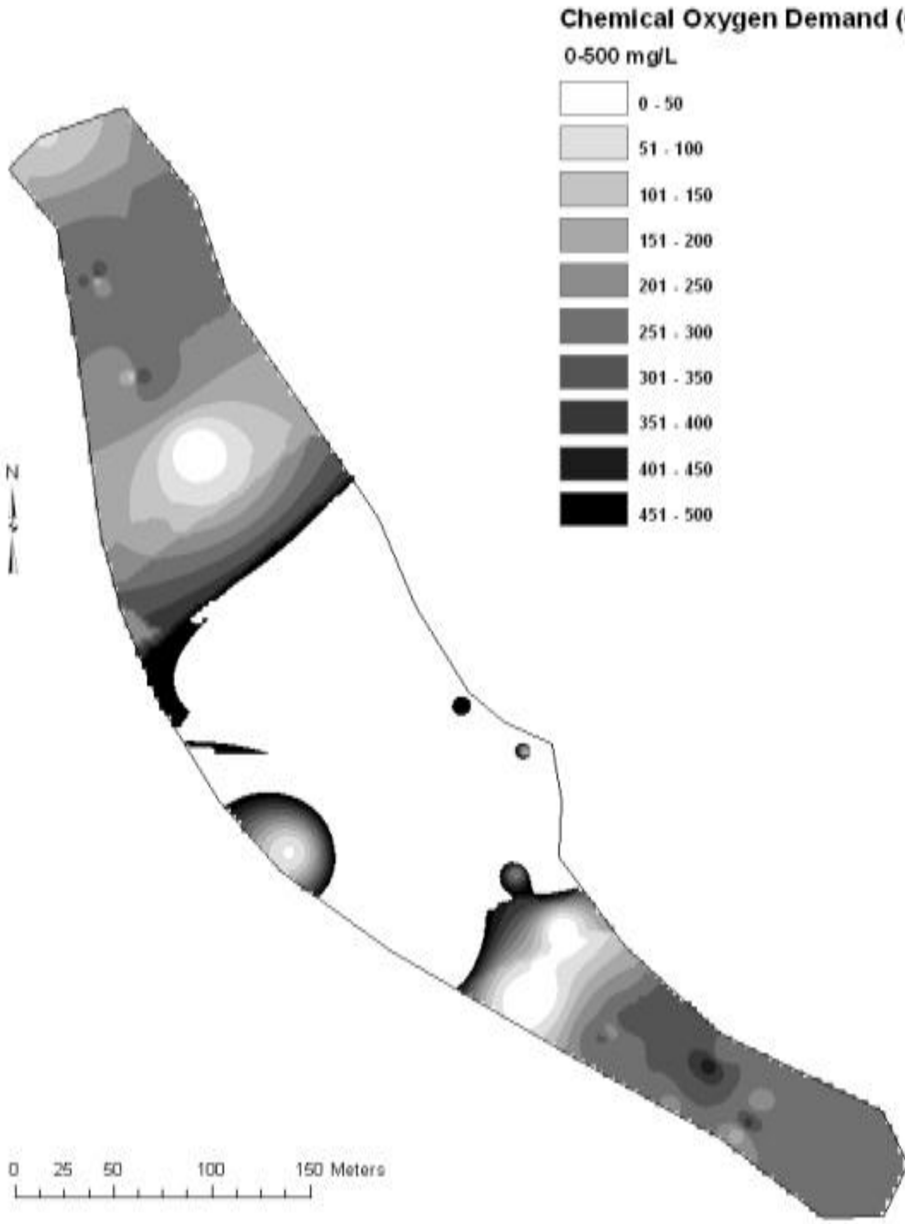

Figure 7. Concentration gradients $cBOD_5$ through the Chesterfield Inlet treatment wetland.

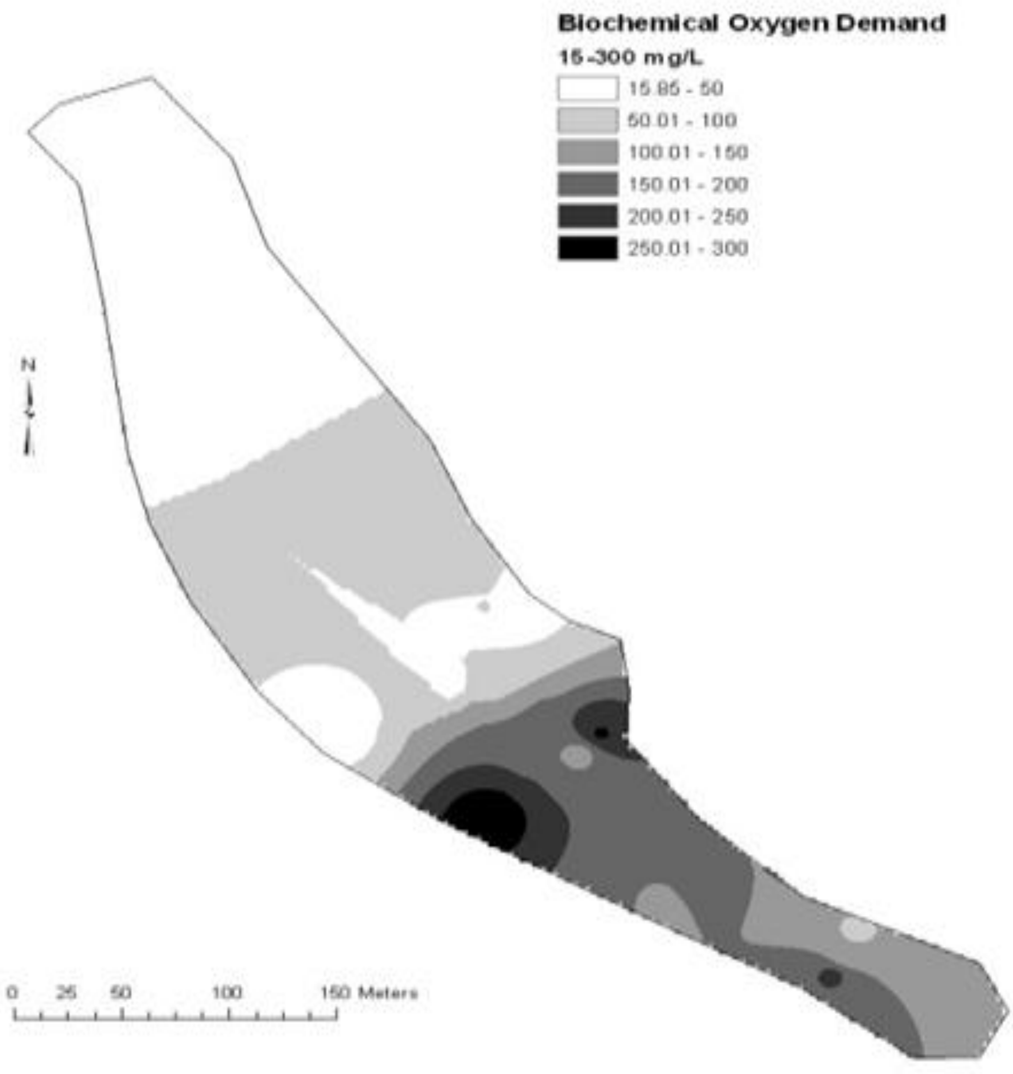

Figure 8. Concentration gradients $cBOD_5$ through the Chesterfield Inlet treatment wetland.

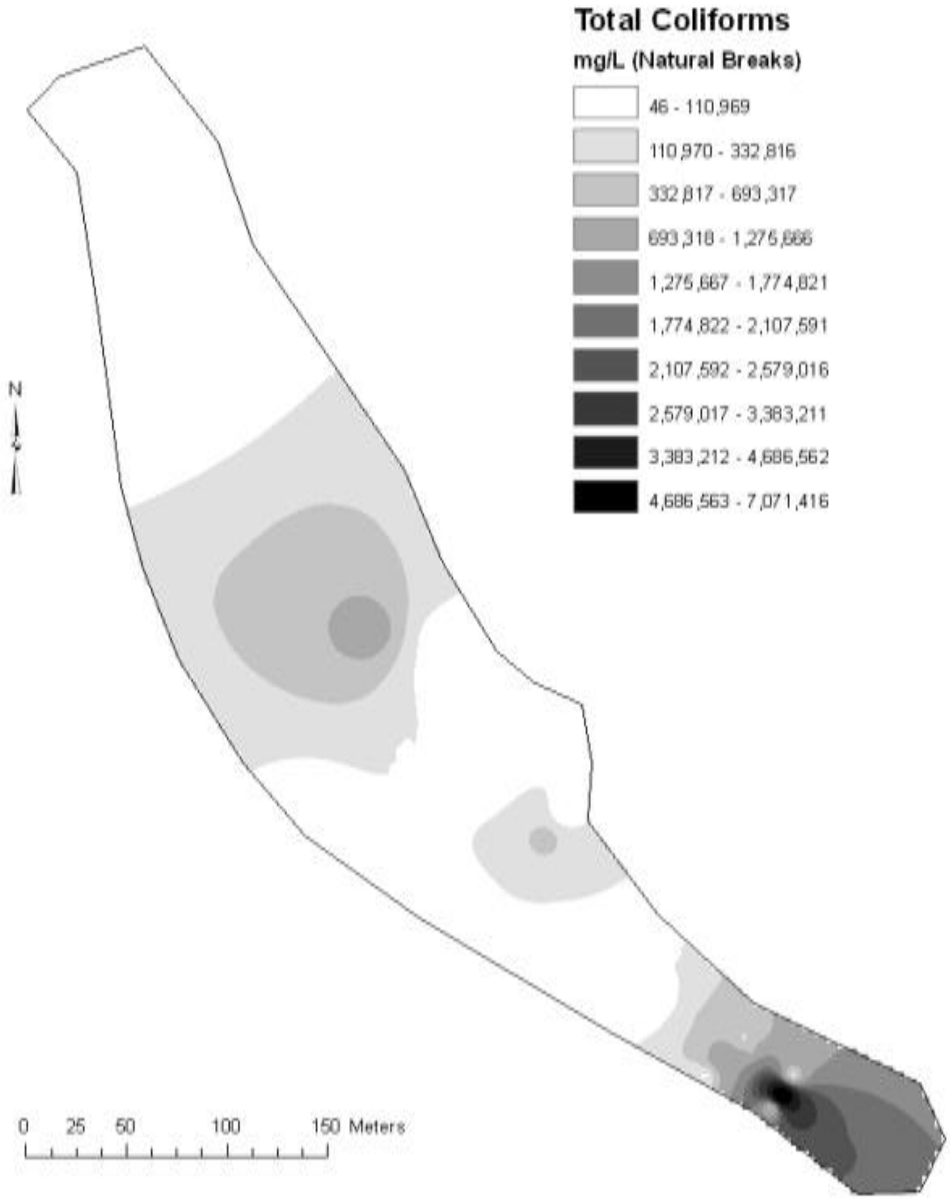

Figure 9. Concentration gradients total coliforms through the Chesterfield Inlet treatment wetland.

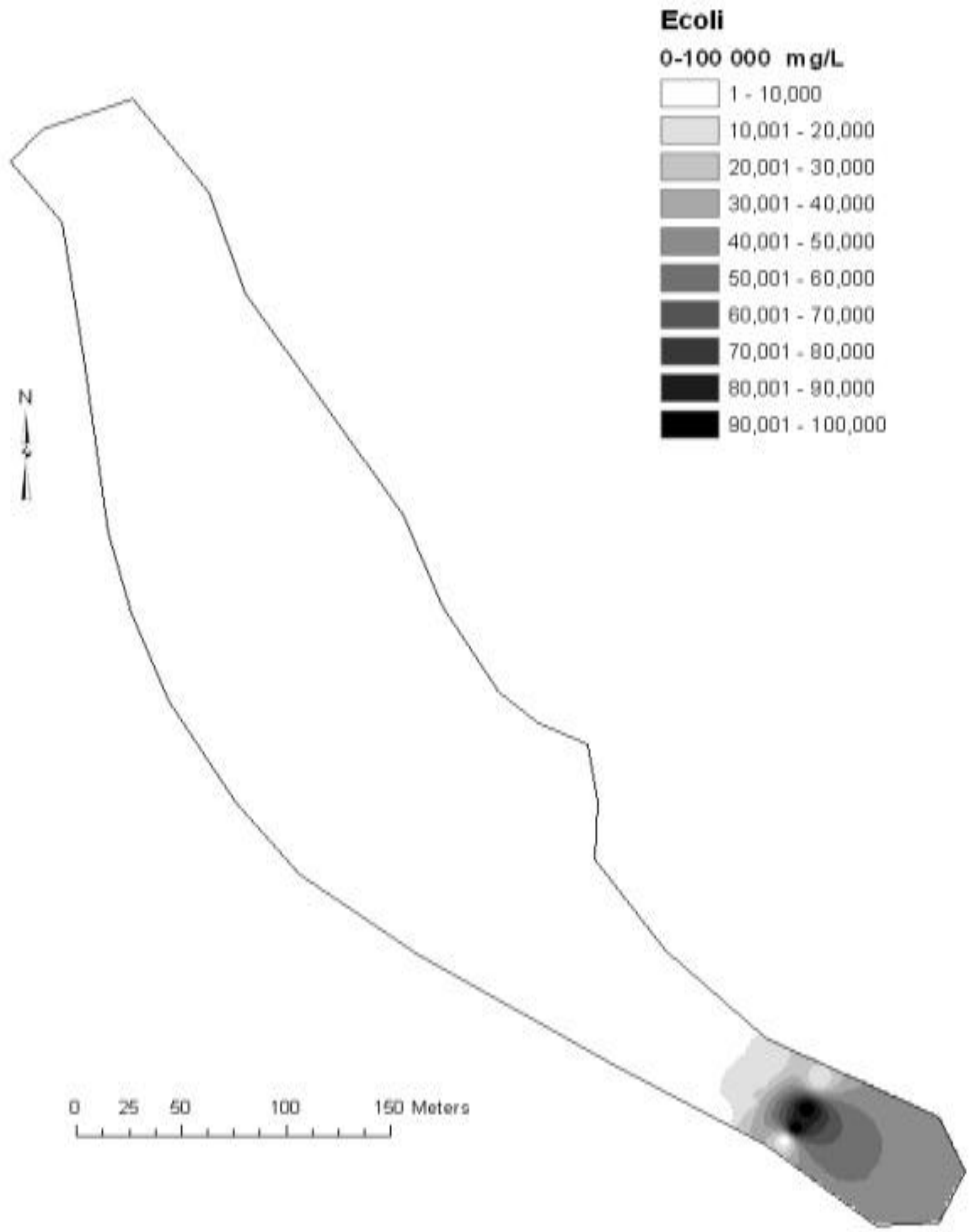

Figure 10. Concentration gradients *E.coli* through the Chesterfield Inlet treatment wetland.

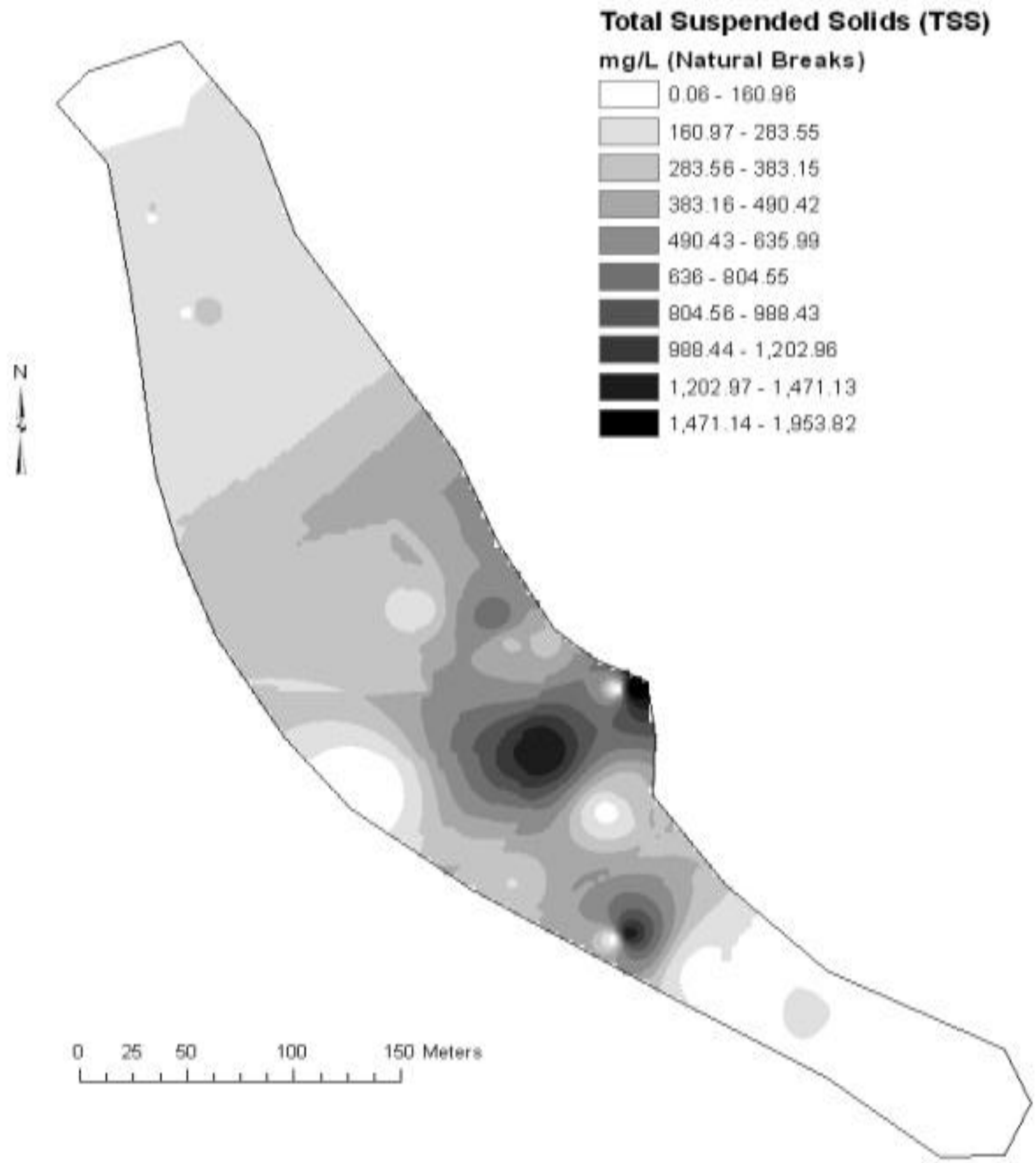

Figure 11. Concentration gradients of total suspended solids through the Chesterfield Inlet treatment wetland.

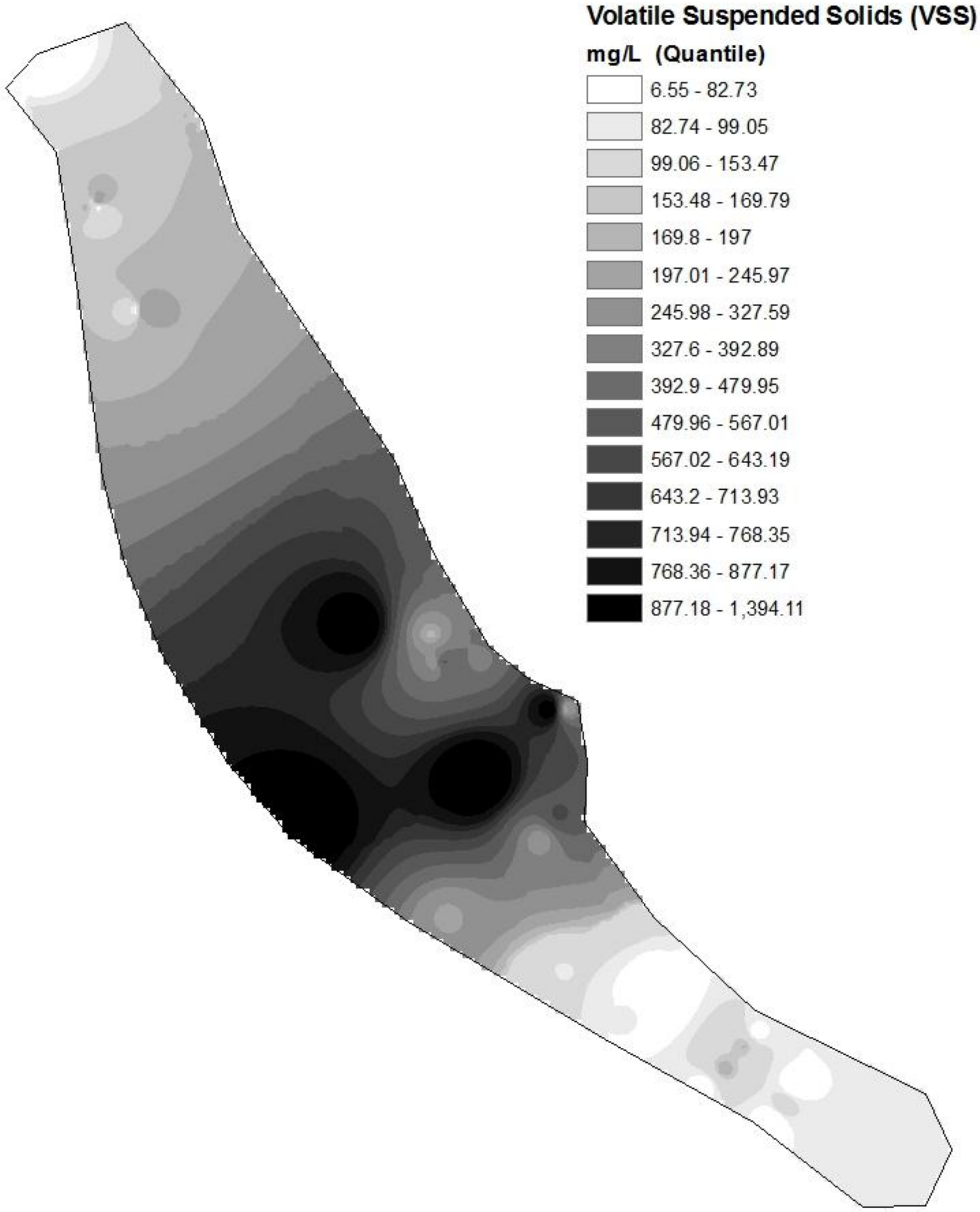

Figure 12. Concentration gradients of volatile suspended solids through the Chesterfield Inlet treatment wetland.

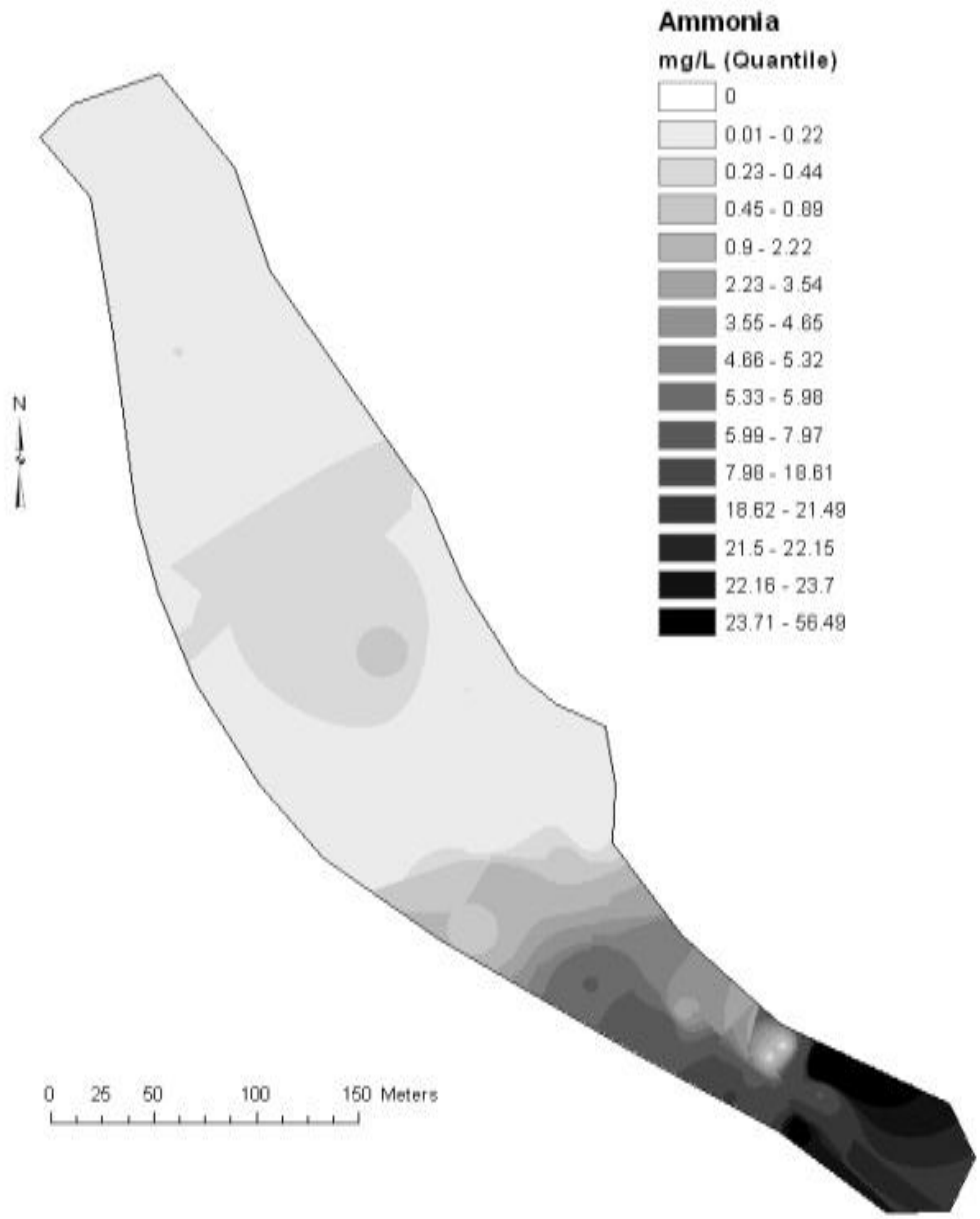

Figure 13. Concentration gradients of NH_3-N through the Chesterfield Inlet treatment wetland.

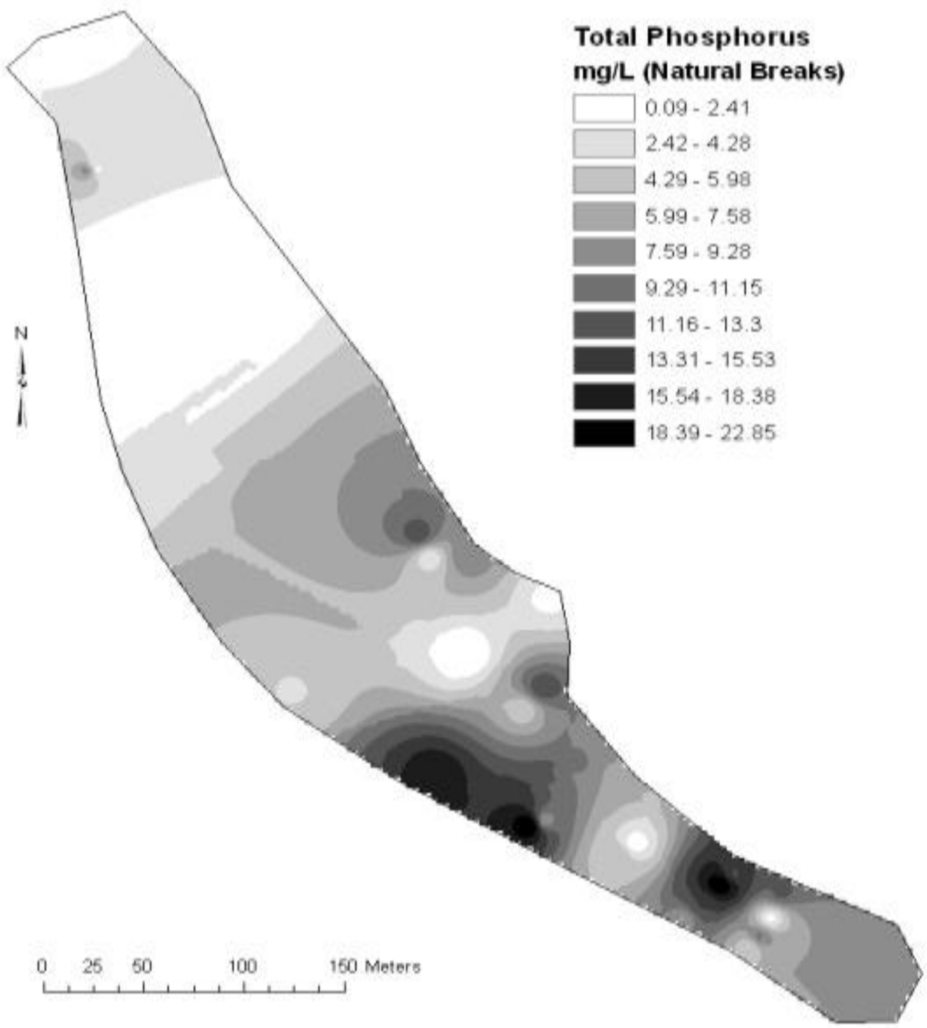

Figure 14. Concentration gradient of total phosphorus in the Chesterfield Inlet treatment wetland.

Wastewater effluent from the facultative lake entering the wetland in Paulatuk maintained low concentrations of all wastewater paramaters. $cBOD_5$, TSS, *E.coli* and total coliforms; 40 mg/L, 35 mg/L, 2850 cfu/100ml and $5.17x10^4$. COD, TP and NH_3-N were also low coming out of the facultative lake, at 200 mg/L, 2.42 and 3.19 mg/L respectively. Based on concentrations observed in the interpolative mapping analysis treatment primary was occurring in the first approximate 75 m (40 m width) of the wetland (Figure 8-12). The effective treatment area was estimated as being approximately 3000 m^2 (0.3 ha).

Wetland effluent concentrations for $cBOD_5$, COD, TSS and *E.coli* was observed to at 2 mg/L, 28 mg/L, 3 mg/L and 1 cfu/100ml respectively. Very low concentrations of effluent NH_3-N, TP, and total coliforms were also noted; 0.01mg/L, 0.04 mg/L, and 365 cfu/100ml. Reference site concentrations for both NH_3-N and TP were both 0.01 mg/L respectively (Table 9).

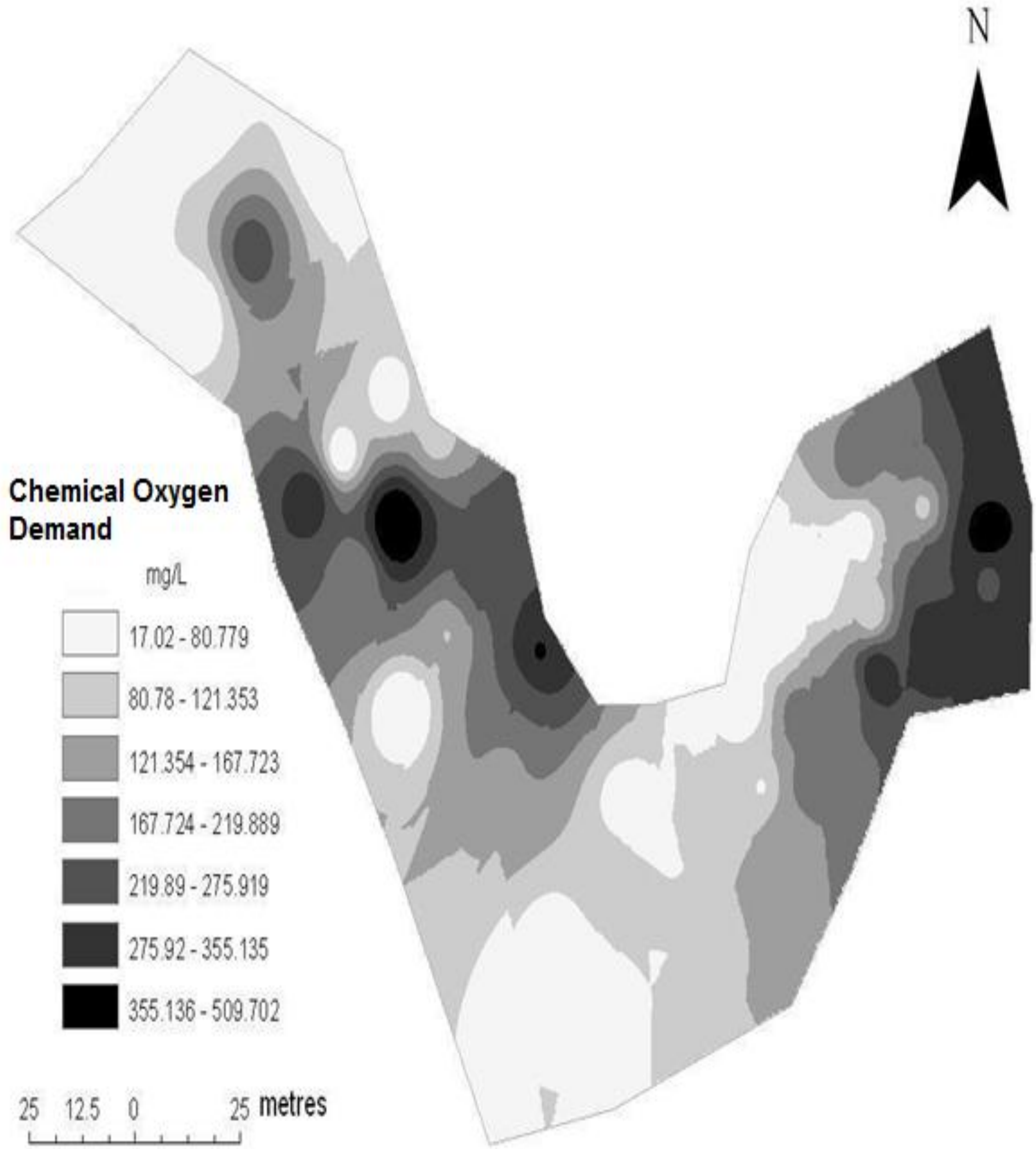

Figure 15. Concentration gradients of COD in the Paulatuk treatment wetland.

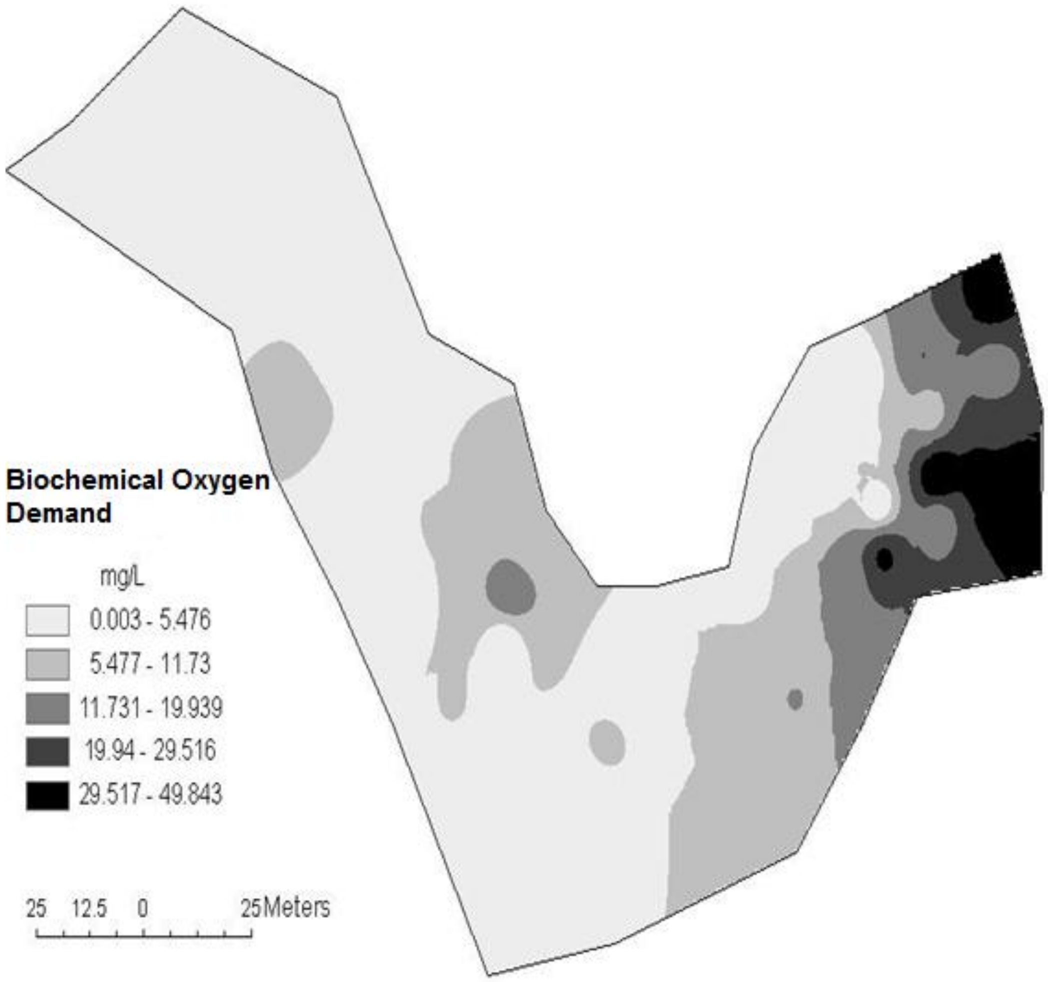

Figure 16. Concentration gradients of $cBOD_5$ in the Paulatuk treatment wetland.

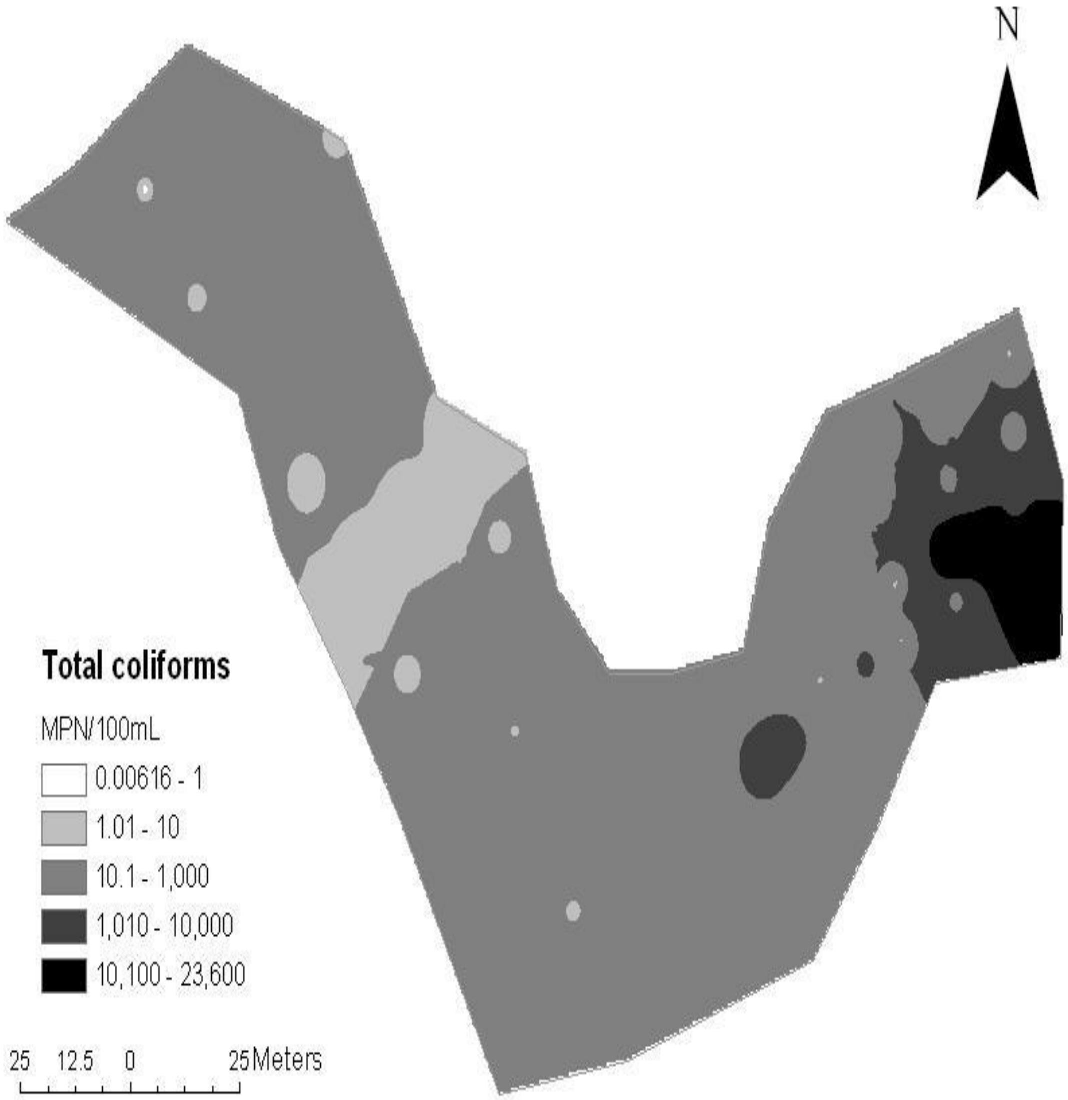

Figure 17. Concentration gradients of total coliforms in the Paulatuk treatment wetland.

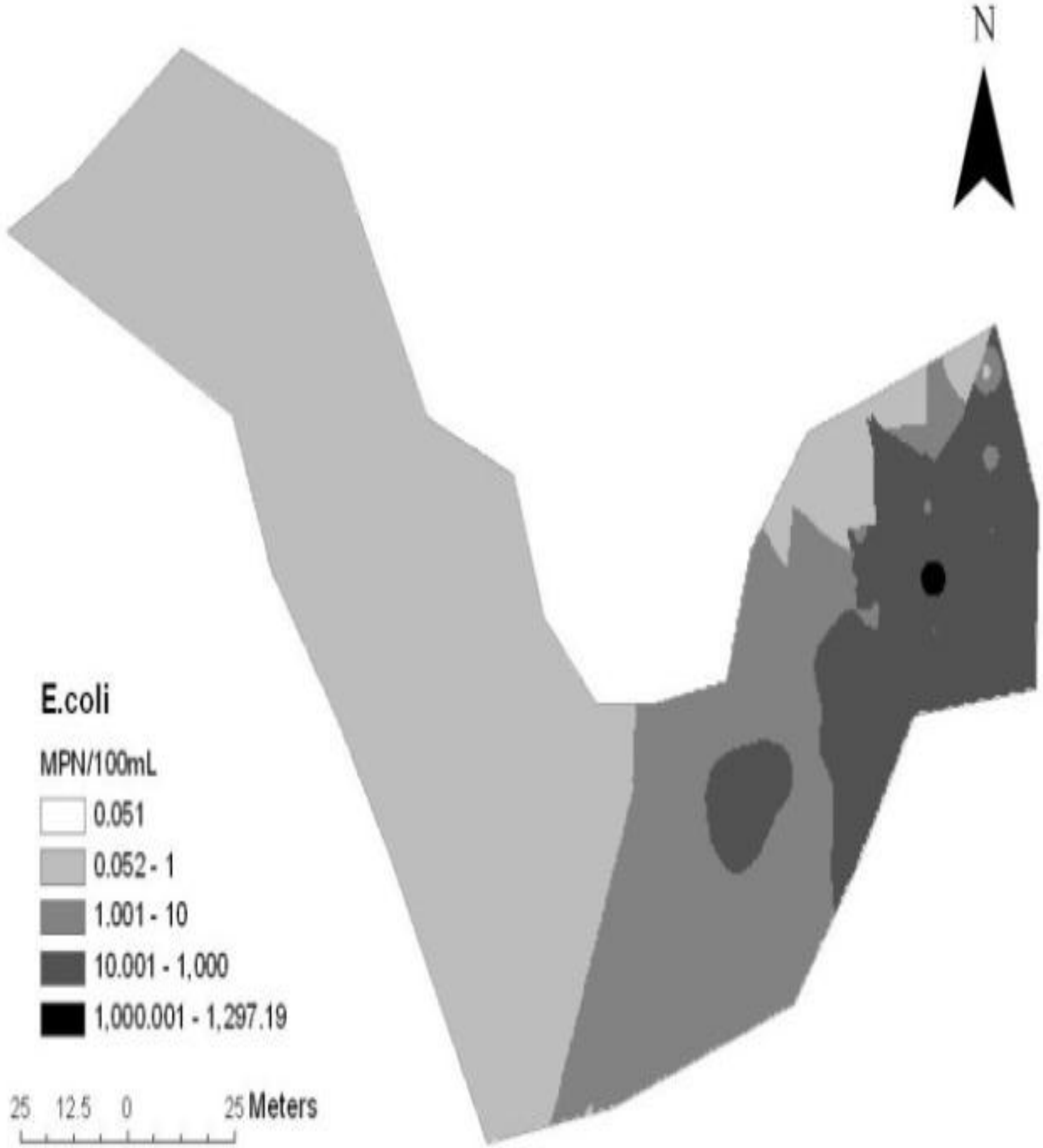

Figure 18. Concentration gradients of *E.coli* in the Paulatuk treatment wetland.

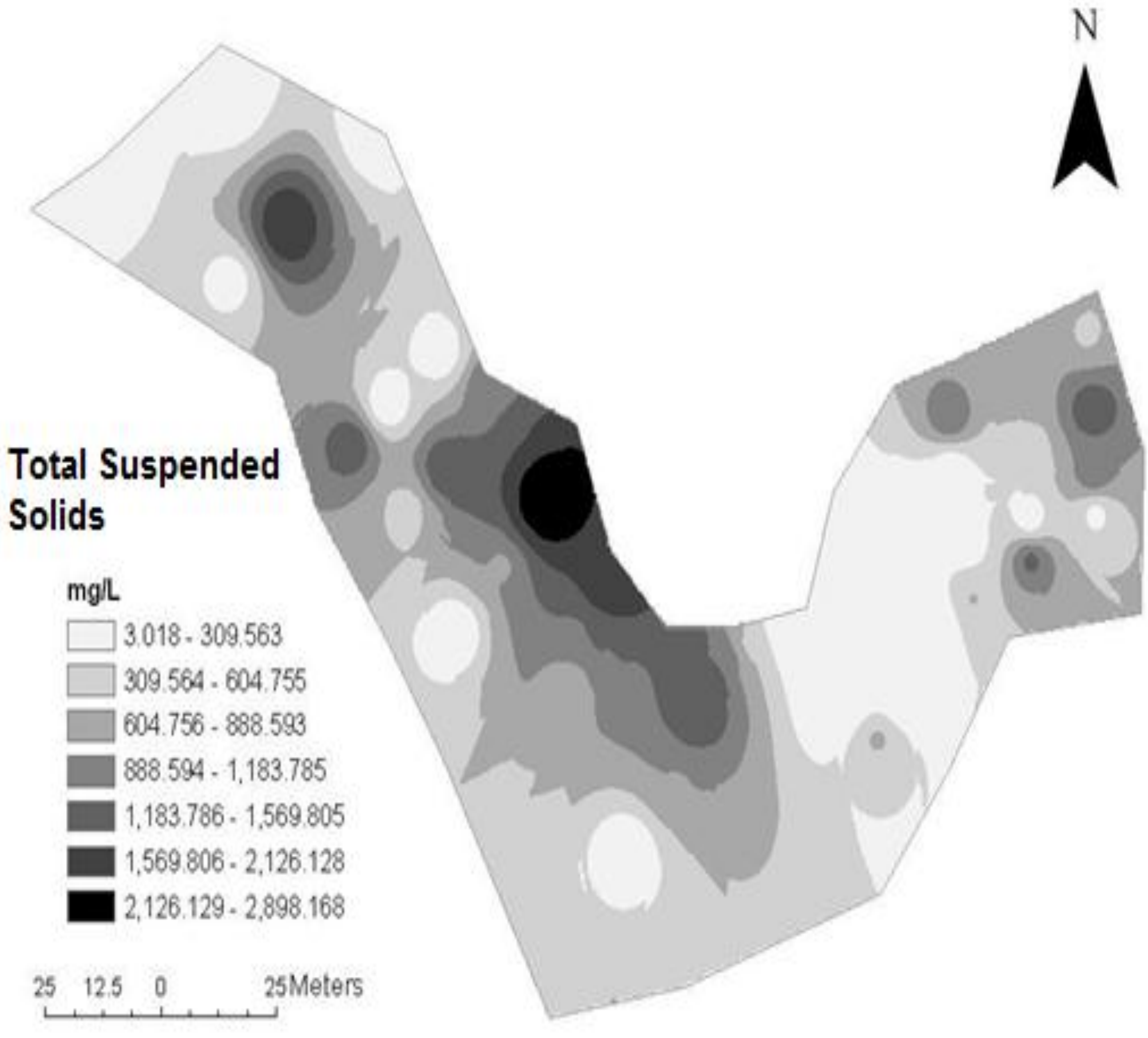

Figure 19. Concentration gradients of total suspended solids in the Paulatuk treatment wetland.

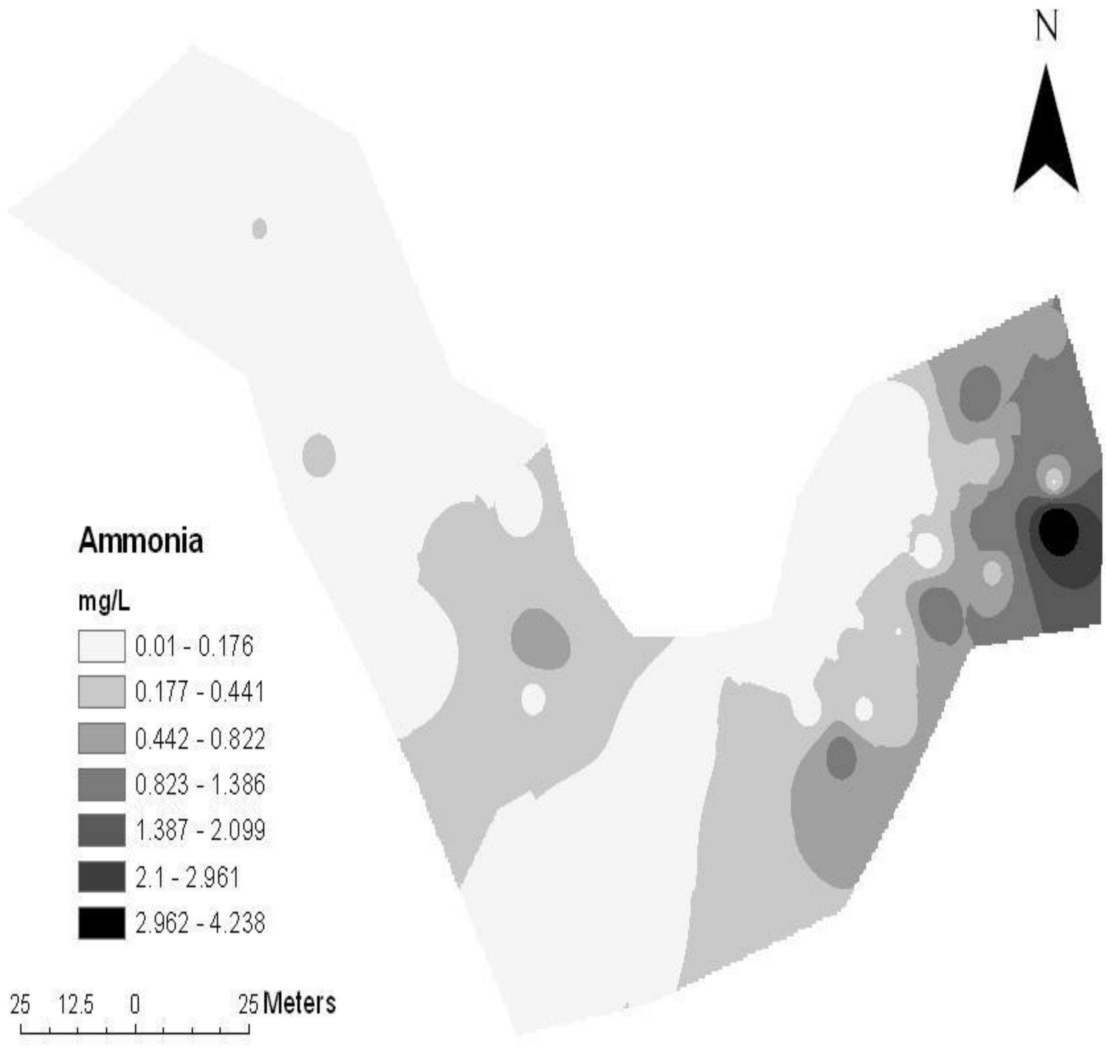

Figure 20. Concentration gradients of NH_3-N in the Paulatuk treatment wetland.

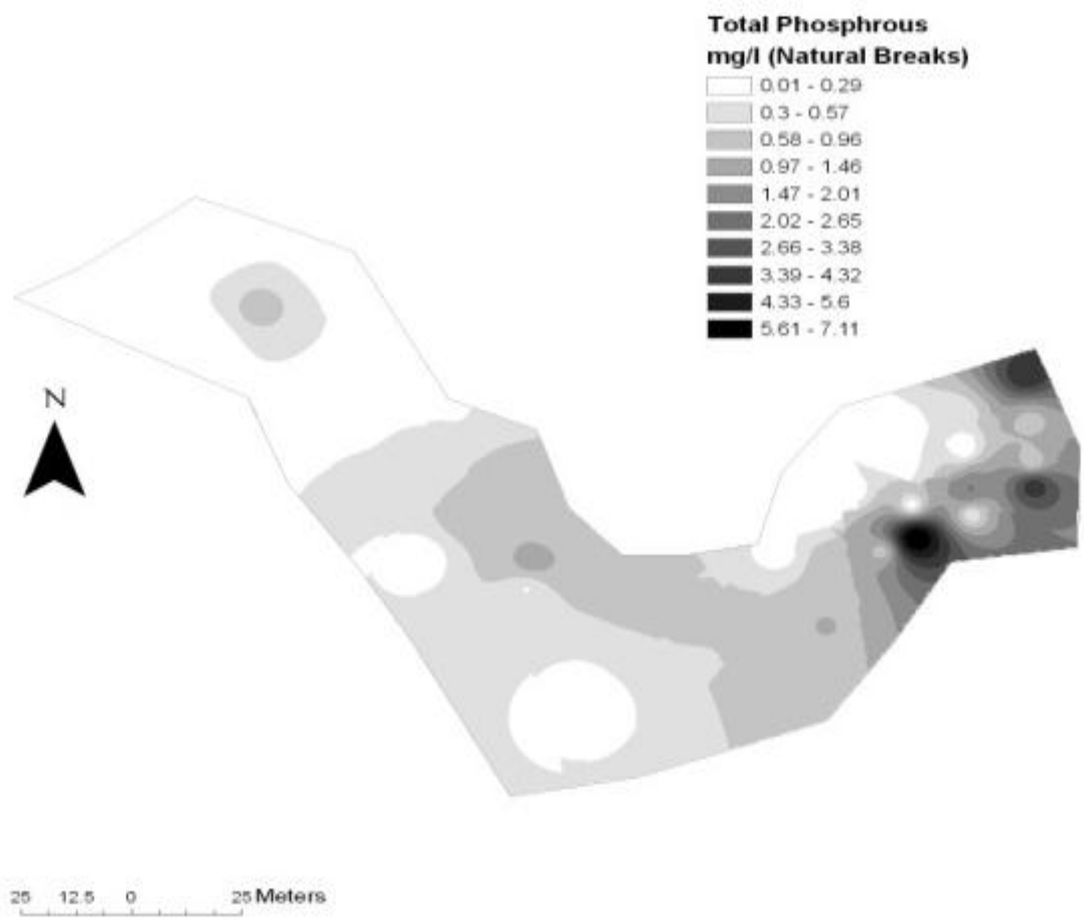

Figure 21. Concentration gradient of total phosphorus in the Paulatuk treatment wetland.

Similar to the Paulatuk wetland, wastewater entering the Uluhaktuk wetland was low in concentration across the entire suite of parameters analyzed. $cBOD_5$ was less than 100 mg/L both in the lagoon and in the beginning of the wetland. Concentrations of wetland influent was observed at 50 mg/L, 190 mg/L, and 48 mg/L for $cBOD_5$, COD, and TSS respectively. Concentrations for the nutrients NH_3-N and TP were also found to be low in entering the wetland; 15.6 mg/L and 7.62 mg/L. Like all other parameters pathogens were also observed to be low entering the wetland. *E.coli* counts were 387 cfu/100ml wetland and total coliforms were not observed to exceed 87000 cfu/ 100ml. The interpolative analysis showed that much of the treatment was occurring in the first 50-75 m (30 m width) of the wetland (Figure 13-17). The effective treatment area was estimated as 2250 m^2 (0.225 ha). Reference/background conditions were not observed at this site.

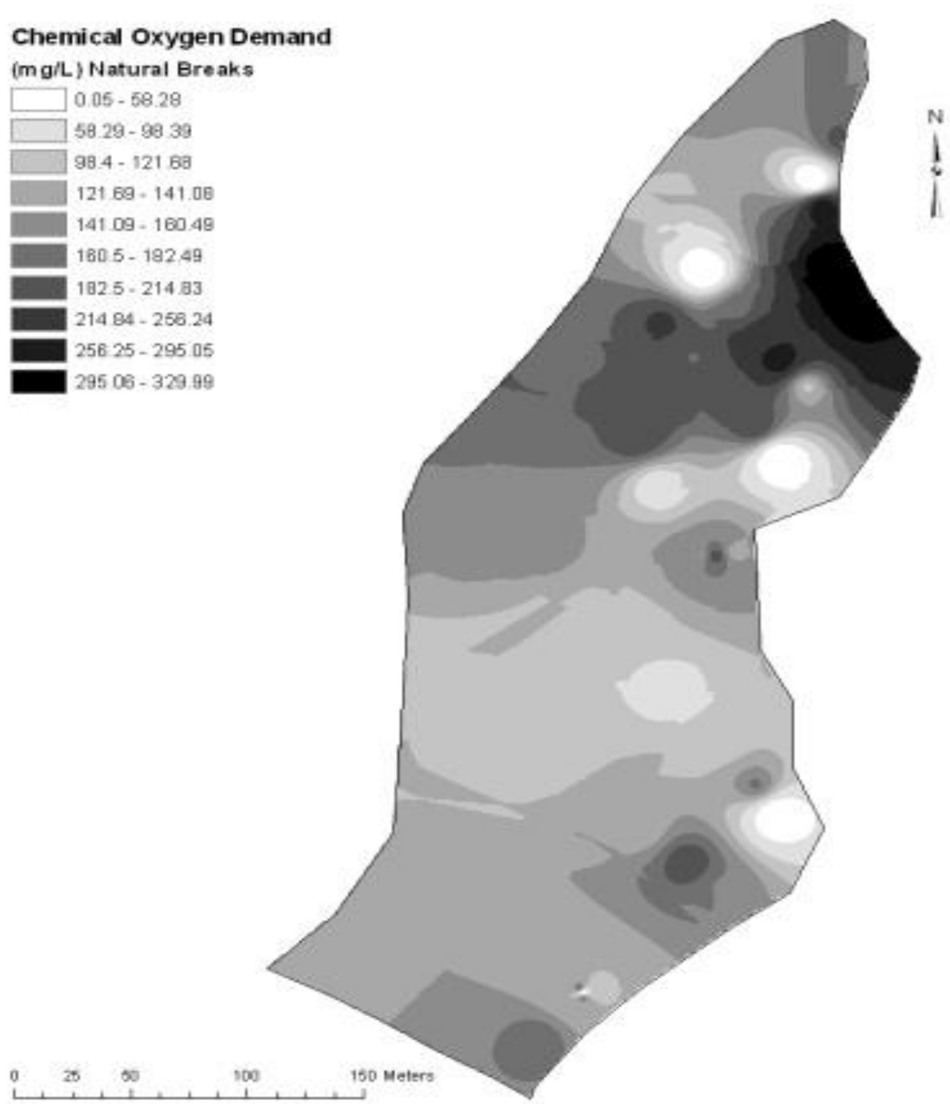

Figure 22. Concentration gradients of COD in the Uluhaktuk treatment wetland.

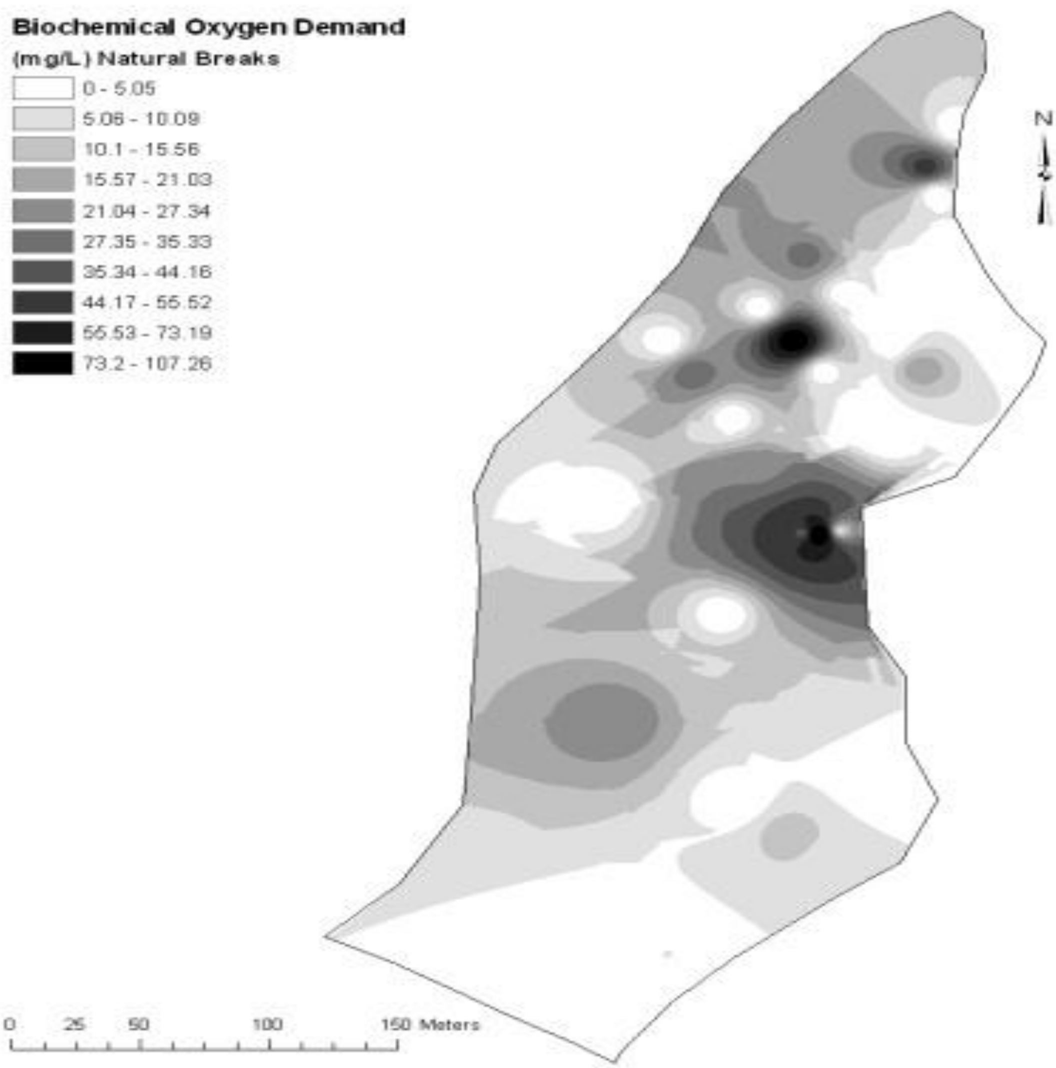

Figure 23. Concentration gradients of $cBOD_5$ in the Uluhaktuk treatment wetland.

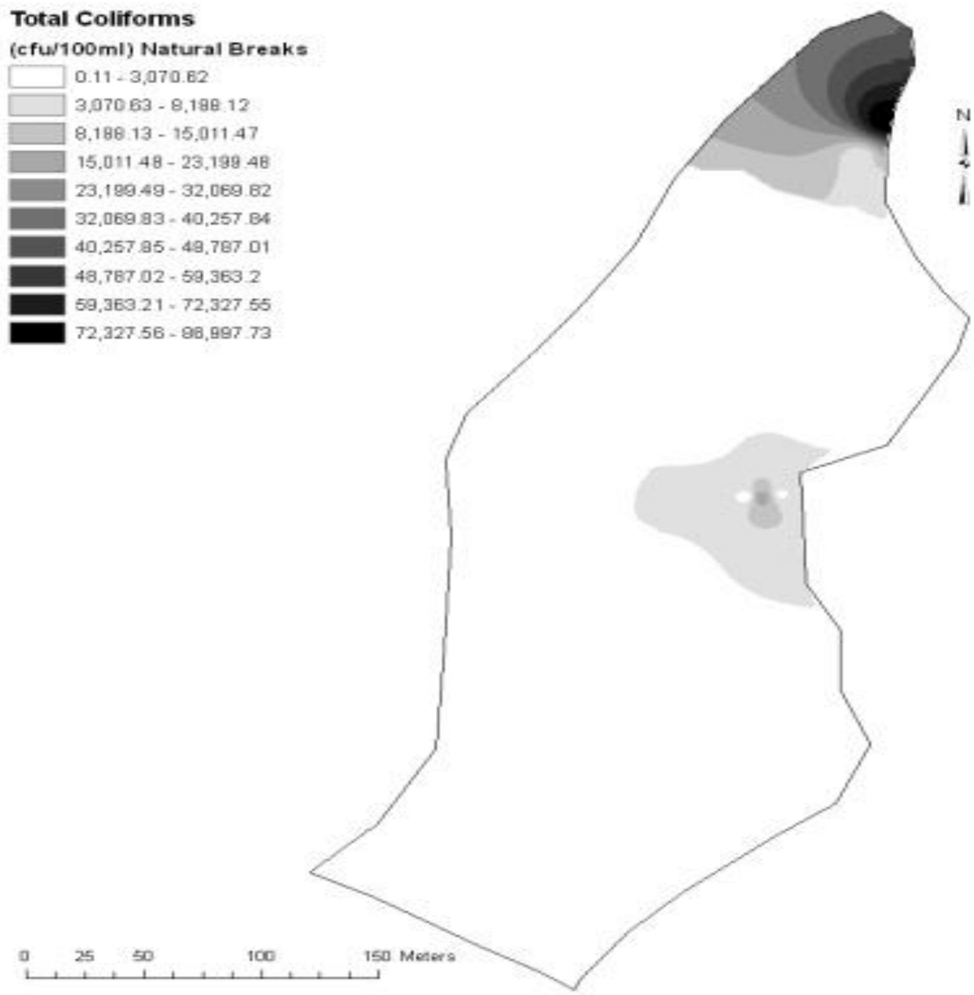

Figure 24. Concentration gradients of total coliforms in the Uluhaktuk treatment wetland.

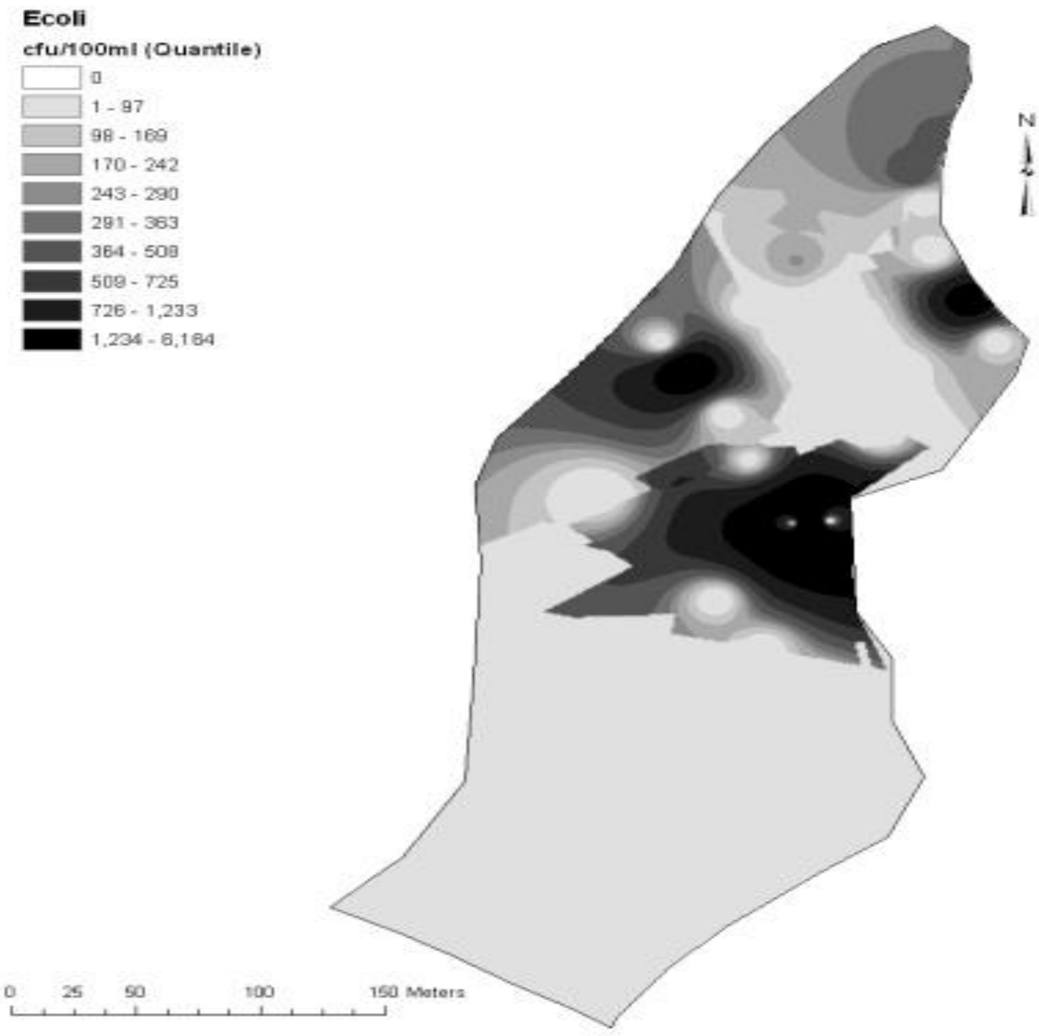

Figure 25. Concentration gradients of *E.coli* in the Uluhaktuk treatment wetland.

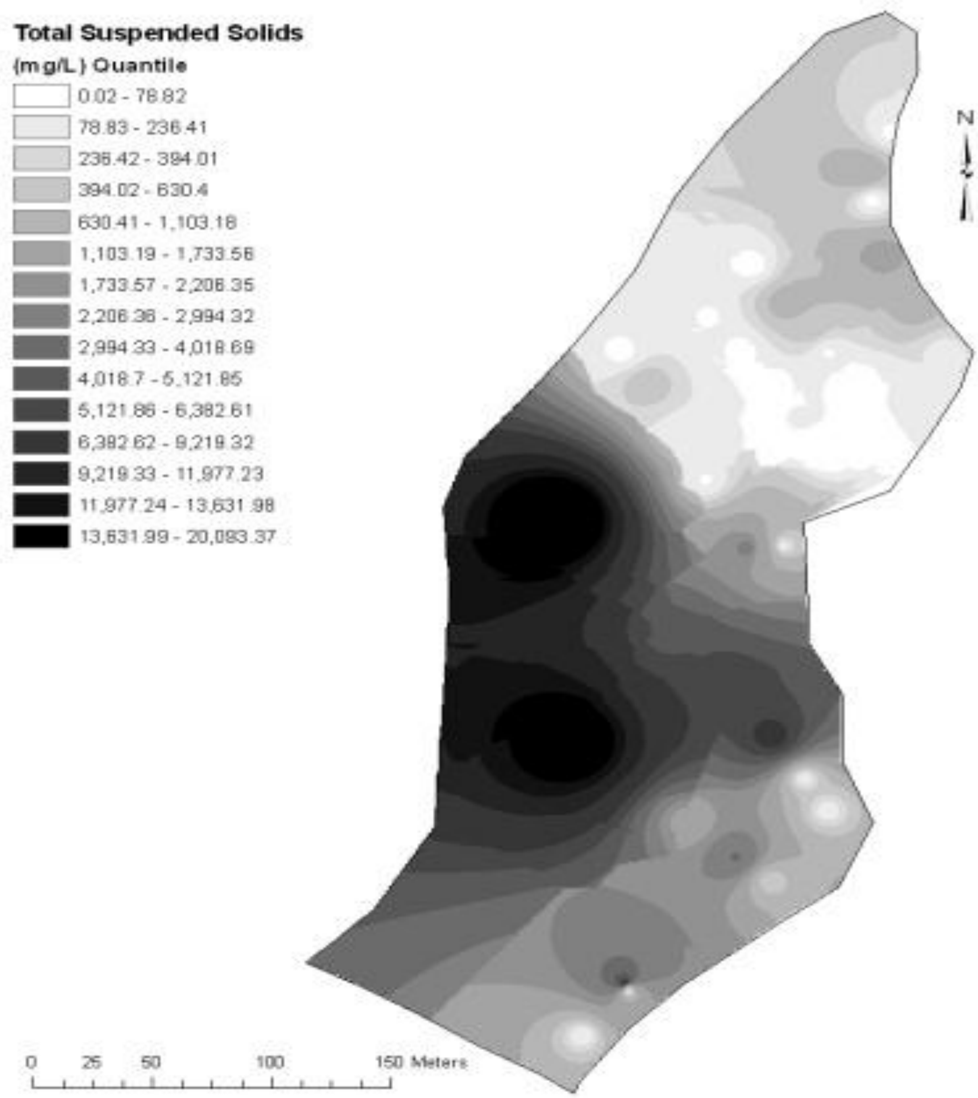

Figure 26. Concentration gradients of total suspended solids in the Uluhaktuk treatment wetland.

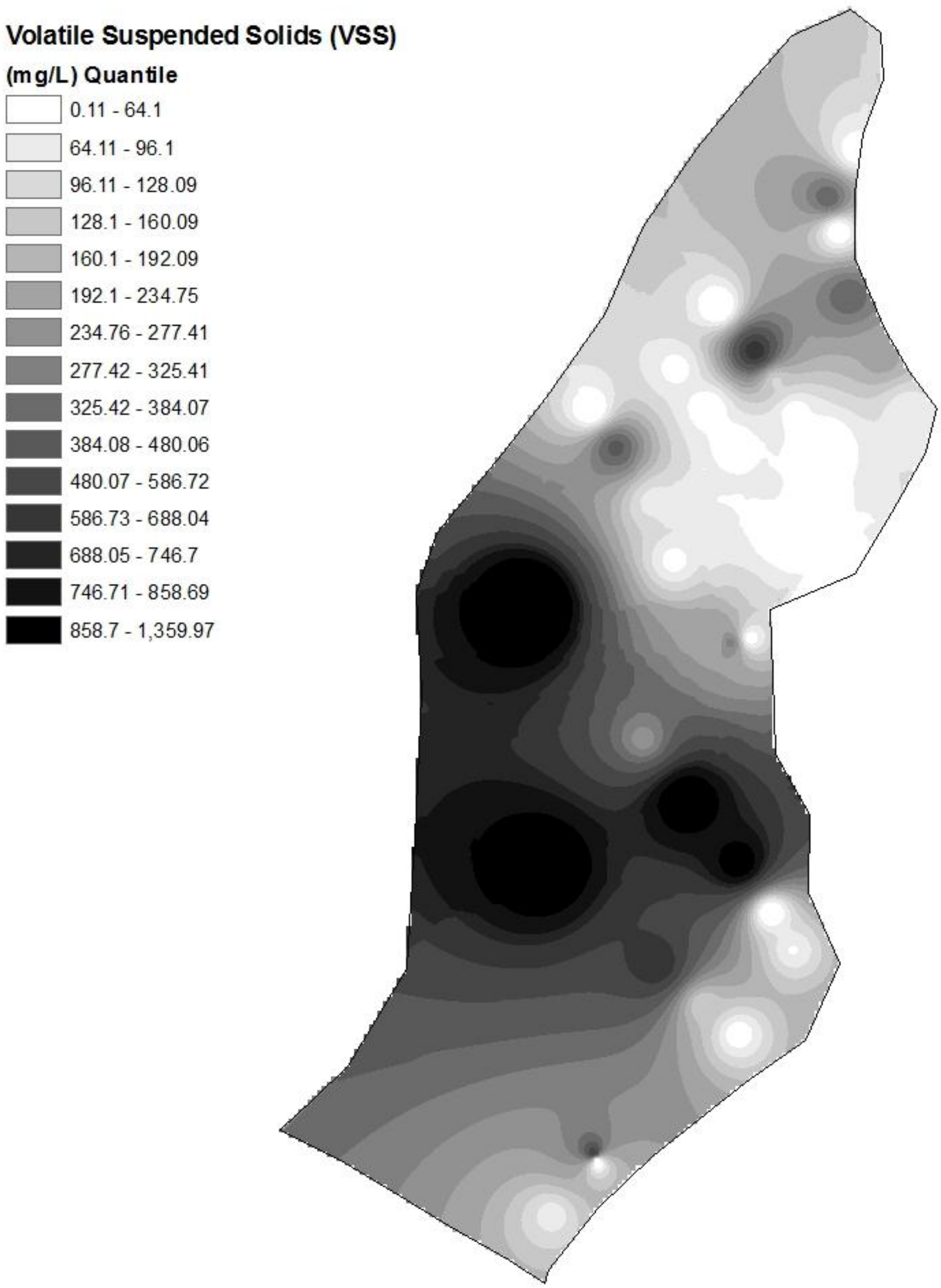

Figure 27. Concentration gradients of volatile suspended solids in the Uluhaktuk treatment wetland.

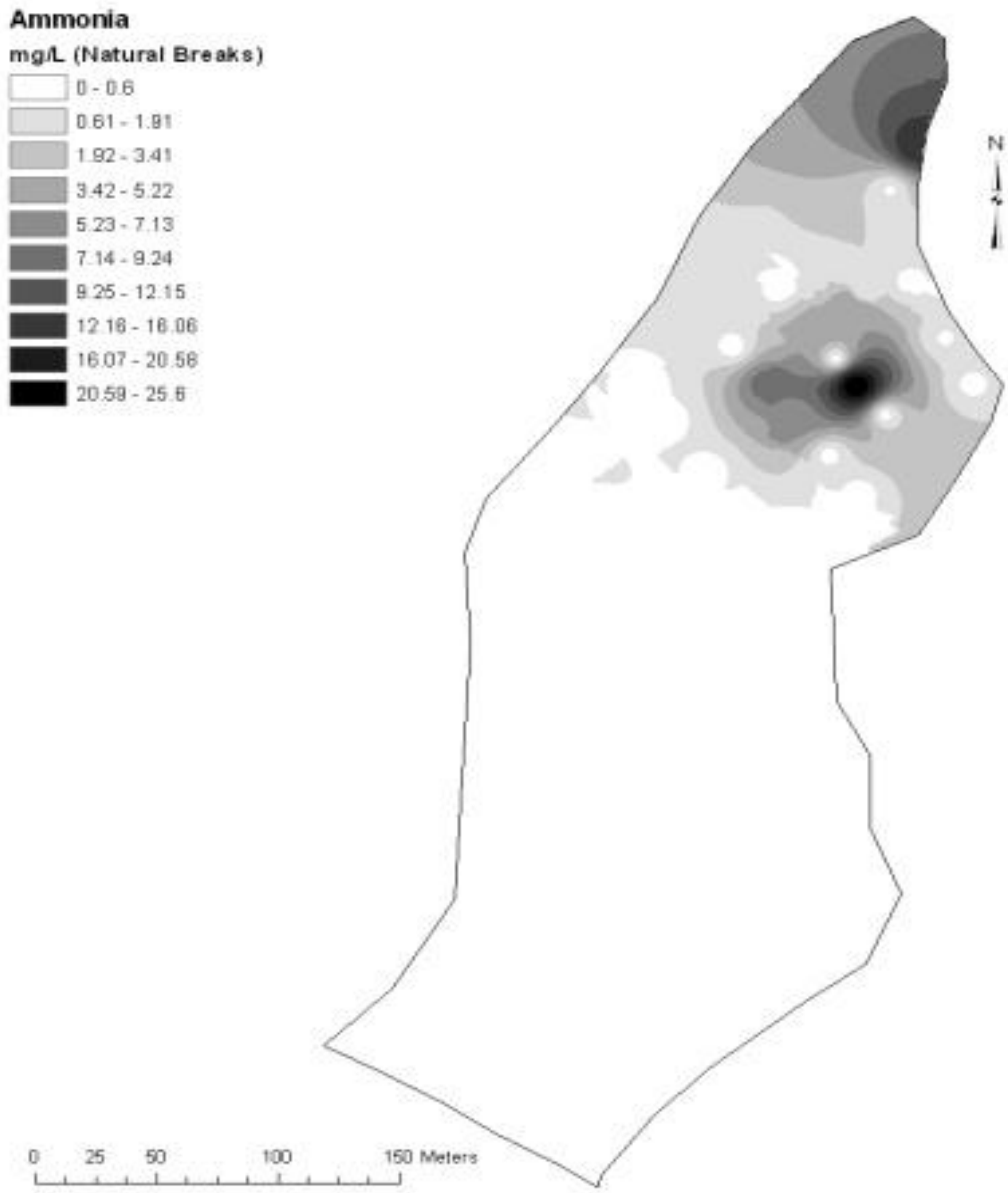

Figure 28. Concentration gradients of NH_3-N in the Uluhaktuk treatment wetland.

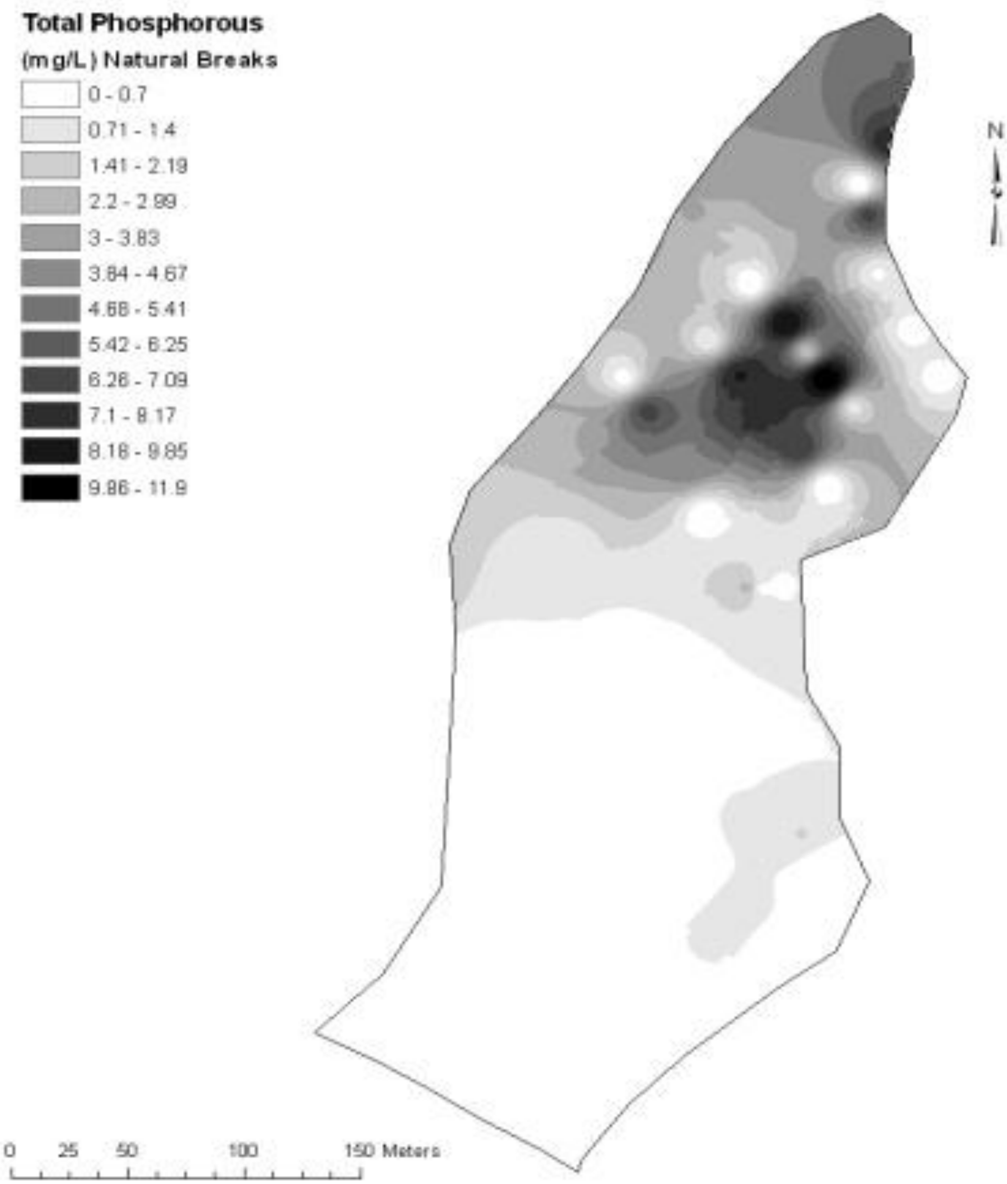

Figure 29. Concentration gradient of total phosphorus in the Uluhaktuk treatment wetland.

The communities selected for analysis provide a number of similarities in the amount of wastewater discharged into the system per day. However, the presence of a facultative lake and lagoon in Paulatuk and Uluhaktuk makes it more difficult to estimate the actual rate of flow of wastewater in to the wetlands. Given the logistical limitations on sampling surface flow rates and background data on discharge volumes it was only possible to estimate areal loading rate and daily hydraulic loading of each of the systems. In Chesterfield Inlet the areal loading rate for $cBOD_5$ was estimated to be at 1 kg $ha^{-1}d^{-1}$ at a hydraulic loading rate of $36m^3$/day. Paulatuk hydraulic loading rate into the facultative lake was estimated at 32 m^3/day. Assuming that the amount of water continuously discharged from the facultative lake is equal to amount as it receives, a $cBOD_5$ areal loading rate of 0.9 kg $ha^{-1}d^{-1}$ was calculated. However, flow rate into the wetland is much less because of evaporation, and some loss into groundwater. Precipitation and runoff from neighboring hillsides may add to the flow through the wetland, but only a minimal amount as this region only receives 84 mm of precipitation between from June to October (Environment Canada, 2011). Similarly, the Hamlet of Uluhaktuk, discharges 40 m^3/day into its engineered lagoon in 2009. Again, assuming an equal of amount of water is received by the wetland, an areal $cBOD_5$ loading of approximately 0.5 kg $ha^{-1}d^{-1}$. Although wastewater continuously flows from the Uluhaktuk lagoon, it permeates through the berm walls, rather than the surface flow channels characteristic of the Chesterfield Inlet and Paulatuk wetlands. Therefore hydraulic and areal loading rates for Uluhaktuk are likely much less. Hydraulic head tests conducted in Uluhaktuk by Yates & Wootton (2011) showed an average groundwater flux of 0.0002 m^3/day. Flow through the berms would have to be explicitly tested to verify this.

Further, the Uluhaktuk wetland possessed physical characteristics not observed in the other wetlands studied. From a hydrological perspective very little flow was moving through the soil. The wetland was found to have a fine clay substrate which caused much of the water to stay on the surface of the ground or top 0.10 m of soil. Much of the flow was overland, rather than in a series of preferential flow channels, as was common in Chesterfield Inlet and Paulatuk wetlands.

From the interpolation analysis, much of the treatment for all parameters was found to be occurring in the first 50-100m of the wetland. After 150 m, flows of wastewater were difficult to detect, as wastewater appeared to be flowing evenly at low velocities across much of the wetland. With a basic understanding of rate of flow and loading of the wetlands, and interpolation of concentration of specific wastewater parameters it is possible to discuss the performance of the systems. Treatment of wastewater was observed to occur primarily in the upper portions of the wetlands, with concentrations quickly dissipating to background levels. In most cases wastewater concentrations were seen to rapidly decrease within the first 100m of the wetland. Only with COD and TSS values did I observe variation from this general trend.

Organic Concentration Gradients

In Chesterfield Inlet, treatment of $cBOD_5$ was observed to occur primarily in the upper 100 m of the wetland. COD concentration gradients were variable, although the highest concentrations still occurred in the top 100m of the wetland. Wetland effluent $cBOD_5$ was observed to be 2 mg/L. This was observed to be same as reference site concentrations observed in samples taken from a nearby stream uninudated with wastewater. When I modeled expected BOD concentrations for the Chesterfield Inlet using the P-k -C* model with a rate constant k_{10}, I observed expected effluent values of 3 mg/L for the first 100 m of the wetland. I used the minimum wetland width of 58 m. Expected BOD effluent values for Paulatuk and Uluhaktuk were 3 mg/L and In the Uluhaktuk and Paulatuk wetlands $cBOD_5$ concentrations decreased even more rapidly, often within the first 50-100 m; likely due to the low influent concentrations from pre-treatment facilities, allowing the top end of the wetland to assimilate or treat remaining organic matter. Again COD concentrations were variable, although not as variable as Chesterfield Inlet, perhaps due to pre-treatment or differences in physiographic features, or more variable background concentrations.

Pathogen Concentration Gradients

Pathogen removal by the wetlands was also observed to occur quickly in the pre-treated wastewaters entering the wetlands in Paulatuk and Uluhaktuk. Concentrations of pathogens (*E.coli* and total coliforms) were observed to be low at the influence of the wetland; 2.85E3 cfu/100ml and 5.17E4 cfu/100ml respectively in Paulatuk. *E.coli* was observed to be quickly removed, only observed in trace concentrations within a third of the wetland distance. Total coliform concentrations persisted longer, but also were removed. Effluent concentrations for both *E.coli* and total coliforms were observed at 1 cfu/100ml and 365 cfu/100ml. Uluhaktuk was observed to be very similar; *E.coli* at 1 cfu/100ml and total coliforms at 691 cfu/100ml. Pathogen concentrations in Chesterfield Inlet wetland persisted much longer, likely due to much higher influent concentrations. However, background concentrations began to be observed after 150m through the wetland. Removal was likely due to sedimentation, and UV penetration in surface water locations of the wetland, facultative lake and lagoon. In subsurface samples removal is likely caused by sedimentation and predation.

Nutrient Concentration Gradients

Nutrient parameters, total phosphorus (TP) and ammonia-nitrogen (NH_3-N) also decreased rapidly down each of the wetlands. This was especially true in Paulatuk and Uluhaktuk wetlands where concentrations dissipated within the first 50 m of the wetland; again likely due to the low influent concentrations. NH_3 -N and TP persisted longer in the Chesterfield Inlet wetland. However, concentrations were observed to be comparable to nearby background concentrations, suggesting removal could still occur despite minimal pre-treatment.

Suspended Solids Concentration Gradients

TSS concentrations in all three wetlands were observed to vary significantly throughout each wetland. TSS concentration in the wastewater entering the wetland was 35 mg/L for Paulatuk, 146 mg/L in Chesterfield Inlet and approximately 50 mg/L in surface water entering the wetland in Uluhaktuk. It is assumed that the facultative lake and lagoon removes much of the suspended solids entering the treatment system through sedimentation in Paulatuk and Uluhaktuk. In surface water sample locations proceeding down the wetland, TSS concentrations were observed to decrease in all cases. However, in subsurface water sample locations throughout the wetland concentrations were exceedingly high as observed in the interpolations. These high values suggest disturbances of the soil media from within the lysimetres. It is believed that due to the very fine sand substrate produced artificially high TSS values. I verified this assumption by examining the percent fraction suspended solid which was organic (VSS) to inorganic. In surface water sample locations in Uluhaktuk an average of 50% (sd 32), was volatile suspended solids and 34% (sd 29), in groundwater, suggesting that more inorganic material was being extracted from groundwater samples. However, in surface flow locations TSS was found to be between 3-5 mg/L near the effluent of the wetland, which was comparable to reference concentration (3 mg/L) of TSS observed in each of the reference sites. Similar results were found in Chesterfield Inlet. Surface water samples contained 93% (sd 8) volatile suspended solids, and groundwater contained 76% (sd 19).

When TSS was modeled for expected effluent from the identified key treatment areas concentrations of 11 mg/L would be expected after the first 100 m of wetland in the Chesterfield Inlet treatment system. 10 mg/L would have been expected in the first 75 m of wetland for Uluhaktuk and Paulatuk systems respectively. Expected effluent values after the first 75-100 m are comparable to those observed in the effluent hundreds of metres down the wetland.

The best estimate for the high level of treatment in the Uluhaktuk and Paulatuk systems is the presence of the lagoon and large facultative lake connected to the wetland and small annual discharge into the system. Dilution, and natural transformation and absorption of nutrients in the wetland can likely accommodate the loads during periods of wetland activity. However in Paulatuk, during winter months and during the spring freshet, the performance of the system would likely be severely limited by frozen soils. Exfiltration likely ceases in the Uluhaktuk system, and that the wetland does not drain over the land to a body of water or ocean, concerns of a spring freshet are not warranted.

Although the Chesterfield Inlet wetland performs very well during the summer months it has been shown to have minimal treatment during the spring due to the freshet and in the late fall before freeze up (Yates et al., 2010). The interpolative mapping analysis showed that most of the treatment of wastewater is occurring in a small portion of the wetlands studied. The First-order kinetic plug flow model showed that expected treatment for $cBOD_5$ and TSS confirm that the estimated actual treatment area was already comparable to observed effluent values much further down the wetland. Despite the observed high performance of the wetlands during the summer, the key mechanisms for removal of nutrients and decomposition of organic matter in these Arctic systems are still speculative. Air temperature and soil temperature likely play the largest, although indirect, role in the treatment of wastewater in the Arctic. Natural ultraviolet radiation (UV), the microbial and plant communities would also uniquely influence wastewater treatment in the Arctic because of the long duration of sunlight during the summer months and the rapid growth of the biological communities. Filtration and sedimentation of suspended solids and adsorption of nutrients within the soil column also likely plays an important role.

Soil temperature relating to plant growth and microbial activity are the most likely candidates for the treatment of wastewater in Arctic wetlands (Hobbie & Chapin, 1996). Arctic soil is known to be an excellent sink of organic matter and nutrients, immobilizing nutrients within the frozen matrix and within the microbial community (Schmidt et al., 1999). Phosphorus has been shown to be bound to soils in the Arctic, rendering it unavailable for plant uptake (Mack et al., 2004). But it is unknown how much the soil matrix is responsible for "treatment" by locking nutrients. Fertilization studies in various Arctic habitats, including wet-sedge tundra, have shown that in nutrient limiting conditions plant communities respond to increased nutrient input based on small nutrient additions (Chapin et al., 1993; Hobbie et al., 2005; Shaver et al., 1998), especially when nutrients were added simultaneously (Gough et al., 2002), as would be the case with wastewater . Some Arctic plants have even demonstrated the ability to uptake organic forms of N because mineralization of organic material is slow due low soil temperatures (Chapin et al., 1993). Plants in tundra treatment wetlands, such as those presented here, may be up-taking the readily available nutrients in such a manner, which may explain low values of inorganic-N in a similar study conducted on Arctic treatment wetlands (Yates et al., 2010).

However, actual nutrient uptake rates in these systems have not been studied to determine rate or percentage of nutrients discharged into the system is taken up by the plant community.

The microbial community may also play an equal role in the uptake of readily available nutrients in wastewater in these Arctic wetlands. Similar to plant communities, microbial activity is generally limited by temperature and available nutrients. Arctic microbial species are more efficient at lower temperatures than their temperate microbial counterparts, as Arctic species continue to transform nutrients throughout the winter (Edwards et al., 2006; Larsen et al., 2007). Hobbie & Chapin (1996) also suggested that microbial activity is able to uptake nutrients in soils at temperatures as low as -5^{o}C. Nutrient uptake at low temperatures was recently validated by Edwards (2009) and Edwards & Jefferies (2010). These observations likely contribute to the rapid increase in wetland performance from late June to early July due to increases in microbial populations as a result of additional nutrient availability in still semi-frozen soils observed by Yates et al. (2010). Whether winter microbial activity is sufficient to continue to mineralize organic matter and nutrients is unknown. It is likely that the microbial community would not be able to significantly consume the excess nutrient and organic loads at the top of the wetland resulting in the gradual infilling of organics at the influence.

Natural ultraviolet radiation (UV) play important role in disinfection of wastewater in surface wetlands and lagoon systems in more temperate systems. The long exposure of sunlight in the Arctic during the summer months in theory should promote increased disinfection. However, if water temperatures are not optimal lysis of bacteria may not occur, as cold temperatures appear to stabilize populations, at least in lagoon environments (Prince et al., 1995). In wetlands which do not maintain large areas of open water, solar radiation cannot penetrate the water column because of the plant canopy (MacIntyre et al., 2006), which is often the case in tundra wetlands which maintain dense stands of *Carex*.

Finally, sedimentation of solids on the wetland surface, in various preferential flow channels throughout the wetlands and entrapment in vegetation. Personal observations from field notes show accumulations of organic matter in many of the wetlands surveyed throughout the Arctic. As discussed earlier, decomposition rates by the microbial community are not as high as deposition rates. Although through much of the wetlands it was observed that water quality was low in organic load, it would be expected that deposition would occur further down the wetland in the future.

CONCLUSIONS

The Paulatuk and Uluhaktuk treatment wetlands were observed to effectively polish primary treated wastewater from the facultative lake and engineered lagoon. Likewise, the Chesterfield Inlet wetland also treated minimally pre-treated wastewater during the summer. In all wetlands wastewater concentrations were measured. The Chesterfield Inlet treatment wetland without the presence of pre-treatment structures was a found to effectively treat wastewater despite the fact influent to the wetland was of an order of magnitude greater than influent into the Paulatuk and Uluhaktuk treatment wetland. It is assumed that the level of treatment is maintained throughout the summer months with minimal treatment occurring in the spring and no treatment occurring during the winter.

Interpolative mapping showed the effective treatment areas of the wetland to be much smaller than the entire delineated area, with most treatment occurring in the first 50-100 m for all three of the wetlands characterised. First-order kinetic modeling demonstrated that the expected effluent estimated from the effective treatment areas were comparable to the effluent observed much further down the wetland.

This study again demonstrates the ability of wetlands to act as sinks and transformers of nutrients, even during short Arctic summers where temperature has been thought to limit efficient treatment.

CHAPTER 5

COMPOSITION OF *CAREX AQUATILIS* IN RELATION TO NUTRIENT GRADIENTS IN ARCTIC TUNDRA WASTEWATER TREATMENT WETLANDS

Summary: Numerous studies have shown how oligotrophic arctic tundra species and communities re-organize their composition in response to increase growth with small scale fertilization and manipulations (e.g. light and moisture). What is not clear is how these community scale results will translate into system dynamics at a spatially explicit landscape scale. Tundra wetlands used to treat wastewater are useful for cross-scalar studies. I examined primary Arctic limiting nutrients (N and P), in the form of NO_3^- - N, NH_3-N, NO_2^- -N and PO_4^{3-} -P as the variables in groundwater. I then spatially correlated the environmental variables with percent cover of *Carex aquatilis* Wahlenb. var. *stans* (Drej.) using Shepards Inverse Distance Weighting method. I validated these spatial relationships using Principal Components Analysis to determine whether % composition was significantly related to concentration of the environmental variables. Spatially, correlations showed that a high percent cover of *C. aquatilis* correlated with areas of high concentration of NH_3-N in the groundwater. Spatial interpolations also showed correlation between other nutrient parameters in the groundwater as well. A principal components analysis verified the spatial results showing significant ($p<0.05$) correlation between *C. aquatilis* cover and NH_3-N concentrations. Analysis also showed strong positive relationship between sites closer to the source of wastewater and *C. aquatilis*. However, opposite to spatial interpolation no significant correspondence was found between the other variables (NO_3^- - N, NO_2^- -N and PO_4^{3-} -P) and *C. aquatilis*. In response to increased nutrient inputs, Arctic tundra, a normally nutrient limited environment re-organizes its dominant species at spatially explicit landscape scales, with nitrophilous species as the new dominant cover. The study also provides further insight into the potential importance of vegetation for wastewater treatment in cold climates.

Keywords: Arctic, *Carex aquatilis*, nutrients, wastewater

INTRODUCTION

The study of plant ecology has not been explored as thoroughly in the Arctic in comparison to more temperate regions; in particular to those studying population or community ecology in response to long-term ecosystem stressors. This is largely because of the longevity of species, difficulty of manipulating plant densities (Hobbie, 2007), and the short growing seasons (Woo & Young, 2003). However, numerous studies have been conducted showing short-term response relationships between particular plant species, nutrients and Arctic herbivores (Cadieux et al., 2005; Ngai & Jefferies, 2004; Tolvanen et al., 2004), and changes in plant community because of bioclimatic gradients (Vonlanthen et al., 2008).

It is well understood that many abiotic factors (temperature and nutrients) strongly influence plant communities in the Arctic (Chapin & Shaver, 1985; Hobbie, 2007) because of oligotrophic conditions present in most Arctic systems. The extreme environment has allowed for species to evolve in very nutrient limited conditions, resulting in low biomass production. Studies of abiotic factors in Arctic plant communities by Chapin & Shaver (1985), and Chapin et al. (1995) have shown that competition within a plant community is primarily driven by nutrient availability in the system, and many Arctic plant species have been shown to respond rapidly to the addition of nutrients. Although temperature does not directly affect plants in the Arctic (Chapin, 1983), it indirectly influences the plant community through nutrient cycling and nutrient availability (Hobbie, 2007; Nadelhoffer et al., 1991). Jonasson & Shaver (1999) suggest that nutrient pools entering from external sources or in vegetative material present in Arctic wetland systems are small, and organically fixed nutrients in the soil are large, but are often unavailable for plant uptake.

Because of oligotrophic conditions in most Arctic systems, the addition of external readily available (mineralized) nutrient sources will have dramatic influence on plant community composition. Fertilization studies in various Arctic and alpine systems have also been used to demonstrate how communities can rapidly respond to increased nutrients and changes in environmental conditions (e.g. light and moisture), often imitating conditions which are expected with a changing climate Gough et al. (2002). Hobbie et al. (2005) showed how biomass rapidly increased in *Betula nana* L. in Arctic tundra with the addition of N and P over two years. However, these responses have been more variable than changes in nutrient availability alone (Hobbie, 2007). Changes in polar systems from climate change have been shown to change nutrient uptake in simulated environments (Wasley et al., 2006), as temperature directly influences nutrient input from N_2 fixation (Ju & Chen, 2008). Despite this empirical evidence to suggest the influence of regional climate change little is understood with respect to how or to what extent plant communities respond to in natural Arctic tundra wetlands when the system experiences regular nutrient loading on a landscape scale from thawing nutrient pools in the permafrost. Small scale fertilization studies (addition of N, and P) in Arctic wet meadows have shown a rapid positive association to increase in plant biomass to specific nutrients generally when added to the system in association (Gough et al., 2002; Hobbie et al., 2005). However, most studies showed that plants responded to the addition of N rather than P in upland tundra environment (Gebauer et al., 1995), and the addition of P in freshwater marshes due to geese feces (Ngai & Jefferies, 2004). These addition studies are generally small on a spatial scale, 5m x 20m or 2.5m x 2.5m (Cornelissen et al., 2001; Hobbie et al., 2005) and have not been implemented at a spatially explicit landscape scale.

Many Canadian Arctic settlements make use of tundra wetlands to treat the community's wastewater. The design of some treatment systems results in daily loads of concentrated wastewater entering tundra. Wastewater from Arctic communities is discharged into the environment at a designated depot, often into an engineered holding cell or lagoon but in some cases the waste is discharged directly into a natural depression in the landscape (Kadlec & Johnson, 2008; Wootton & Yates, 2010). Soil percolation allows the waste to pass into the open environment or natural treatment wetland. In treatment wetlands in southern environments, daily discharges are generally closely monitored (Kadlec & Knight, 1996), contain known plant communities and interactions between edaphic nutrients (Kadlec & Wallace, 2009). In contrast treatment wetlands used by Arctic communities to treat municipal wastewater are often poorly monitored and to date very little research has been conducted on them (Johnson, 2008; Wootton & Yates, 2010). Therefore little is known of the plant communities, or plant interaction with the environmental factors, such as influx of nutrients into these systems from municipal wastewater. In tundra wetlands which receive natural nutrient addition from Snow Geese (*Chen caerulescens* L.) Kotanen (2002) noted that that rapid responses to fertilization generally only occur in freshwater species, when nutrients are added at much greater levels than that of the background levels. For example, Pineau (1999) observed when inorganic N was added at 20 times the natural rate that with within-season growth responses of sedge fen species was significant. Cornelissen et al. (2001) and Press et al. (1998) saw that plant communities shifted with the long-term presence of increased nutrients from moss-lichen to graminoid communities (grass and sedges). Hobbie et al. (2005) suggested that the high levels of nutrients may be toxic to the mosses and lichens; changes in environmental conditions such as shading/moisture may also influence the shift in community.

Because these wetlands have been receiving wastewater for long periods of time (e.g. decades, they provide a ready-made environment to test the observations of nutrient response by plant communities and individual species at a landscape scale. From pre-study observations of the Chesterfield Inlet treatment wetland *Carex aquatilis* Wahlenb. var. *stans* (Drej.) Boott was observed to dominate many portions of the treatment wetland. Mono-culture stands were most prevalent near the point of influence of wastewater in the treatment wetland. *Carex aquatilis* is often associated with freshwater wetlands (Aiken, 2007), and is known to be nitrophilous and maintains a high concentration of nitrogen in its above ground tissue (Murray, 1991). It is also a common species with circumpolar distribution, commonly found along rivers, pond edges, and wet meadows (Hulten, 1968; Porsild & Cody, 1980). *C. aquatilis* also has much ecotypic differentiation in size and phenology, respiration, photosynthesis and nutrient absorption across regions and even in micro habitat (Chapin & Chapin, 1981). Muskoxen (*Ovibos moschatus*) regularly feed on stands of this species, fertilizing it with feces and urine. Raillard (1992) showed that *C. aqualitis* may be responding to the presence of more nutrients from muskoxen feces and urine promoting greater *C. aquatilis* stands on Ellesmere Island, Nunavut. In light of these observations I asked the question of whether the plant community could be re-ordering itself in response to the high nutrient loading the wetland is experiencing through wastewater inputs from the community of Chesterfield Inlet similar to fertilization experiments, and natural fertilization which I highlighted earlier. Using *C. aquatilis* as an indicator species I performed spatial correlation and multivariate analyses to determine whether the species was consistently found to be locations of high nutrient concentrations, specifically nitrogen (N) species. And therefore, I expected that as nutrient concentrations dissipate throughout the wetland due to treatment of the wastewater, the dominance of *C. aquatilis* would decrease correspondingly.

METHODS

Site Description

The Hamlet Chesterfield Inlet (63^{o}N, 90^{o}W) is located in the Kivalliq Region of Nunavut, Canada. The treatment wetland in this community services approximately 366 residents (Statistics Canada, 2006a). The wetland is located in a shallow depression in the landscape, with an approximate area of 5 ha (50,000 m^2) and a length of 720 m, with a minimum width of 58 m and a maximum width of 225m near the end of the wetland complex. It is estimated that approximately 36 m^3 is discharged directly into the wetland per day. Only a shallow natural depression slows the movement of wastewater before it enters the wetland. The wetland is dominated by *Carex aquatilis*, *Stellaria crassifolia* Ehrh, and *Arctophila fulva* var. *similis* (Rupr.). Occasional stands of *Salix arctophila* Cock. ex Heller line preferential flow channels further down the wetland. The average annual temperature for the hamlet is -11^{o}C, and the mean summer temperature of 9.4^{o}C (Environment Canada, 2011).

Field Methods

I used a line-intercept (transect) sampling (LIS) method to capture spatial variation in the primary treatment areas in the wetland. LIS shows how vegetation can change, as the environment varies (Kaiser, 1983), and therefore test the influences of groundwater chemistry on vegetation. The transect length and placement was determined by observing visual variation of the wetland where different points in treatment of influent might be expected.

To specifically characterize vegetation communities, sub-surface water quality twenty-three (n=23) sample points throughout the wetland were collected. Because of logistical challenges for sample shipment times, sample transport cost, and field time in northern research directly related to performing analysis in a temporary lab environment large data sets were difficult to obtain. *C. aquatilis* composition was obtained by estimating the percent cover (by 5% increments) of each species identified within a quadrat (square shaped; 1m x 1m).

I collected subsurface water samples at the sample points where vegetation composition was assessed. A lysimeter (0.05m diameter) constructed from polyvinyl chloride (pvc) piping was placed into a bore hole of maximum depth of 0.3m (often this will be shallower, or as depth to bedrock). Collection of subsurface water is important when characterizing wetland response, particularly vegetation community response studies as groundwater flows in a wetland can be an equally important source of nutrients as surface water (Cronk & Fennessy, 2001; Mitsch & Gosselink, 2000). I analyzed water samples for concentration of NH_3-N, NO_3^--N, NO_2^--N, PO_4^{3-}-N, all in mg/L. I was interested in nutrients known to be limiting in Arctic systems; phosphorus has been particularly noted as such (Ngai & Jefferies, 2004).

Analysis

Interpolation analysis was performed using ArcGIS 9.3's ArcMap Spatial Analyst tools, correlating concentration of nutrient parameters with the composition of *Carex aquatilis* in each of the blocks for all the sites in the wetland. These spatially plotted point concentrations were converted to raster maps by inverse distance weighting (IDW) using ArcMap's standard Shepard's method of multivariate interpolation with no smoothing. IDW is often used for irregularly spaced data in geographic space to create a continuous surface and portray concentration gradients (Shepard, 1968). Nutrient parameter values and percent composition of *C. aquatilis* were classified into qualitative value ranges; very low, low, medium, high and very high after creating their individual raster maps so as to easily compare the disparate datasets. The *C. aquatilis* raster map was then compared to any one of the nutrient parameter raster maps using ArcMap Cell Statistics overlay comparison method. This created a further raster map calculating the mean of each cell in the two combined raster maps. This final map was again classified into qualitative value ranges; very low, low, medium, high and very high using quantile breaks (an even as possible distribution of values within the given number of classes) to best show the contrast between classes. All the maps were created using a UTM Zone 15 E projection and the cells within the raster maps measured 2x2m. Although Kriging methods of interpolation have been shown to be optimal in many cases, no significant difference has been found between Kriging and IDW when data sets are irregular (Zimmerman et al., 1999). Principal components analysis (PCA) was used to confirm whether spatial correlations were significant. PCA was chosen as it was assumed that cover of *C. aquatilis* would respond in a linear relationship to increasing or decreasing nutrient concentrations in the wastewater as observed in other natural wetlands converted for wastewater treatment (e.g. Houghton Lake, Michigan) (Kadlec & Bevis, 2009). McCune & Mefford (1999) suggest that PCA should not be used with community data, but is conducive to relationships to species abundance. The PCA was run using PC-ORD v.5.10 (MjM Software); running a cross-products correlation matrix, conducting a randomized test of 999 iterations (Monte Carlo) to determine significance at $p < 0.05$. The randomized test was run because of the small sample size in the wetland. PCA has the tendency of over-extraction of components, especially in small data sets where random data can more greatly influence results (Franklin et al., 1995). A Monte Carlo test for significance eliminates some of the distortion by rearranging a sub-sample of the dataset to make sure the results are real and not false because of the smaller sample size.

A PCA including all nutrient parameters and *C. aquatilis* were run simultaneously. The test was then repeated for each parameter with *C. aquatilis* individually. A final run was conducted with NH_3-N and PO_4^{3-}-N, as many fertilization studies had shown the addition of N and P together often had the greatest influence on plant communities (Gough et al., 2002; Hobbie et al., 2005). The scatter-plot and correlations showed potential relationships with *C. aquatilis* and NH_3-N with sites closest to the source of sewage, although no significant value was captured by the PCA. Because of this observation I re-ran the PCA with cover of *C. aquatilis* and NH_3-N alone. This analysis was performed because PC analysis is strongly influenced by outliers in the data (McCune & Mefford, 1999).

RESULTS

Wastewater being discharged into the Chesterfield Inlet wetland in 2009 was observed to have NH_3-N concentrations between 50-60 mg/L, compared to 0.08 mg/L background concentration (Yates et al., 2010); an estimated 600 times the natural rate increase. NO_2^--N ranged from 0.015-3.16 mg/L. NO_3^--N and PO_4^{3-}-P was highly variable in subsurface water samples; ranging 0.01-17 mg/L and 0.02-36 mg/L respectively.

Interpolation analysis conducted in ArcMap depicted concentration gradients of nutrients and cover of *C. aquatilis*, using quartile ranges. Maps were generated for each of the nutrient parameters and then correlated with cover of *C. aquatilis*. Spatial analysis showed the greatest concentration of NH_3-N where wastewater enters the wetland, then rapidly dissipating within approximately the first 100m of the wetland (Figure 1). Similar patterns of *C. aquatilis* cover were also observed, although in both cases higher concentrations can be observed at further distances from the point of wastewater influence. Interpolation of NO_3^--N and PO_4^{3-}-P showed variability throughout the wetland, which aligns with the broad range of concentrations indicated above (Figure 2-3). Interpolation map of NO_2^--N shows concentrations increasing with distance away from the source of wastewater (Figure 4).

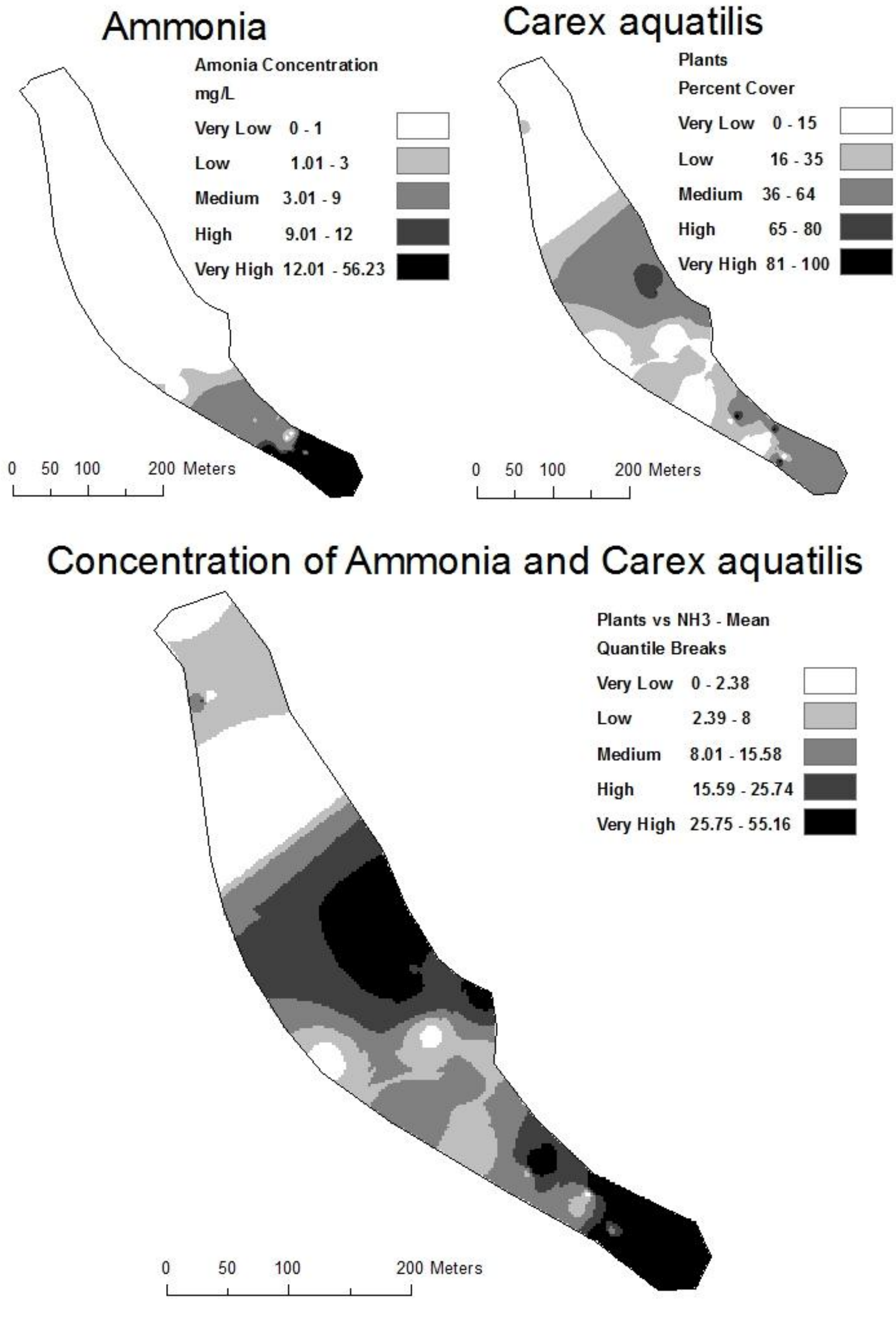

Figure 30. Concentration of ammonia-nitrogen (NH_3-N) and % cover of *C. aquatilis*; spatial correlation of species-nutrient using quantile breaks.

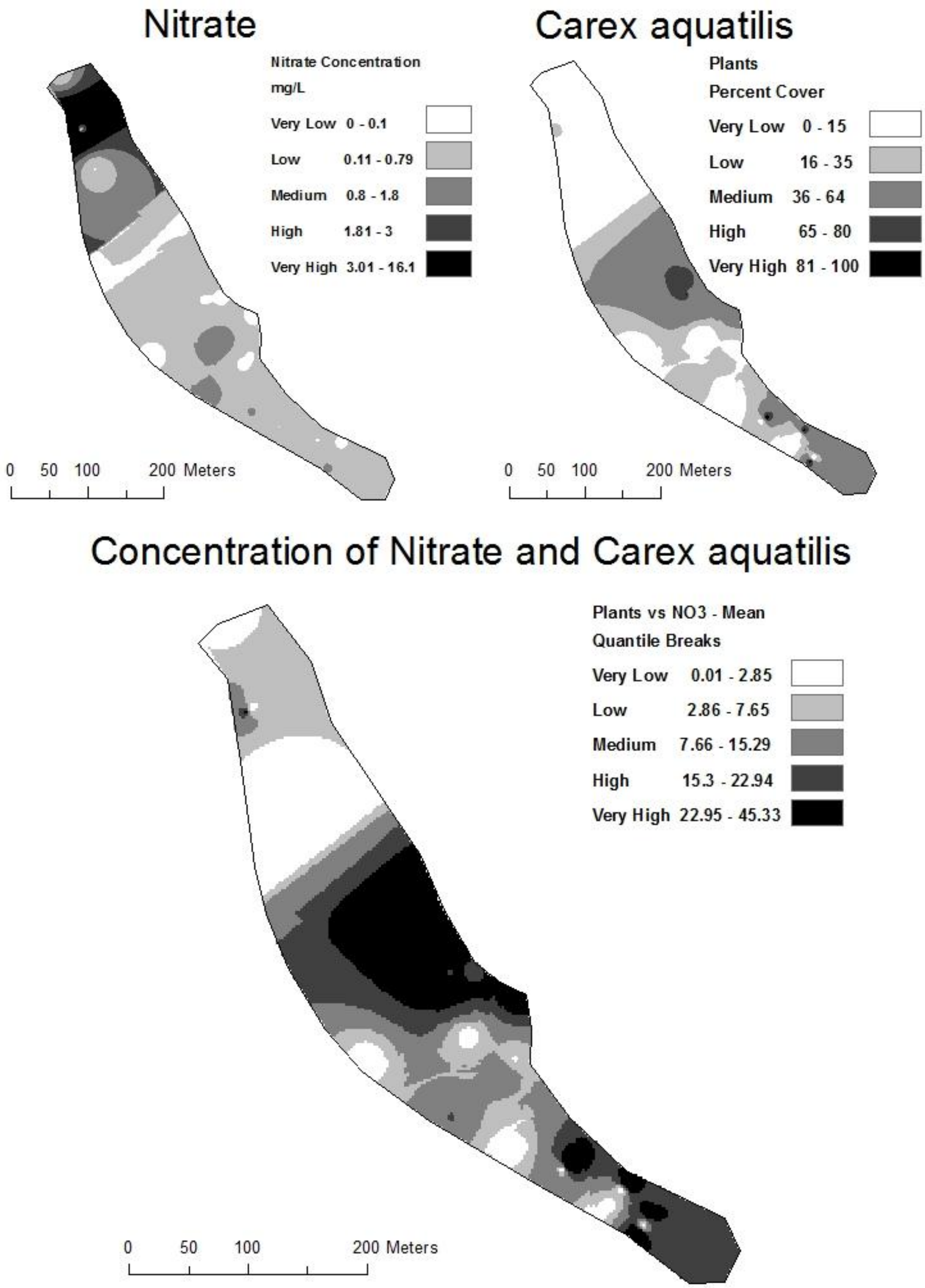

Figure 31. Concentration of nitrate (NO_3^- -N) and % cover of *C. aquatilis*; spatial correlation of species-nutrient using quantile breaks.

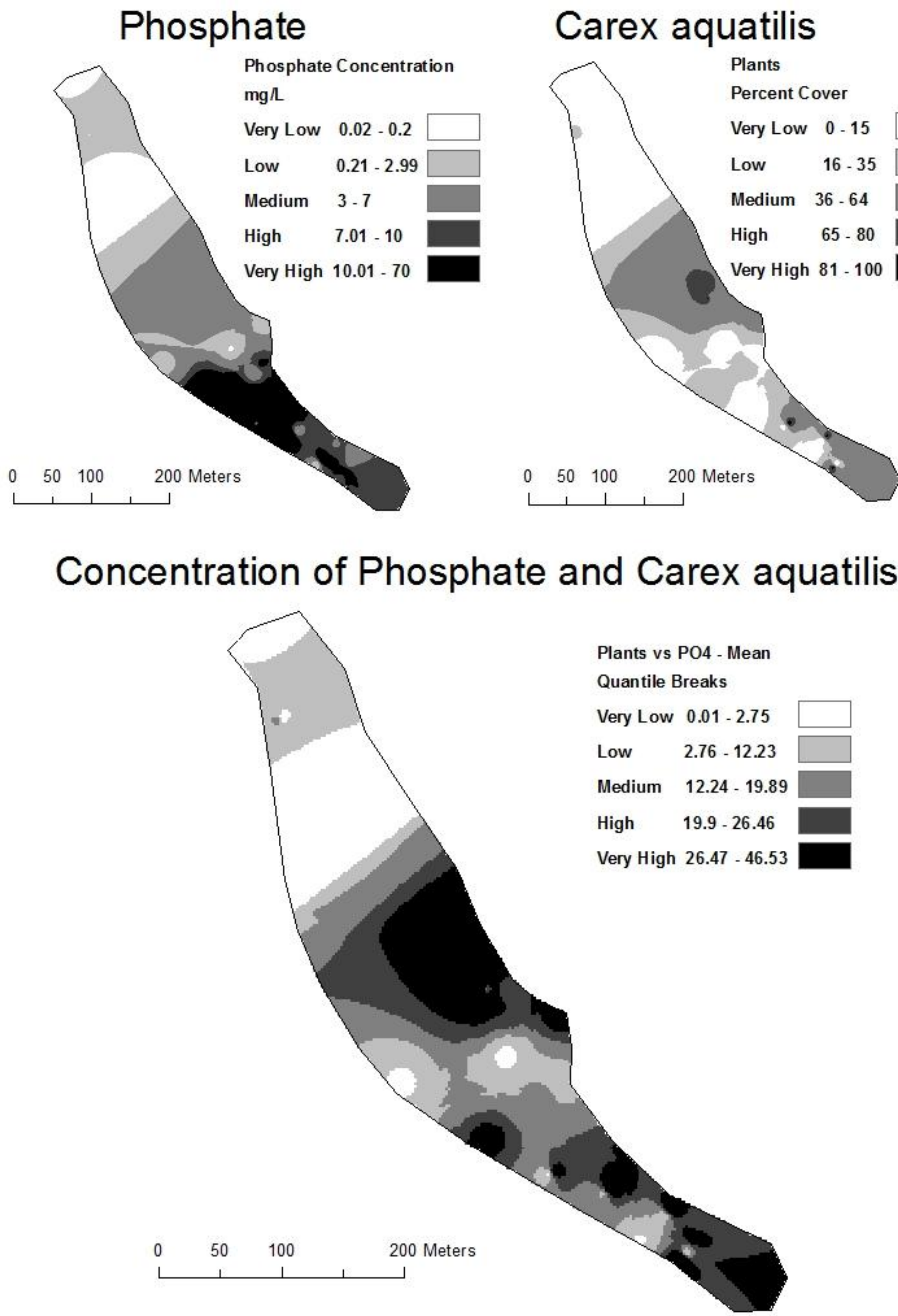

Figure 32. Concentration of phosphate (PO_4^{3-} -P) and % cover of *C. aquatilis*; spatial correlation of species-nutrient using quantile breaks.

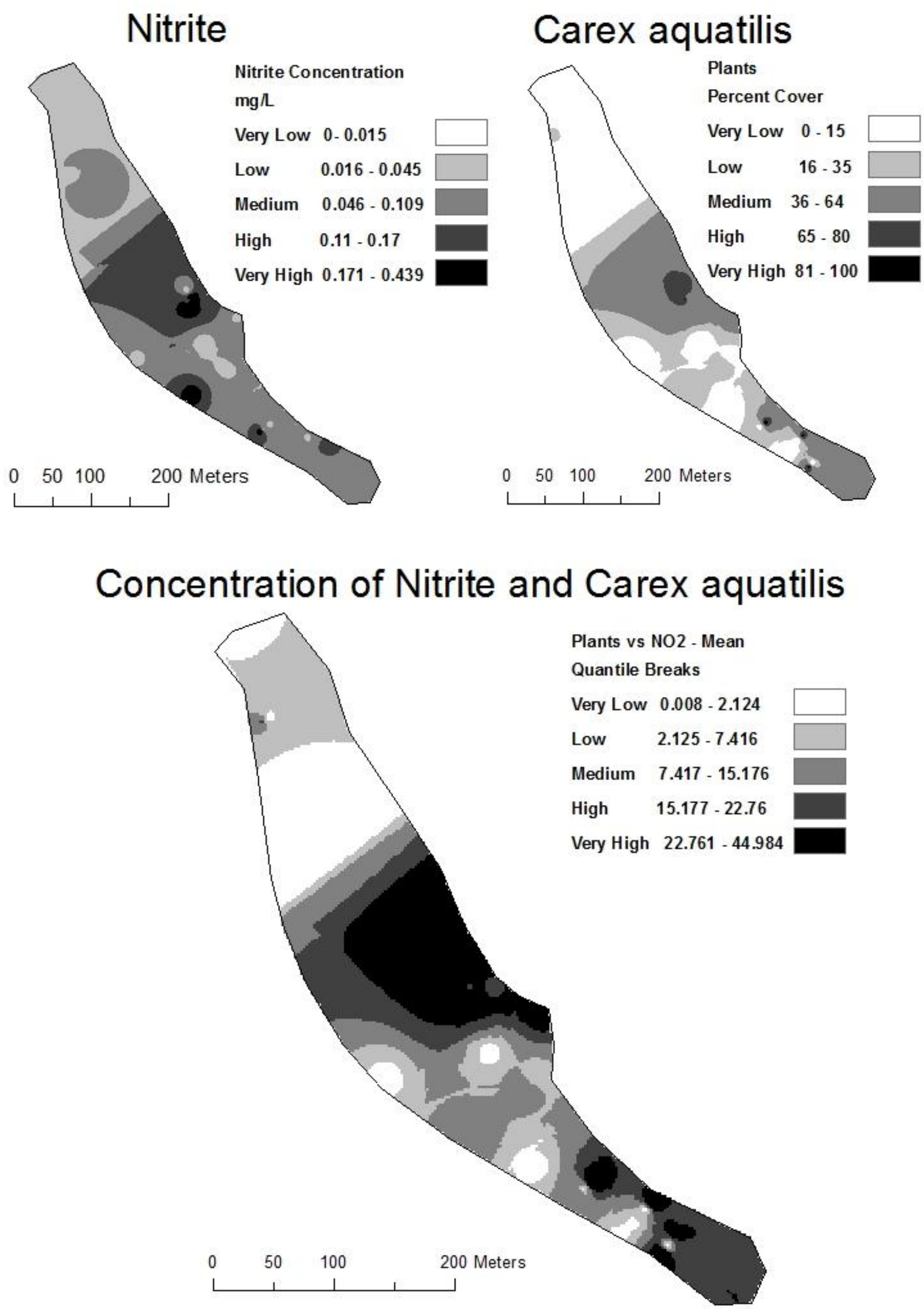

Figure 33. Concentration of nitrite (NO_2^- -N) and % cover of *C. aquatilis*; spatial correlation of species-nutrient using quantile breaks.

PC analysis showed that in the first run, no significant ($p<0.05$) correlations were found when all parameters were analysed in relation to *C. aquatilis* together. The first 2 axes explained the greatest amount of variance, 56.3%. A strong positive relationship between sites and *C. aquatilis* ($r=0.832$) as well as NH_3-N and sites ($r=0.702$) was observed. *C. aquatilis* was found to be associated with sites closest to the source of sewage, as was NH_3-N (e.g. Cit 13a & Cit 12a). Correlations from the correlation matrix showed a positive moderate correlation between *C. aquatilis* and NH_3-N of 0.39.

Indications of some relationships could be seen in the scatter-plot generated from the first PCA, although, no significance was found in the first run (Figure 5). The second PCA was then re-run with individual nutrient variables and *C. aquatilis* (Figure 6). I re-ran the PCA as McCune & Grace (1999) suggest that this multivariate technique is often strongly influenced by outliers in the data. NO_2^- -N, NO_3^- -N and PO_4^{3-} -P were all drawn towards outlying sites (Figure 35) which was hiding the true relationship between NH_3-N and *C. aquatilis*. A PC analysis with *C. aquatilis* and NH_3-N showed significant ($p=0.05$) correlations between the species and nutrient (Figure 36). This PC analysis showed most of the variation in the first axis at 69%. In this run relationships between sites and species were positive and high, $r=0.832$. The correlation matrix returned the same correlation (0.39), but with significance.

PCA runs with other nutrient parameters alone did not show significant correlations, although NO_2^--N was observed to have some influence, negative relationship ($r= -0.620$) although not significant ($p=0.07$). The PCA run with *C. aquatilis*, NO_3^--N and PO_4^{3-}-P also demonstrated no significant correlation.

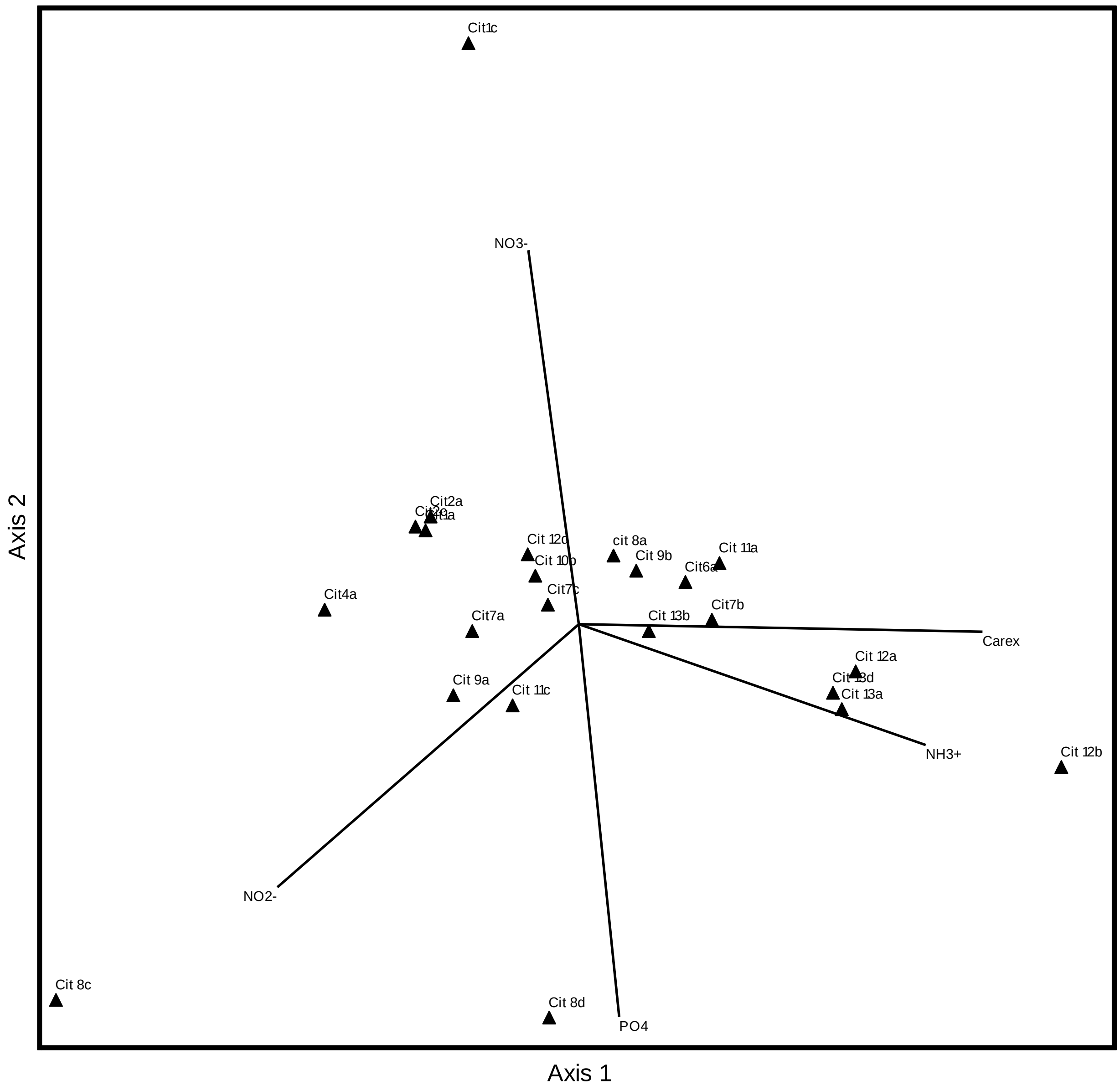

Figure 34. Principal components analysis showing *C. aquatilis* and NH_3-N association. Mineralized nutrients more distantly correlated to wetland sites with low concentration of wastewater.

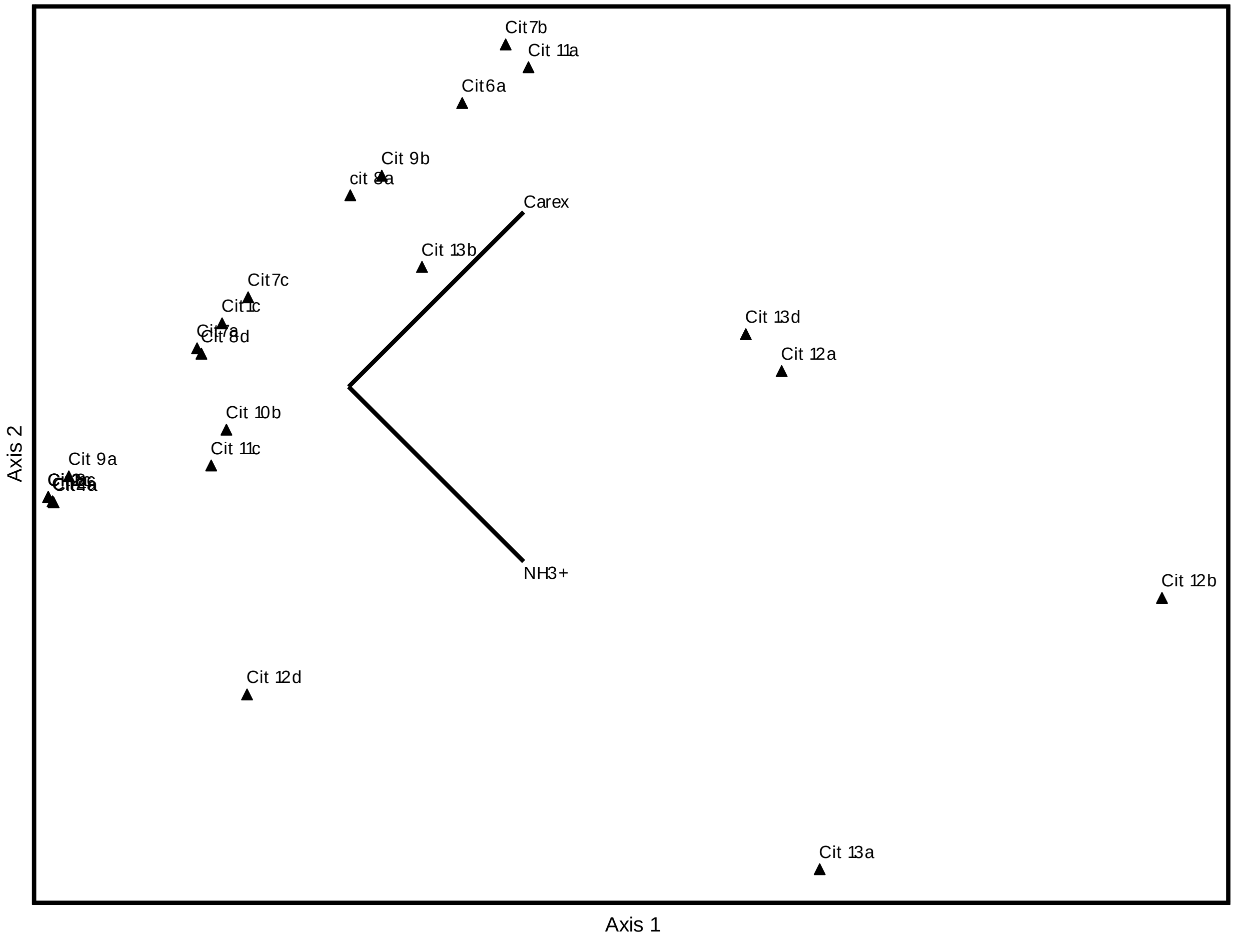

Figure 35. Optimization of NH_3-N to *C. aquatilis*, showing highest concentration and greatest cover at sites closest to source of wastewater.

DISCUSSION

Cover of *C. aquatilis* demonstrated no significant correlation between all parameters when analysed together. However, the scatter-plot and correlations showed potential relationships with *C. aquatilis* and NH_3-N with sites closest to the source of sewage. When the PC analysis was re-run with each of the other nutrient parameters singularly, no significance was found in the correlations. NO_2^- -N showed an inverse relationship although not significant (p=0.07). And, NO_3^- -N nitrate and PO_4^{3-} -P showed no relationship. As expected NO_2^- -N was found to be inversely related to sites. NO_2^- -N increased in concentration away from the sewage source, as soil oxygen would be expected to increase with increasing distance from the wastewater source, as nitrifying bacteria are often quickly outcompeted for available oxygen by heterotrophic bacteria in zones of concentrated wastewater where oxygen is limiting (Henze, 1997; Tanner & Kadlec, 2003). However, one would also assume that NO_2^- -N would remain constant as nutrient limited Arctic plants would be expected to rapidly uptake any form of available inorganic-N. This may be because in the anoxic soils, that NO_2^- -N was quickly denitrified into N_2O by facultative bacteria (Nichols, 1983), before plants could absorb it.

NO_3^--N was found to be more consistent throughout the wetland, not directly associated with sites furthest away from the sewage source, or closest to the source. In non-tundra environments one would expect NO_3^--N to increase down the wetland if sufficient oxygen was present (Nichols, 1983), as observed with NO_2^--N. However in Arctic environments, soil temperatures often inhibit full nitrification, as soil temperature indirectly influences weathering and recycling of nutrient, limiting nutrient supply (Chapin & Bloom, 1976; Edwards et al., 2006; Nadelhoffer et al., 1991).

Surprisingly, *C. aquatilis* was not found to be responding to higher PO_4^{3-}-P. Like NO_3^--N, PO_4^--P was not found to be associated with sites with low or high wastewater concentration. Previous studies on wet-sedge tundra showed they were primarily P limited (Ngai & Jefferies, 2004; Shaver & Chapin, 1995; Shaver et al., 1998), or respond to both N and P more strongly because of the general limitation of N and P across the Arctic (Gebauer et al., 1995; Gough et al., 2002). This observation was unexpected because nutrient addition studies examining natural sources of nutrients from muskoxen and snow geese found positive responses of *C. aquatilis* to both N and P (Ngai & Jefferies, 2004; Raillard, 1992). Further, much like the description of muskoxen graved tundra are akin to oases of green provided by Raillard & Svoboda (1999), wastewater treatment wetlands in the Arctic are qualitatively very similar. Murray (1991) noted high concentrations of NO_3^--N and NH_3-N in the surface water of 0.0194 mg/L and 0.0278 mg/L respectively. Whereas, I observed 56.4 mg/L and 1.0 mg/L for NH_3-N and NO_3^--N, significantly greater than Murray (1991) observed. Because of these previous observations more direct relationships were expected. One, *C. aquatilis* and NH_3-N were found to have a significant correlation *C. aquatilis* increasing in cover in areas of greater concentrations of wastewater. This observation was to be expected, given *C. aquatilis* nitrophilic nature (Aiken, 2007). However, it was expected that the correlations would have been stronger than 0.39. Therefore other factors, beyond nutrients were also influencing the cover of *C. aquatilis* throughout the wetland. Other variables of such moisture, related to microtopographic variation, soil oxygen, and temperature could also have been influencing the cover and location of *C. aquatilis* within the wetland (Shaver & Billings, 1979).

Variability in response may be a function of the relatively large range of ecotypic differentiation of *C. aquatilis* in size and phenology, respiration, photosynthesis and nutrient absorption across regions and micro habitats (Chapin & Chapin, 1981). Shaver et al. (1979) observed *C. aquatilis* in ice-wedge polygons of Barrow, Alaska finding that there were distinct differences in P-uptake by *C. aquatilis* in different microhabitats in very close proximity to each other. Ecotypic differentiation has also been noted in other Arctic species in the past as well. Teeri (1972) found that *Saxifraga oppositifolia* was ecotypically differentiated between closely located beach ridge and meadow sites. Therefore, *C. aquatilis* in the Chesterfield Inlet treatment wetland could be demonstrating ecotypic differentiation to various environmental variables presented by wastewater, which plant cover and association to concentration of nutrients may not linearly explain in a PCA. For example, *C. aquatilis* stands at influence of the wetland may be more efficient at uptake of NH_3-N explaining the strong association shown in Figure 6. Dense cover of *C. aquatilis* further away from the point of discharge of wastewater may be responding equally to available NH_3-N and NO_3^--N, or other environmental variables. Yates and Wootton's (unpublished) preliminary results of laboratory experiments on *C. aquatilis* transplanted from a discharge area in wastewater treatment wetland in Baker Lake, Nunavut demonstrates *C. aquatilis* affinity for NH_3-N. They found in an arctic summer simulated mesocosm trial, one planted with *C. aquatilis* and another control (unplanted), that the planted trial significantly removed more NH_3-N, but was no different in removal of NO_3^--N and NO_2^--N; suggesting that in this case *C. aquatilis* was selecting the first available source of inorganic-N. It has also been observed that plants, including *Carex spp*. have the greatest influence on wastewater treatment at lower temperatures (Hook et al., 2002). Again, suggesting that the role of plants in treatment wetlands in Arctic environments may be of great importance and that the tundra wetlands in the Arctic used for wastewater treatment may be naturally engineering themselves in response to anthropogenic nutrient loads.

In locations of the wetland where wastewater concentrations were high, generally anoxic, unmineralized nutrient and organic rich locations *C. aquatilis* stands were dominant. In these locations *C. aquatilis* formed near mono-culture stands particularly at the point of influence of wastewater into the treatment wetland. Whereas further away from the source of wastewater species richness increased. Indicating that overtime the most abundant species in the community had changed over the landscape in response to the addition of nutrients and likely other environmental variables altered by the presence of wastewater, such hydrologic regime. Such re-organization of vegetation communities is not unexpected. Kadlec & Bevis (2009) observed great shifts in the community at the Houghton Lake treatment wetland in Michigan, where partially treated wastewater was being discharged in a natural wetland. They observed *Typha* spp. displacing the original plant community which was likely susceptible to the new hydrologic and nutrient regime more favourable for *Typha* sp. A similar response likely occurred in the Chesterfield Inlet wetland, with *C. aquatilis* a nitrophilic and hydrophilic species becoming dominant.

As research on wastewater treatment wetlands in the Arctic is in its infancy further studies are clearly required to bring light to additional questions generated in this paper. I suggest a closer examination of physiological traits of *C. aquatilis* in response to nutrients in wastewater treatment wetlands rather than cover, such as below and above ground biomass, tissue nutrient concentration, and tillerage. Laboratory studies on different colonies of *C. aquatilis* from the same treatment wetland will also provide insight into potential ecotypic differentiation within treatment wetlands.

CONCLUSIONS

Both *C. aquatilis* and NH_3-N showed positive relationship to sites; increasing in cover and concentration towards the source of wastewater. Therefore, showing that linear relationships exists between *C. aquatilis* and NH_3-N and some to NO_2^--N, the correlations as expressed through the PC analysis were not nearly as strong as expected. Suggesting non-linear responses between *C. aquatilis* and other environmental variables were present and stronger; perhaps responding to soil moisture, temperature and or microtopographic variation. *C. aquatilis* stands were dominant at the influence of the treatment wetland, indicating shifts in community composition because of the presence of wastewater.

Further studies on physiological traits both in the field and laboratory trials may bring more light to the response specific plants and plant communities are having to the discharge of municipal wastewater. This study also draws more light on the potential importance of the plant community in the treatment of wastewater in Arctic tundra treatment wetlands and role of plants in wastewater treatment in cold climates. Also, of note is that the interpolation method used in this chapter should be reviewed, as other methods of analysis are likely more appropriate given the small sample size.

CONCLUSIONS

SUMMARY OF CONCLUSIONS

To date our understanding of tundra wetland treatment systems has been very limited. In large, performance data on wetland treatment systems in Arctic communities is non-existent because of the remote location of many of the communities, and a number of socio-economic factors which I discussed in Chapter 1. Understanding the limitation of minimal background knowledge of how tundra wastewater treatment wetland perform and function the questions asked throughout this research project were broad in scope and focused largely on exploratory studies with the intention of developing a general basis of understanding of tundra treatment wetland performance, their primary treatment mechanisms, and identifying limitations to wastewater treatment/management (because of natural and socio-economic environments). Taking advantage of the extreme environmental conditions present in the Arctic I wished to study an engineered wetland system to analyze its performance and to determine their applicability as wastewater treatment technologies for remote communities. Through the resulting analysis and interpretation I provide a series of general conclusions: First the management planning and treatment of wastewater will continue to be difficult for communities in Canada's Arctic. These challenges clearly extend beyond the extreme climate, impending unknowns resulting from climate change, and absence of long term performance data of existing systems. Socio-cultural and political differences and varying understanding of the concepts of planning between Inuit and various levels of government will have the greatest, although indirect influence on wastewater treatment in the future. This will in turn will affect the determination but mostly implementation and follow through of the new wastewater effluent performance standards for the Canadian Far North. From my analysis, interpretation of the literature and observation I recommend that the impending performance standards should take careful consideration of the diverse climate, and socio-economic environment of Arctic communities. These considerations should incorporate aspects of population, and small regional climates. Performance standards should remain adaptive, allowing for meaningful consultation between aboriginal groups and scientists to change standards as more experience and knowledge is obtained in regard to Arctic wastewater treatment.

Second, in regard to the performance of tundra treatment wetlands; tundra wetlands used to treat wastewater are an appropriate technology for Canadian Arctic communities where other technologies are not economically or technologically feasible. I observed significant ($p<0.05$) changes in concentration of key wastewater parameters, namely $cBOD_5$, TSS, NH_3–N, *E.coli* and total coliforms. Removals for $cBOD_5$ were even below regulatory standards for effluent for southern Canada in all cases during the summer. However, large lagoons or facultative lakes to store wastewater over the winter period would be an appropriate management strategy to prevent spring freshet containing large volumes of frozen wastewater. Continuous flow lagoons, which slowly decant throughout the summer months, would be most preferential. The performance analysis of the several treatment wetlands studied over the course of an Arctic summer exemplifies the ability of natural wetlands to act as sinks and transformers of nutrients, organic material and pathogens even in the very harsh climatic conditions and low biomass producing ecosystems of the Canadian Arctic. Characterisation of the wetlands worked to explain effective treatment area and potential treatment mechanisms responsible for the performance observed from the baseline studies. A number of sites were selected for additional characterization, one which was included in the baseline study, Chesterfield Inlet.

The characterisation studies conducted in Chesterfield Inlet, Paulatuk and Uluhaktuk followed with interpolative mapping further demonstrated the efficiency of the tundra wetlands to treat municipal wastewater and the important role of lagoons and facultative lakes in the treatment/management of wastewater. The Paulatuk and Uluhaktuk treatment wetlands were observed to effectively polish primary treated wastewater from the facultative lake and engineered lagoon, within the first 50-100 m of the wetland. Likewise, the Chesterfield Inlet wetland also treated minimally pre-treated wastewater during the summer, with most of the wastewater parameters dissipating to near background concentrations within a 100 m from the point of influence. In all three of these wetlands wastewater concentrations in the effluent of the wetland was observed to be similar to background concentrations measured in adjacent wetlands. Although these sites were characterised and water quality data gathered they only represented a single point in time, and assumptions were made that suggest that performance would be consistent throughout the Arctic summer, with deviations occurring in the early fall with little to no treatment occurring during the winter and early spring.

As tundra wetlands are extensively used in the Canadian Arctic, constructed wetlands have excellent potential to act as low cost technologies for Arctic communities. I studied the performance of the first experimental engineered HSSF system in the Canadian Arctic. The system demonstrated very promising results in its first year (2009) of operation despite high loading rates; observed reductions of wastewater concentrations were 25%, 31%, 52%, 99.3%, 99.3%, and 5% for $cBOD_5$, COD, TSS, *E. coli*, Total Coliforms, and TP respectively. In 2010 with a lower loading rate it was expected the system would achieve greater reductions, but this was not the case. Concentrations in the wetland effluent were observed to be greater than the effluent. Based on these observations I concluded that high organic loading prior to biofilm and plant establishment and high organic loading during the first year of study saturated the system with organics resulting in the release of solids and unmineralized nutrients into a less concentrated influent. Overall the HSSF system did not perform as expected, but did demonstrate indications as being potential technology for remote Arctic communities. However, further investigations of various other constructed wetland designs should be undertaken in the future.

Through the characterisation of the tundra wetlands I observed *Carex aquatilis* was commonly found throughout all the tundra wetlands studied. Because of its abundance in the tundra wetland in Baker Lake, it was also used to vegetate the pilot scale constructed wetland. Its prevalent occurrence led me to question whether the species was responding to increased level of nutrients in the treatment wetlands. Using spatial interpolative analysis I mapped percent composition across the Chesterfield Inlet wetland against ground water nutrient (NH_3-N, NO_2^--N, NO_3^--N and PO_4^{3-}-P) concentration gradients. Correlations were observed between concentration gradients of *C. aquatilis* and ground water using interpolative mapping. However, when a principal components analysis was employed to verify the observed relationships were not as strong as expected.

Through the PC analysis both *C. aquatilis* and NH_3-N showed positive relationship to sites; increasing in cover and concentration towards the source of wastewater. A significant ($p<0.05$) correspondence was also found between *C. aquatilis* and NH_3-N and some to NO_2^--N. NO_3^--N and PO_4^{3-}-P showed no significant relationship with *C. aquatilis*. The weaker than expected relationship between *C. aquatilis* and the nutrient parameters suggests that responses between *C. aquatilis* and other environmental variables were present and stronger; perhaps responding to soil, nutrients, soil moisture, temperature and or microtopographic variation. Further studies on physiological traits both in the field and laboratory trials may bring more light to the response specific plants and plant communities are having to the discharge of municipal wastewater. This study also draws more light on the potential importance of the plant community in the treatment of wastewater in Arctic tundra treatment wetlands and role of plants in wastewater treatment in cold climates.

DISCUSSION OF CONCLUSIONS

A significant portion of my thesis has examined the effects of tundra wetlands on water quality, and conversely, the effects of wastewater on the wetlands themselves. This includes the performance of the tundra wetlands to treat raw and pre-treated wastewater, the influence of wastewater on specific macrophytes and the ability to transfer the knowledge gained from natural systems to engineered systems in cold climate regions. Also, I have provided discussion on wastewater management in small remote communities, with specific dialogue on the process for establishing new regulatory standards for wastewater effluent in the Canadian far North.

The issues I discussed on wastewater management largely pertain to wastewater management in the Canadian Arctic; however they do reflect on similar situations in remote communities elsewhere in the world, cold and warm climate alike. Similar scenarios have been recently described by Jenssen (2011) in Greenland, which have similar demographics to the Canadian Arctic. In the mid-1990's rural communities in Estonia were also facing similar challenges with insufficient treatment facilities because of shortcomings in economic resources Tenson (1996). Denny (1997) and Kivaisi (2001) describe how constructed wetlands could have potential for developing countries, specifically those in Africa. As suggested by the previous examples the discussion of wastewater management for developing countries is prevalent in the literature, yet little attention until this point has been directed towards remote under-developed communities in the Canadian Arctic. It is important to note that many common themes run throughout all of these regions which are not dissimilar to those I described in the Canadian Arctic; these include but are not limited to low-economic capacity, absence of skilled labour, and complex socio-cultural environments. The recommendations I made for wastewater management in the Canadian Arctic contribute to knowledge development in all remote regions globally. Also a similar set of approaches which include the use of an adaptable management framework, and accounting for differences in understanding from the experts in the field (e.g. engineers and planners) designing systems to those adopting the technology (e.g. wastewater operators) in the communities could be easily adopted or tested outside the Canadian Arctic. The continued and optimized use of wetlands, particularly constructed wetlands is one avenue that could be more extensively explored in all cases.

Cold climate treatment wetlands have been identified as significant area of interest for those studying treatment wetlands in the past two decades (Vymazal, 2011). He also identified the important role which natural wetlands historically played in our understanding of wetland function for wastewater treatment. However, because of the growing knowledge of the importance of wetland function and values early in the adoption of wetlands to treat wastewater their use has largely ceased except in controlled conditions (Mander & Jenssen, 2003; Kadlec, 2009a), and in a few other locations around the world (Vymazal, 2011). The tundra wetlands in the Canadian Far North are among those still used to treat wastewater. My research on tundra wetlands has furthered both the understanding of potential performance of natural treatment wetlands as well as contributed to the knowledge base of cold climate systems. Most importantly the results presented in this thesis provide an important milestone in the investigation of wetland systems in the Far North. As the results cover an entire operational year of wetland systems in the Canadian Arctic, on not just one system, but six natural tundra systems and an experimental engineered system. To date such a comprehensive study has not been undertaken in this region. Future research on wastewater treatment in extreme cold climates, specifically with wetlands will be able to use the data presented as a basis of understanding; testing the techniques used to characterize and evaluate performance of the systems, as well as making practical management decisions on how to design and maintain treatment systems in the future.

My observations on the performance of the tundra wetlands help to validate many findings from the long-term study conducted on Houghton Lake treatment wetland. Popular thought on treatment wetlands was that they had finite life-spans, that soils would become saturated with nutrients and organics ceasing the function of the wetland to treat wastewater (Kadlec, 2009a). However, as was the case with the Houghton Lake treatment wetland, the tundra wetlands studied here have been operating for decades (e.g. Chesterfield Inlet) yet continue to achieve optimal performance despite environmental conditions which in theory would have predicted otherwise. Further, the water quality of the tundra wetlands characterized in Chapter 4 (Chesterfield Inlet, Uluhaktuk and Paulatuk) demonstrated reductions in concentration close to background levels within150 m down the wetland in all cases. My findings validate the results by Andersson et al. (2002) and Kadlec (2009b), that natural wetlands can effectively polish pre-treated wastewater, often in a much small area than was original calculated by mass balance equations. Also, my observations of sludge accumulation at the top (influence) of the tundra wetlands coincide with those of Kadlec (2009a). He found that sludge and newly created soils played an important role in storage of phosphorus, after the native soils became saturated. The rapid removal of nutrients in tundra wetlands may be explained through such a mechanism, but will need to be substantiated in the future.

Early belief was that cold climate conditions would not allow wetlands to optimally treat wastewater, and therefore treatment wetlands would not find a place in cold climate wastewater treatment (Wittgren and Maehlum, 1997). Studies from both North America and Scandinavia have largely shown that this has not been the case, and in most instances only minor impediments to treatment have been observed [see Maehlum and Stalnacke, 1999; Jenssen et al. (2005); Wallace et al. (2002)]. The performance results I observed further prove the ability of wetlands, specifically natural systems, to treat wastewater in a cold climate. But more significantly, my results demonstrate the resilience of wetlands to produce low concentration effluents following approximately nine months of frozen conditions. Although the scope of my research did not determine which mechanisms are largely responsible for tundra wetlands high efficacy, specialized bacteria and macrophytes which have evolved in the low temperature conditions of the Canadian Arctic are likely candidates. Vymazal (2011) also commented on the future importance of identifying bacteria responsible for efficient wastewater treatment in constructed wetlands.

By piloting constructed wetland technology in the Canadian Arctic, I was able to test a number of commonly made assumptions in the use of this technology in other cold climate regions. Constructed wetland design manuals suggest deeper media to be most the appropriate for cold climate regions (Wallace & Knight, 2002; Kadlec & Wallace, 2009). However, in testing a pilot HSSF system in the Canadian Arctic I hypothesized that the soil depth may have been reason for the systems' premature failure. Significant differences of soil temperature can lead to vertical stratification of water in the bed media (Kadlec & Wallace, 2009). Such differences in temperature would be expected in a permafrost zone of the Canadian Arctic, and lead to poor mineralization of organics. However, the shallow layers of the soil in the Arctic become quite warm because of high solar radiation during the summer months (Serreze & Berry, 2005). Therefore, in extreme cold climate conditions shallower bed media may be more appropriate, especially in conditions where treatment cannot be sustained during winter months. Mesocosm studies on different soil depths after prolonged freezing would address this gap in knowledge. Concurrently, first order kinetic models do not accurately predict actual performance of constructed wetland systems in Arctic environments. The current temperature coefficients have been used with effective results in cold temperate climates of the northern United States and in Canada as well as are commonly used to predict performance of systems in the Canadian Arctic by practitioners designing for natural treatment wetlands [see Kadlec & Johnson (2008) and Dillon Consulting Ltd. (2009)]. My results in Chapter 3 suggest that even changing the temperature coefficient to be appropriate for Arctic conditions is not sufficient to model actual conditions in a constructed system. Further examination of temperature data from the experimental wetland tested in this project may provide more evidence, but was not within the project's scope. Therefore, more emphasis in the cold climate wastewater treatment community will need to be placed on determining an appropriate temperature coefficient(s) for the Arctic region in the future.

Based on my observations from Chapter 5, plant species, particularly *C. aquatilis* respond to the presence of additional nutrients in the tundra and may play a significant role in the treatment process through the removal of nutrients. These observations play an important role in furthering the collective understanding of the function of plants in the treatment process of wetlands and are timely given the recent significant attention given to the subject. Particular attention has been directed towards macrophytes in constructed wetland systems (CWS) for the uptake and removal of contaminants, particularly nutrients in wastewater (Tanner, 2001). It is clear in the literature that macrophytes play an indirect role in wastewater treatment through subsurface flow constructed wetlands, by providing surface area for microbial attachment/growth, oxygen and reduced carbon supply into the rhizosphere (Brisson & Chazarenc, 2009), and direct roles of nutrient uptake (Salvato & Borin, 2010). However, the overall significance of some of these roles has been questioned. Design of horizontal subsurface flow (HSSF) wetlands suggested that macrophytes would diffuse enough oxygen into the rhizosphere for both breakdown of organic matter and nitrification of ammonia-nitrogen (NH_3-N) (Brix, 1997). However, Tanner & Kadlec (2003) found that oxygen flux from vegetation into the rhizosphere is not enough for mineralization of organics and nitrification. Also, a review by Brisson & Chazarenc (2009) highlighted the presence of significant variation in removal efficiencies by different plant species. More specifically, most macrophytic plants used in HSSF systems have been various forms of rushes, particularly *Typha sp*. and *Phragmites sp*. Although the sedge family (Cyperaceae) has been employed, very few *Carex sp.* in particular have been used in CWs (Brisson & Chazarenc, 2009). Although the more recent works by Taylor et al. (2011) and Stein et al. (2006) have demonstrated the effectiveness of sedges in treatment wetlands. Many sedge species, *Carex sp*. in particular are nitrophilic and/or hydrophilic making them excellent candidates to use in various treatment wetlands. Still more additional evidence from the observations I made during this study show positive relationships between a particular species in a non-engineered (natural) environment and that plants play more than just an indirect role in the treatment process. My results also agree with Taylor et al. (2011) findings in laboratory experiments, that *C. aquatilis* is very efficient at removing nitrogen from wastewater. Despite the growing evidence for the importance of macrophytes in treatment wetlands, more study, particularly identification of species best suited for different environments and the removal of different contaminants is still required.

Finally, tundra treatment wetlands represent some of the few living laboratories to study the effects of wetlands on water quality as the use of natural systems to treat wastewater in most developed countries do not permit such experimentation (Kadlec & Wallace, 2009; Vymazal, 2011). This study provided a comprehensive investigation of only a few of these living laboratories, although much knowledge was gained from the exercise, more questions arose as a final result. However, these questions will provide some direction to future research as well as bringing light to the current absence of knowledge. It should be anticipated that with extensive and continued study of these systems, the wastewater treatment community should observe significant implications for treatment wetland's practical usage in remote communities in the Canadian Arctic but also for understanding of cold climate wastewater treatment globally.

IMPLICATIONS OF STUDY

A consistent theme throughout this thesis has been that our current understanding of the use of treatment wetlands to treat wastewater in the Canadian Arctic is minimal. And, that any rigorous study of tundra treatment wetland systems will result in significant enhancement of our understanding wastewater treatment wetlands and their application in Arctic environments.

By employing a descriptive approach to study tundra treatment wetlands through this project, I was able to develop a strong baseline of understanding in several important areas; including seasonal performance of several tundra treatment wetlands, and a constructed system. Several wetlands were extensively characterised and mapped to show effective treatment area as well as examining plant relationship with wastewater concentration. And, finally the importance of appropriate planning practice for wastewater treatment in the remote communities of Nunavut.

Short-term Implications

Short-term implications of this research have already been seen or will emerge within the next five years. The primary short-term implication is, i) the contribution of the data gathered on wetland performance which will be used to help established new municipal wastewater effluent standards for the Canadian Far North in 2013. ii) The data I collected has assisted Hamlets to meet current water licensing requirements under the current Nunavut Water Board regulations.

Long-term Implications

Long-term implications of this research will be far reaching as knowledge development on the subject can now begin to investigate narrow questions related specific performance mechanisms as well as other specific questions. This will be achieved because, i) the data I collected throughout the project will act as background reference material for future research on treatment wetlands in the Canadian Arctic, as well as in similar systems globally. ii) I have identified a number of likely primary mechanisms in wetland wastewater treatment; these proposed mechanisms have brought forth more questions related to specific treatment process and their role. iii) In this thesis I also include the first study on an experimental HSSF constructed wetland in the Canadian Arctic; never before has a constructed wetland been tested in such extreme cold climate environment. Although the constructed wetland did not perform as well as anticipated, a number of valuable observations were made. First, confirming the rate of organic matter accumulation in soils is much more rapid because of slower mineralization rates;

which, is also directly related to the use of anaerobic technology (HSSF CWs) in a cold climate. Loading rates will have to be minimalized, again demonstrating the importance of pre-treatment for wetland systems in the Arctic. This study will be used as a frame of reference to further studies on constructed wetlands in extreme cold climate environments, particularly examining mineralization rates, and management practices for appropriate loading. iv) I found that plants may play a significant role in the treatment process of wastewater in tundra wetlands; the nitrophilic species *C. aquatilis* being of special interest. Specific studies on this species should be undertaken to examine nutrient uptake rates, and preference towards mineralized or unmineralized forms of nutrients. Finally, v) I have brought forth discussion on planning practice and regulatory procedures on wastewater treatment in the Canadian Arctic, which will help to facilitate discussion among the aboriginal community, regional and federal government on how to approach developing wastewater treatment plans in remote communities.

CONCLUDING REMARKS

Throughout this thesis I have commented numerous times on the complex nature that the management and treatment of wastewater is in the Canadian Arctic. Climate, remoteness, socio-economic and difference in understanding as a result of culture are a few of the factors that were addressed. It is in all likelihood that the complexity of this problem will not be alleviated in the future. The socio-economic environment and remoteness of many of the communities will inhibit the ability of communities to be completely self-sufficient. Further, unknown factors such as climate change and rate of population growth because of industrialization of the Arctic may cause an already complex problem to become more so. Climate change coupled with increased wastewater discharge will lead to increased risk of contamination of freshwater sources and presence of waterborne diseases in communities.

The research findings presented in this thesis have provided invaluable insight into the treatment of wastewater with wetlands in the Kivalliq Region and the Canadian Arctic as a whole. However, this research has only provided a part of the foundation towards developing an understanding of wetland wastewater treatment in this region, and because of this research numerous more questions have now arisen. Although as I stated above, I have developed an understanding of performance of the treatment wetlands, performance testing was only conducted over one summer period. Only minimal replication of summer performance sampling occurred; this was conducted on the Baker Lake treatment wetland. Long-term performance monitoring should be conducted over a series of years, as a one off season of sampling does not account for climatic variability and succession within the treatment wetland itself. Longer monitoring will also better identify optimal treatment periods from a wastewater management perspective. Unfortunately current regulatory monitoring is not conducted on a regular enough basis to provide such long term data, nor does this seem like it will change in the future either. I have also made a series of suggestions as to the possible most important treatment mechanisms for the wetlands. However, as stated earlier, these are based on scientific reason and indications based on nutrient cycling, decomposition and processes studied away from wastewater treatment in the Arctic and should be explicitly tested in the Arctic to confirm. Such things as organic matter decomposition rates in treatment wetlands will be important to determine system longevity especially in areas with increasing population growth. Also, more specific studies focusing on nutrient cycling; specifically of N and the specific role of plants in this process will also be required. As mentioned in Chapter 5, the plant species *C. aquatilis* may be specifically seeking NH_3 -N as its primary source of N. This may have significant applications for engineered wetlands in the future.

The treatment performance of Arctic wetlands in the future may be largely dictated by climate change. Direct implications would be thought to be positive, as nutrient cycling and organic matter decomposition would increase with increasing temperature. However, thawing of permafrost, and changes in precipitation among other variables may lead to increases in the presence of pathogens which could not previously survive colder temperatures.

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CONCLUDING CHAPTER

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APPENDIX A: IMAGES OF TUNDRA WETLANDS

Figure 37. Repulse Bay tundra municipal wastewater treatment wetland.

Figure 36. Whale Cove tundra municipal wastewater treatment wetland.

Figure 38. Baker Lake tundra municipal wastewater treatment wetland.

Figure 39. Chesterfield Inlet tundra municipal wastewater treatment wetland.

Figure 41. Coral Harbour tundra municipal wastewater treatment wetland.

Figure 40. Arviat tundra municipal wastewater treatment wetland.

Figure 43. Uluhaktuk tundra municipal wastewater treatment wetland.

Figure 42. Paulatuk tundra municipal wastewater treatment wetland.

APPENDIX B: ADDITIONAL RESULTS FROM BAKER LAKE BASELINE STUDIES (2009)

Table 9. Results of 2009 baseline study in Baker Lake.

	Influent				Effluent				
	Mean	Standard Deviation	Max	Min	Mean	Standard Deviation	Max	Min	% Change
$cBOD_5$ (mg/L)	435	66.5	549	368	6.60	4.43	13.9	1.98	98
COD (mg/L)	880	74.5	1020	796	16.3	9.3	25.2	3	98
TSS (mg/L)	143.6	25.2	181.0	112.0	6.3	3.9	11.0	0.0	96
NH_3-N(mg/L)	86.1	16.6	102.5	60.0	0.35	0.74	2.0	0	99
TP (mg/L)	15.1	2.0	18.3	12.4	0.12	0.04	0.16	0.04	99
TC (cfu/100ml)	217000000	81900000	343200000	93200000	1060	1721	4850	44	100
E.coli (cfu/100ml)	3680000	1970000	6400000	1200000	34	33	69	4	100
DO (mg/L)	2.1	1.4	4.3	0.3	10.8	1.1	12.5	9.6	81

APPENDIX C: BASELINE STUDY – RAW DATA

Table 10. Arviat baseline assessment raw data Part 1 of 2.

Sample	Date of Collection	Total Coliforms (cfu/100mls)	*E.coli* (cfu/100mls)	COD (mg/L)	CBOD5 (mg/L)	DO (mg/L)	TSS (mg/1 L)	POM (as %)
1	29-Jun-08	4.52E+06	6.00E+04	411	291.39	0.25	91.00	NA
2	29-Jun-08	1.30E+06	6.00E+04	328	193.39	2.98	60.00	NA
3	29-Jun-08	3.20E+01	<12	148	23.78	11.84	26.00	NA
1	7-Jul-08	8.68E+06	1.60E+05	383	96.4	0.79	377.00	NA
2	7-Jul-08	6.34E+05	5.60E+04	334	104	1.27	30.00	NA
3	7-Jul-08	4.00E+00	<4	154	24.03	8.65	74.00	NA
1	14-Jul-08	5.96E+06	6.00E+04	326	115.68	0.65	38.00	39.5
2	14-Jul-08	1.48E+06	5.60E+04	278	163.14	0.75	46.70	42.8
3	14-Jul-08	>2424	6.90E+01	124	14.51	9.33	6.00	83.3
1	21-Jul-08	1.39E+07	2.60E+05	335	144.85	1.07	70.00	25.7
2	21-Jul-08	6.78E+05	3.80E+04	305	164.79	3.87	52.00	40.4
3	21-Jul-08	>4848	1.02E+03	157	16.35	10.23	10.00	70.0
1	28-Jul-08	1.59E+07	3.20E+05	276	143.8	1.49	156.00	18.6
2	28-Jul-08	3.64E+05	1.00E+04	222	102.05	1.88	145.00	16.6
3	28-Jul-08	4.15E+03	1.61E+03	42.7	18.01	9.71	45.00	75.6
1	5-Aug-08	5.10E+06	2.20E+05	287	91.18	0.83	104.00	NA
2	5-Aug-08	1.58E+05	1.00E+04	175	70.18	0.3	72.00	NA
3	5-Aug-08	>9696	4.40E+01	53.4	6.92	8.31	0.00	NA
1	11-Aug-08	>48480000	6.60E+05	278	68.75	1.85	27.50	NA
2	11-Aug-08	1.92E+05	2.20E+04	174	94.5	1.06	55.00	NA
3	11-Aug-08	2.42E+04	4.51E+03	66.2	10.1	9.28	6.00	NA
1	18-Aug-08	1.03E+07	1.50E+05	171.8	32.53	5.94	90.00	NA
2	18-Aug-08	2.40E+05	1.30E+04	254	44.82	0.93	100.00	NA
3	18-Aug-08	5.00E+02	6.00E+01	171	24.27	4.24	37.00	NA
1	2-Sep-08	2.50E+05	<150000	140	48.83	6.57	75.00	NA
2	2-Sep-08	1.62E+06	1.87E+04	186	57	1.86	5.00	NA
3	2-Sep-08	4.69E+03	2.19E+03	61.4	7.07	9.1	0.00	NA
1	10-Sep-08	8.00E+05	<150000	256	29.7	5.3	20.00	25.0
2	10-Sep-08	1.95E+05	1.50E+04	156	33.51	2.62	6.67	30.0
3	10-Sep-08	2.80E+02	1.30E+02	54.7	10.69	9.71	1.00	0.0
1	24-Sep-08	5.00E+05	6.00E+04	251	179.52	9.34	73.33	27.3
2	24-Sep-08	1.10E+05	2.60E+04	187	104.22	3.49	40.00	7.5
3	24-Sep-08	1.03E+03	2.30E+02	71.6	15.55	10.10	5.00	0.0

Table 11. Arviat baseline assessment raw data Part 2 of 2.

Sample	Date of Collection	Nitrite (mg/L as NO2-N)	Nitrate (mg/L as N03-N)	Ammonia-N (mg/L as NH_3-N)	TKN (mg/L as N)	Phosphate (mg/L as PO4)	Total Phosphorus (mg/L as P04)	Total Phosphorus (mg/L as P)	pH	Cond. (uS)
1	29-Jun-08	0.13	0.1	58.2	NA	18.8	23.90	7.80	7.63	843
2	29-Jun-08	0.082	0.5	57.2	NA	22.2	30.50	9.95	7.45	864
3	29-Jun-08	<0.015	0.2	<0.4	NA	0.32	3.50	1.14	9.49	908
1	7-Jul-08	0.06	<0.1	59.4	NA	19.7	24.70	8.06	7.72	851
2	7-Jul-08	0.05	0.7	58.6	NA	20	23.20	7.57	7.57	953
3	7-Jul-08	0.018	1.6	4.2	NA	0.54	11.00	3.59	7.39	946
1	14-Jul-08	0.12	1.2	57	NA	19.8	22.50	7.34	7.71	870
2	14-Jul-08	0.074	0.2	53.6	NA	17.7	20.40	6.66	7.63	982
3	14-Jul-08	0.072	0.5	4.2	NA	3.56	4.43	1.45	7.5	811
1	21-Jul-08	0.05	<0.1	56	47.44	20.6	25.8	8.42	7.66	904
2	21-Jul-08	0.042	0.3	58.4	51.06	18.9	22.6	7.37	7.41	1036
3	21-Jul-08	0.026	0.2	11.7	9.00	4.6	6.9	2.25	7.12	1125
1	28-Jul-08	0.046	<0.1	53.2	61.64	18.8	37	12.07	7.67	877
2	28-Jul-08	0.072	1.5	56.4	48.62	20.6	38	12.40	7.36	1099
3	28-Jul-08	0.06	0.6	11.2	11.08	2.7	3.5	1.14	7.02	1549
1	5-Aug-08	0.052	0.8	56.4	29.44	19.2	6	1.96	7.57	869
2	5-Aug-08	0.026	0.4	65	17.34	29.1	25	8.16	7.11	1254
3	5-Aug-08	0.092	1.6	9.4	2.59	2.3	3	0.98	6.96	1269
1	11-Aug-08	0.04	1.4	58.6	67.80	17.3	22.1	7.21	7.51	836
2	11-Aug-08	0.094	0.1	65.8	54.04	16.15	19.3	6.30	7.32	1159
3	11-Aug-08	0.101	0.9	8	2.93	2.02	2.95	0.96	7.02	1349
1	18-Aug-08	0.046	<0.1	52.2	37.64	17.2	24	7.83	7.61	846
2	18-Aug-08	0.034	3	209.4	60.82	18.8	44.6	14.55	7.12	1296
3	18-Aug-08	0.028	3.6	40.4	22.24	4.65	27.5	8.97	6.63	1300
1	2-Sep-08	0.069	0.2	51.2	50.48	15.3	24	7.83	7.56	821
2	2-Sep-08	0.022	2.4	54.3	54.92	14.9	106.5	34.74	7.14	1381
3	2-Sep-08	0.045	0.4	11.5	5.68	4.08	5.2	1.70	6.8	1584
1	10-Sep-08	0.02	0.2	49.4	33.96	15.7	24	7.83	7.47	828
2	10-Sep-08	0.022	0.4	65.4	49.82	13.2	23	7.50	7.09	1398
3	10-Sep-08	0.037	1	17.1	14.55	4.08	4.85	1.58	6.54	178.3
1	24-Sep-08	<0.015	0.2	44.1	NA	14.7	17.3	5.64	7.77	836.0
2	24-Sep-08	0.054	0.4	60.6	NA	11.4	26.4	8.61	7.22	1492.0
3	24-Sep-08	0.758	2.1	3	NA	3.82	4.4	1.44	6.76	1550.0

Table 12. Baker Lake baseline assessment data Part 1 of 2.

Sample	Date of Collection	Total Coliforms (cfu/100mls)	*E.coli* (cfu/100mls)	COD (mg/L)	CBOD5 (mg/L)	DO (mg/L)	TSS (mg/1 L)	POM (as %)
1	23-Jun-08	>24240000	>24240000	1019	941.87	0.69	1775.00	40.0
2	23-Jun-08	>24240000	>24240000	670	1111.87	0.69	217.00	49.2
3	23-Jun-08	<30000	<30000	653	1152.87	0.66	133.00	47.2
4	23-Jun-08	3.60E+04	3.00E+03	69	249.13	3.71	13.00	38.5
5	23-Jun-08	1.84E+04	1.20E+03	68.3	54.12	9.52	5.00	40.0
6	23-Jun-08	6.20E+03	3.00E+02	39.4	26.3	9.09	0.00	NA
7	23-Jun-08	6.00E+01	<60	21.8	12.15	11.4	0.00	NA
8	23-Jun-08	<30	<30	33	9.88	9.6	0.00	NA
1	30-Jun-08	>121200000	6.85E+07	2920	962	0.48	980.00	NA
2	30-Jun-08	>121200000	1.28E+07	712	382.25	0.66	115.00	NA
3	30-Jun-08	>969600	>969600	286	275.77	0.72	26.00	NA
4	30-Jun-08	5.00E+02	<60	81.9	18.29	5.2	28.00	NA
5	30-Jun-08	1.17E+04	9.50E+02	175	38.97	9.95	1.00	NA
6	30-Jun-08	1.60E+02	6.00E+01	36.1	3.73	9.46	7.00	NA
7	30-Jun-08	3.70E+01	1.00E+01	22.6	3.91	11.67	6.00	NA
8	30-Jun-08	1.16E+02	<6	36.8	2.16	8.8	4.00	NA
1	7-Jul-08	1.70E+08	1.06E+07	750	262.75	0.7	120.00	NA
2	7-Jul-08	2.42E+08	4.60E+06	750	260.63	0.63	97.00	NA
3	7-Jul-08	1.21E+08	3.25E+06	466	234	0.52	36.00	NA
4	7-Jul-08	8.08E+04	3.40E+03	65.6	4.84	9.23	13.00	NA
5	7-Jul-08	3.80E+02	6.00E+01	82.7	6.05	9.84	28.00	NA
6	7-Jul-08	1.04E+02	<6	25.3	3.73	9.38	6.00	NA
7	7-Jul-08	>3232	5.70E+01	18	2.39	10.04	4.00	NA
8	7-Jul-08	2.26E+02	<3	11.5	0	9.17	2.00	NA
1a	14-Jul-08	>484800000	5.60E+06	730	483.5	0.39	360.00	NA
1b	14-Jul-08	3.39E+08	1.52E+07	744	364.35	0.87	138.10	NA
2	14-Jul-08	2.74E+08	1.30E+07	678	451	0.74	57.50	27.8
3	14-Jul-08	1.04E+08	1.60E+06	528	319.68	0.68	46.00	34.8
4	14-Jul-08	1.71E+04	1.60E+03	80.8	16.85	6.97	8.00	100.0
5	14-Jul-08	5.20E+01	1.20E+01	70.3	19.6	9.07	20.00	75.0
6	14-Jul-08	2.10E+01	4.00E+00	61.5	8.45	9.04	22.00	77.3
7	14-Jul-08	1.60E+01	<6	22.3	3.76	9.6	2.00	100.0
8	14-Jul-08	2.42E+03	5.20E+01	20.8	5.43	9.39	7.00	28.6
1	21-Jul-08	4.85E+08	5.60E+06	1058	377.88	1.01	36.70	46.3
2	21-Jul-08	>484800000	4.40E+06	932	616.8	0.75	36.00	47.2

3	21-Jul-08	2.42E+08	2.50E+06	516	285.48	0.75	22.50	75.6
4	21-Jul-08	>242400	3.30E+03	175	19	6.9	21.25	103.5
5	21-Jul-08	2.20E+02	<6	48.7	8.27	9.4	5.00	NA
6	21-Jul-08	2.12E+02	2.20E+01	71.2	7.96	9.4	5.00	NA
7	21-Jul-08	>3232	2.51E+02	34.3	8.11	9.91	3.00	NA
8	21-Jul-08	1.25E+03	<4	109	6.81	9.66	3.00	NA
1	28-Jul-08	4.85E+08	1.38E+07	494	433.5	1.05	180.00	10.0
2	28-Jul-08	3.39E+08	8.60E+06	386	469.5	0.85	277.00	12.3
3	28-Jul-08	1.39E+08	6.00E+06	268	220.14	1.02	64.00	23.4
4	28-Jul-08	2.80E+05	1.10E+04	118	16.18	7.7	24.00	54.2
5	28-Jul-08	1.80E+04	1.12E+02	34.5	14.16	8.9	111.00	38.7
6	28-Jul-08	>4848	1.60E+01	27.1	5.15	9.84	12.00	41.7
7	28-Jul-08	1.72E+03	<6	<3	8.03	10.7	5.00	80.0
8	28-Jul-08	>3232	4.00E+00	33.4	17	8.59	13.00	92.3
1	5-Aug-08	5.48E+08	1.56E+07	366	392.38	0.19	56.00	NA
2	5-Aug-08	>484800000	1.24E+07	534	381.13	0.13	70.00	NA
3	5-Aug-08	>484800000	7.20E+06	>7500	816.5	0.11	1000.00	NA
4	5-Aug-08	9.50E+03	1.50E+03	67.2	14.52	8.81	40.00	NA
5	5-Aug-08	1.05E+05	<1200	69.5	8.7	10.35	3.00	NA
6	5-Aug-08	>12120	<15	30.5	5.81	9.43	0.00	NA
7	5-Aug-08	6.06E+03	2.00E+01	118	8.49	10.5	0.00	NA
8	5-Aug-08	4.85E+03	<6	14.8	8.61	6.95	0.00	NA
1	11-Aug-08	3.32E+07	8.80E+06	423	245.63	0.37	63.00	NA
2	11-Aug-08	9.70E+08	1.56E+07	414	327.75	0.31	55.00	NA
3	11-Aug-08	9.04E+07	3.20E+06	362	185.25	0.31	22.00	NA
4	11-Aug-08	1.30E+04	<1000	62.7	8.25	6.86	0.00	NA
5	11-Aug-08	8.77E+04	<1000	42.8	5.03	5.83	1.00	NA
6	11-Aug-08	1.17E+04	<30	27.9	3.74	8.72	2.00	NA
7	11-Aug-08	>9696	<12	15	2.34	9.06	0.00	NA
8	11-Aug-08	1.32E+02	<12	17.8	6.69	6.37	4.00	NA
1	18-Aug-08	1.61E+08	3.20E+06	402	346.25	0.61	587.00	NA
2	18-Aug-08	2.96E+08	1.20E+07	310	333.13	0.68	105.00	NA
3	18-Aug-08	6.24E+07	2.00E+06	278	131.38	1.3	756.00	NA
4	18-Aug-08	2.12E+04	2.20E+03	47.8	0.83	7.39	6.00	NA
5	18-Aug-08	8.00E+03	<857	46.4	6.7	8.71	5.00	NA
6	18-Aug-08	5.78E+03	1.60E+02	21.2	1.76	8.57	31.00	NA
7	18-Aug-08	8.70E+02	<30	14.1	2.75	9.73	26.00	NA
8	18-Aug-08	3.16E+02	2.00E+01	11.2	2.61	6.36	0.00	NA
1	25-Aug-08	2.78E+08	1.72E+07	430	396.63	0.75	90.00	NA
2	25-Aug-08	2.62E+08	5.20E+06	555	429.25	0.27	1.00	NA
3	25-Aug-08	>969600000	2.62E+08	332	195.63	0.8	3.00	NA

4	25-Aug-08	4.12E+04	2.60E+03	54.6	22.81	6.85	1.00	NA
5	25-Aug-08	1.44E+04	1.00E+03	13.88	10.64	10.79	1.00	NA
6	25-Aug-08	1.24E+03	1.00E+02	30.1	10.6	10.13	3.00	NA
7	25-Aug-08	1.65E+03	1.01E+03	14.8	8.99	9.97	3.00	NA
8	25-Aug-08	8.00E+02	1.70E+01	1.43	5.5	8.55	1.00	NA
1	2-Sep-08	9.70E+08	4.40E+06	476	368.5	0.71	13.33	NA
2	2-Sep-08	2.78E+08	3.20E+06	418	448.75	0.65	53.33	NA
3	2-Sep-08	1.36E+08	5.20E+06	219	132.63	0.77	60.00	NA
4	2-Sep-08	9.80E+03	1.60E+03	27.4	7.95	10.24	3.00	NA
5	2-Sep-08	4.40E+03	6.00E+02	23	7.16	10.54	1.00	NA
6	2-Sep-08	1.30E+03	1.00E+02	13.6	7.26	10.66	0.00	NA
7	2-Sep-08	9.40E+02	3.30E+01	11.9	6.45	10.61	7.00	NA
8	2-Sep-08	4.70E+02	<10	8.57	2.31	11.47	1.00	NA
1	10-Sep-08	1.27E+08	1.44E+07	614	426	0.77	7.00	85.7
2	10-Sep-08	2.48E+08	1.56E+07	562	400.13	0.9	15.00	86.7
3	10-Sep-08	6.04E+07	3.20E+06	369	301.13	1.19	117.78	3.4
4	10-Sep-08	<600	<600	14.7	14.98	7.79	2.00	100.0
5	10-Sep-08	7.90E+03	8.00E+02	15.9	13.64	11.69	0.00	0.0
6	10-Sep-08	1.00E+02	<60	3	9.4	11.76	5.00	100.0
7	10-Sep-08	7.30E+01	<20	14.7	8.65	10.91	31.11	64.3
8	10-Sep-08	1.70E+01	<10	4.21	3.53	11.2	0.00	0.0
1	24-Sep-08	2.48E+08	1.20E+07	677	535.78	0.99	32.86	51.7
2	24-Sep-08	9.88E+07	4.40E+06	590	422.53	0.78	31.25	67.2
3	24-Sep-08	9.32E+07	2.00E+06	405	302.16	0.93	21.25	65.9
4	24-Sep-08	2.42E+05	1.88E+04	25	17.12	10.71	5.00	60.0
5	24-Sep-08	6.54E+04	3.00E+03	24	14.22	10.18	5.00	40.0
6	24-Sep-08	1.10E+02	<30	18.1	5.97	11.81	90.00	8.9
7	24-Sep-08	8.77E+02	3.67E+01	14.3	2.02	11.87	9.00	0.0
8	24-Sep-08	4.80E+02	<6	9.88	2.9	9.84	7.00	14.3

Table 13. Raw data for Baker Lake baseline study in 2008.

Sample	Date of Collection	Nitrite (mg/L as NO2-N)	Nitrate (mg/L as N03-N)	Ammonia-N (mg/L as NH_3-N)	TKN (mg/L as N)	Phosphate (mg/L as PO4)	Total Phosphorus (mg/L as P04)	Total Phosphorus (mg/L as P)	pH	Cond. (uS)
1	23-Jun-08	0.078	<0.1	84	NA	33.2	44.40	14.49	7.38	1163
2	23-Jun-08	0.084	<0.1	81.2	NA	28.4	36.80	12.01	7.36	1171
3	23-Jun-08	0.06	0.1	87.6	NA	24.6	29.50	9.62	7.31	2028
4	23-Jun-08	0.016	0.1	4.5	NA	2.9	4.00	1.30	6.8	192.7
5	23-Jun-08	0.038	0.3	5.4	NA	2.5	3.07	1.00	7.2	176.4
6	23-Jun-08	0.031	0.9	4.9	NA	2.12	2.43	0.79	7.13	172.9
7	23-Jun-08	<0.015	0.2	0.42	NA	0.05	0.22	0.07	7.27	63.1
8	23-Jun-08	<0.015	1.3	<0.02	NA	0.03	0.09	0.03	7.31	191.9
1	30-Jun-08	<0.015	1.5	81	NA	37.8	78.80	25.71	7.3	1122
2	30-Jun-08	0.052	<0.1	76.2	NA	28	35.2	11.48	7.37	1141
3	30-Jun-08	0.09	0.2	51	NA	16.6	18	5.87	7.36	967
4	30-Jun-08	0.015	0.3	4.1	NA	2.94	4.5	1.47	6.69	179.4
5	30-Jun-08	0.043	<0.1	4.9	NA	1.58	3.075	1.00	7.8	180
6	30-Jun-08	<0.015	0.2	<0.02	NA	0.04	0.125	0.04	7.25	97.5
7	30-Jun-08	<0.015	0.2	0.03	NA	0.05	0.19	0.06	7.48	63.2
8	30-Jun-08	0.186	1	<0.02	NA	0.04	0.15	0.05	7.22	191.6
1	7-Jul-08	0.208	0.4	82.8	NA	29.8	35.8	11.68	7.71	1155
2	7-Jul-08	0.03	0.6	82.6	NA	29.2	34.6	11.29	7.7	1164
3	7-Jul-08	0.04	<0.1	60.2	NA	18.4	23.6	7.70	7.54	981
4	7-Jul-08	0.099	<0.1	5	NA	2.05	3.6	1.17	7.59	160
5	7-Jul-08	0.15	0.7	2.3	NA	1.9	3.05	1.00	8.79	156
6	7-Jul-08	<0.015	0.1	<0.02	NA	0.02	0.163	0.05	7.4	115.9
7	7-Jul-08	<0.015	0.1	0.02	NA	0.07	0.288	0.09	8	63.2
8	7-Jul-08	<0.015	0.5	<0.02	NA	0.01	0.088	0.03	7.56	244
1a	14-Jul-08	0.216	1.2	72.8	NA	29	46	15.01	7.98	1125
1b	14-Jul-08	0.252	1.2	69.4	NA	27.4	37.4	12.20	7.81	1082
2	14-Jul-08	0.102	1.4	76.4	NA	27.6	33.8	11.03	7.67	1142
3	14-Jul-08	0.048	1	65.8	NA	25	30	9.79	7.81	1084
4	14-Jul-08	0.368	0.9	3.4	NA	2.25	3.3	1.08	7.32	154.2
5	14-Jul-08	0.09	0.4	0.6	NA	3.02	3.8	1.24	8.9	146.2
6	14-Jul-08	0.093	1.2	0.25	NA	3.14	4.09	1.33	7.3	143.4
7	14-Jul-08	<0.015	<0.1	0.05	NA	0.05	0.4	0.13	7.89	61.9
8	14-Jul-08	<0.015	0.2	0.11	NA	0.13	0.313	0.10	7.35	67
1	21-Jul-08	0.108	0.2	72.8	161.76	29.4	35	11.42	7.49	1196
2	21-Jul-08	0.064	1.4	72	208.00	29.8	38.6	12.59	7.46	1180

3	21-Jul-08	0.076	0.7	66.8	5.22	22	30	9.79	7.64	1140
4	21-Jul-08	0.36	0.4	3.5	8.76	3.15	4.5	1.47	7.11	181.2
5	21-Jul-08	0.143	0.5	1.4	0.23	3.8	4.5	1.47	7.34	166.3
6	21-Jul-08	0.091	1.4	0.39	4.17	3.4	6	1.96	7.16	157.3
7	21-Jul-08	0.043	1	1.33	37.85	0.04	0.39	0.13	7.6	123.5
8	21-Jul-08	<0.015	<0.1	0.03	NA	0.08	0.57	0.19	7.4	242
1	28-Jul-08	0.088	<0.1	77.2	113.56	27	42	13.70	7.39	1183
2	28-Jul-08	0.108	<0.1	81.8	123.04	27.4	43	14.03	7.37	1205
3	28-Jul-08	0.072	0.2	59	45.42	20.1	43	14.03	7.5	1071
4	28-Jul-08	0.515	0.7	4.2	12.46	2.73	8.5	2.77	7.08	205.6
5	28-Jul-08	0.354	1.3	1.72	8.89	4	11.4	3.72	7.1	181.4
6	28-Jul-08	0.114	2	0.53	5.36	2.28	NA	0.00	7.14	159.5
7	28-Jul-08	<0.015	0.4	0.21	6.12	0.02	1.65	0.54	7.43	66.8
8	28-Jul-08	<0.015	0.1	0.22	0.95	0.1	0.55	0.18	7.24	299
1	5-Aug-08	0.076	0.2	67.4	152.16	26.5	43	14.03	7.4	1141
2	5-Aug-08	0.058	0.2	74.4	150.20	26	50	16.31	7.28	1230
3	5-Aug-08	0.168	<0.1	105.4	NA	43.4	201	65.57	6.78	1493
4	5-Aug-08	0.122	0.1	8.5	11.10	4.05	11	3.59	7.05	258
5	5-Aug-08	0.221	0.2	1.27	69.95	2.25	20.3	6.62	6.97	178.8
6	5-Aug-08	0.087	1.5	0.16	0.20	1.66	2.55	0.83	7.16	166.9
7	5-Aug-08	0.015	2.8	2.2	14.11	0.02	1.25	0.41	7.53	99.5
8	5-Aug-08	<0.015	0.1	0.04	10.19	0.03	0.85	0.28	7.27	343
1	11-Aug-08	0.046	1.2	73.4	151.24	25.9	34	11.09	6.35	1154
2	11-Aug-08	0.03	0.6	82.4	112.24	25.4	38	12.40	7.27	1168
3	11-Aug-08	0.038	1	63.6	7.58	19.8	30.5	9.95	7.38	1087
4	11-Aug-08	0.066	0.3	9.1	1.58	5.57	11	3.59	7.1	316
5	11-Aug-08	0.157	0.5	1.4	9.73	1.13	10.9	3.56	6.72	201.1
6	11-Aug-08	0.043	1.4	0.11	38.25	1.12	2.25	0.73	7.05	182.6
7	11-Aug-08	<0.015	<0.1	<0.02	44.67	0.02	0.55	0.18	7.36	65.5
8	11-Aug-08	<0.015	<0.1	<0.02	NA	0.04	0.35	0.11	7.16	335
1	18-Aug-08	0.046	0.2	133.2	180.08	31.2	40.5	13.21	7.22	1215
2	18-Aug-08	0.062	0.4	93	224.88	29.6	38	12.40	7.28	1233
3	18-Aug-08	0.016	1.1	53.7	96.44	20.4	57	18.60	6.98	828
4	18-Aug-08	0.125	0.2	7.92	14.48	3.7	10	3.26	6.98	260.7
5	18-Aug-08	0.124	1.3	2.32	1.83	1.3	3.3	1.08	6.91	233.3
6	18-Aug-08	0.1	0.8	2.92	2.43	1.06	1.8	0.59	6.89	211.5
7	18-Aug-08	0.025	0.8	1.34	0.64	0.05	0.65	0.21	6.97	107.2
8	18-Aug-08	<0.015	0.6	0.04	5.33	0.02	0.55	0.18	7.21	311
1	25-Aug-08	0.038	0.3	81.8	202.60	29.2	38.5	12.56	7.27	1278
2	25-Aug-08	0.034	0.3	83.6	170.84	29.4	45	14.68	7.23	1261
3	25-Aug-08	0.042	0.2	66.8	94.08	19.1	28	9.13	7.45	1046

4	25-Aug-08	0.242	1	4.8	83.44	1.9	7	2.28	6.83	161.7
5	25-Aug-08	0.125	0.8	1.76	6.24	1	2.3	0.75	7.31	177.1
6	25-Aug-08	0.053	2.3	0.2	8.99	0.7	3.4	1.11	6.65	166.4
7	25-Aug-08	0.087	4.1	4.4	2.99	0.07	0.55	0.18	6.8	131.2
8	25-Aug-08	<0.015	0.5	<0.02	16.79	0.07	0.6	0.20	7.2	251.1
1	2-Sep-08	0.045	0.2	86.2	230.36	28.9	39.5	12.89	7.22	1271
2	2-Sep-08	0.073	0.2	80.8	23.08	27.2	35.5	11.58	7.22	1295
3	2-Sep-08	<0.015	0.4	54	4.00	16.7	24.5	7.99	7.28	947
4	2-Sep-08	0.028	0.2	0.8	6.64	0.42	5.5	1.79	6.6	71.8
5	2-Sep-08	0.046	0.5	0.58	3.59	0.34	1.9	0.62	6.92	104.9
6	2-Sep-08	0.027	0.7	0.23	5.72	0.32	1.05	0.34	6.89	103.1
7	2-Sep-08	<0.015	0.2	0.03	31.13	0	0.55	0.18	6.84	76.9
8	2-Sep-08	<0.015	0.5	0.18	33.40	0.08	0.55	0.18	7.19	77.1
1	10-Sep-08	0.045	0.2	84.8	135.08	30.9	45.5	14.84	7.38	1657
2	10-Sep-08	0.057	0.4	91.8	175.00	29.5	37	12.07	7.26	1658
3	10-Sep-08	0.047	0.2	71	59.70	21	33	10.77	7.33	1408
4	10-Sep-08	0.016	0.4	1.4	1.84	0.42	7.5	2.45	5.97	164.6
5	10-Sep-08	0.029	0.7	0.39	0.47	0.32	1.6	0.52	7.09	114.6
6	10-Sep-08	<0.015	0.9	0.04	0.21	0.3	1	0.33	7.01	113.1
7	10-Sep-08	<0.015	0.1	<0.02	6.47	0.04	0.75	0.24	7.02	74.7
8	10-Sep-08	<0.015	1.1	<0.02	42.09	0.02	0.6	0.20	7.34	315
1	24-Sep-08	0.042	1.4	78.4	126.96	27.3	41.2	13.44	7.25	1487.0
2	24-Sep-08	0.042	0.2	79.4	55.24	26.2	31.2	10.18	7.21	1549.0
3	24-Sep-08	0.032	0.2	63.8	2.00	19.7	24.5	7.99	7.25	1319.0
4	24-Sep-08	0.032	0.3	1.5	1.86	0.64	1.9	0.62	6.73	159.0
5	24-Sep-08	0.041	0.8	0.77	3.08	0.34	1.5	0.49	6.78	141.2
6	24-Sep-08	<0.015	0.1	<0.02	0.27	0.06	3	0.98	7.31	100.6
7	24-Sep-08	<0.015	0.2	0.03	0.00	0.05	1.3	0.42	7.27	74.1
8	24-Sep-08	<0.015	2.9	<0.02	2.52	0.05	2.9	0.95	7.30	338.0

Table 14. Chesterfield Inlet baseline study raw data Part 1 of 2.

Sample	Date of Collection	Total Coliforms (cfu/100mls)	*E.coli* (cfu/100mls)	COD (mg/L)	CBOD5 (mg/L)	DO (mg/L)	TSS (mg/1 L)	POM (as %)
1	25-Jun-08	8.48E+07	7.80E+05	359	348.13	0.38	75	NA
2	25-Jun-08	3.80E+03	6.00E+02	97	7.71	10.93	50	NA
1	30-Jun-08	5.59E+07	5.00E+05	318	281	0.7	70	NA
2	30-Jun-08	1.60E+02	6.00E+01	138	19.91	11.07	17	NA
1	7-Jul-08	1.51E+07	3.00E+05	383	137.8	4.16	140	NA
2	7-Jul-08	5.71E+02	<9	114	10.94	10.15	NA	NA
1	14-Jul-08	1.21E+08	1.40E+06	569	358.68	1.15	86.7	18.45
2	14-Jul-08	7.20E+01	<6	NA	44.08	9.2	NA	17.84
1	23-Jul-08	1.36E+07	5.00E+05	357	130	0.15	46.7	23.55
2	did not take sample-dry	NA	NA	NA	NA	NA	NA	NA
1	28-Jul-08	8.48E+07	6.50E+05	362	308.94	2.1	100	20.00
2	28-Jul-08	1.10E+01	<3	67.2	14.49	11.43	9	22.22
1*	5-Aug-08	NA	NA	250	NA	NA	70	NA
2*	5-Aug-08	NA	NA	51.2	NA	NA	0	NA
	11-Aug-08			*did not sample week of August 11				
1	18-Aug-08	>242400000	9.40E+06	396	379.86	0.61	102.5	NA
2	18-Aug-08	2.08E+03	3.80E+01	26.2	5.27	11.32	1	NA
1	25-Aug-08	2.20E+06	6.00E+05	139	70.53	3.36	23.3	NA
2	25-Aug-08	5.60E+01	1.00E+01	32	11.41	11.29	13	NA
1	2-Sep-08	3.00E+05	<300000	99.4	74.58	3.72	15	NA
2	2-Sep-08	3.20E+01	2.60E+01	39.9	6.3	10.97	1	NA
1	10-Sep-08	7.76E+06	8.60E+05	211	189.55	1.45	17.5	22.86
2	10-Sep-08	7.20E+01	4.30E+01	41.5	5.96	11.26	2	0.00
1	24-Sep-08	6.00E+05	6.00E+04	154	155.27	1.39	152.5	1.31
2	24-Sep-08	8.58E+02	7.60E+01	35.8	12.72	12.02	0	0.00

Table 15. Chesterfield Inlet baseline study raw data Part 2 of 2.

Sample	Date of Collection	Nitrite (mg/L as NO2-N)	Nitrate (mg/L as NO3-N)	Ammonia-N (mg/L as NH_3-N)	TKN (mg/L as N)	Phosphate (mg/L as PO4)	Total Phosphorus (mg/L as P)	pH	Cond. (uS)
1	25-Jun-08	0.033	0.8	35.3	NA	11.3	5.01	7	613
2	25-Jun-08	<0.015	0.8	0.2	NA	0.02	0.11	8.13	261
1	30-Jun-08	0.044	0.7	43.7	NA	12.4	4.86	7.3	749
2	30-Jun-08	<0.015	<0.1	0.01	NA	0.04	0.27	7.72	265
1	7-Jul-08	0.05	<0.1	43.2	NA	11.7	6.52	7.64	826
2	7-Jul-08	<0.015	<0.1	<0.02	NA	<0.02	0.20	7.83	273
1	14-Jul-08	0.048	0.1	37.3	NA	11.9	6.98	7.65	890
2	14-Jul-08	<0.015	<0.1	0.09	NA	<0.02	0.49	8.33	526
1	23-Jul-08	0.076	<0.1	42.8	NA	12.8	5.90	7.4	961
2	did not take sample-dry	NA	NA	NA	NA	NA	NA	NA	NA
1	28-Jul-08	0.046	<0.1	38.6	43.20	13	9.13	7.51	957
2	28-Jul-08	<0.015	3.4	<0.4	2.97	1.6	0.80	8.75	276
1	5-Aug-08	NA	0.1	NA	30.82	12.8	7.34	NA	NA
2	5-Aug-08	NA	0.1	NA	1.63	2	0.86	NA	NA
	11-Aug-08	No data collected this week							
1	18-Aug-08	0.062	0.1	90.4	14.60	58.6	5.06	7.47	1371
2	18-Aug-08	<0.015	<0.1	<0.02	1.12	0.2	0.05	7.06	263.5
1	25-Aug-08	0.038	0.2	25.8	19.32	7.2	5.06	7.4	640
2	25-Aug-08	<0.015	0.1	0.02	1.21	1.3	0.62	8.03	198.9
1	2-Sep-08	0.035	1.8	23.6	22.12	6	3.91	6.98	674
2	2-Sep-08	<0.015	0.1	<0.02	2.94	1.04	0.60	7.61	269.2
1	10-Sep-08	0.029	0.2	27.6	27.38	6.2	4.73	7.04	719
2	10-Sep-08	<0.015	0.1	<0.02	0.45	1.14	0.60	7.39	281.3
1	24-Sep-08	0.152	0.2	27.2	23.64	6.4	3.23	7.28	685.0
2	24-Sep-08	<0.015	0.1	0.05	2.93	0.66	0.29	7.56	282.1

Table 16. Coral Harbour baseline study raw data part 1 of 2.

Sample	Date of Collection	Total Coliforms (cfu/100mls)	E.coli (cfu/100mls)	COD (mg/L)	CBOD5 (mg/L)	DO (mg/L)	TSS (mg/1 L)	POM (as %)
1	20-Jun-08	2.42E+07	1.30E+05	449	NA	2.47	46	43.5
2	20-Jun-08	7.94E+04	5.00E+02	123	NA	10.07	19	36.8
1	23-Jun-08	2.74E+07	1.00E+05	310	649.2	0.59	49.1	44.4
2	23-Jun-08	2.00E+03	<1200	114	53.92	10.98	46	23.9
1	30-Jun-08	9.50E+05	<150000	314	275	0.68	50	NA
2	30-Jun-08	9.80E+02	6.00E+01	173	22.19	9.79	19	NA
1	7-Jul-08	NA	NA	738	227.5	4.19	560	NA
2	7-Jul-08	1.65E+02	<15	198	8.32	9.61	23	NA
1	14-Jul-08	8.00E+04	<15000	569	246.78	5.77	125	31.2
2	14-Jul-08	>3232	>3232	75.7	7.76	9.18	20	45.0
1	21-Jul-08	2.60E+04	<6000	304	215.88	5.91	63	15.9
2	21-Jul-08	1.04E+02	3.80E+01	112	7.65	9.93	26.36	34.1
1	28-Jul-08	3.60E+04	3.00E+03	433	361.9	0.8	160	18.7
2	28-Jul-08	4.80E+01	1.50E+01	44.6	12.67	9.42	691	37.9
1	7-Aug-08	1.21E+06	1.65E+04	250	104.88	1.98	75	NA
2	7-Aug-08	4.34E+02	1.51E+02	26.2	10.15	10.77	2	NA
1	11-Aug-08	4.40E+04	<6000	240	83	0.57	58	NA
2	11-Aug-08	1.28E+02	2.10E+01	39.2	12.43	9.65	2	NA
1	18-Aug-08	3.56E+05	<2000	147	33.18	1.65	58	NA
2	18-Aug-08	2.10E+01	4.00E+00	19	7.36	10.6	14	NA
1	25-Aug-08	2.87E+04	2.00E+03	244	85.98	1.3	10	NA
2	25-Aug-08	5.90E+01	1.90E+01	25.6	9.02	10.85	27.5	NA
1	2-Sep-08	9.50E+03	<1500	173	47.4	7.31	6	NA
2	2-Sep-08	1.46E+02	1.10E+01	10.1	5.8	11.19	0	NA
1	10-Sep-08	2.38E+04	6.00E+02	195	62.46	11.86	18	27.8
2	10-Sep-08	3.00E+01	<3	11	4.58	12.39	1	0.0
1	24-Sep-08	2.08E+05	4.40E+03	209	62.34	6.70	28	50.0
2	24-Sep-08	6.20E+01	1.90E+01	11.5	6.32	11.97	6	0.0

Table 17. Coral Harbour baseline study raw data Part 2 of 2.

Sample	Date of Collection	Nitrite (mg/L as NO2-N)	Nitrate (mg/L as N03-N)	Ammonia-N (mg/L as NH3-N)	TKN (mg/L as N)	Phosphate (mg/L as PO4)	Total Phosphorus (mg/L as P)	pH	Cond. (uS)
1	20-Jun-08	0.066	5	40	NA	14.1	5.71	7.33	721
2	20-Jun-08	0.112	2.2	16	NA	4.7	2.02	8.39	583
1	23-Jun-08	0.043	<0.1	41	NA	13	5.66	7.37	720
2	23-Jun-08	0.187	0.8	14	NA	4.33	1.78	8.28	604
1	30-Jun-08	0.03	0.8	32	NA	10.9	4.94	7.53	708
2	30-Jun-08	0.054	<0.1	0.4	NA	4.6	2.18	8.82	555
1	7-Jul-08	0.836	0.4	6.1	NA	5.6	6.59	9.43	640
2	7-Jul-08	0.033	<0.1	0.59	NA	2.31	1.61	9.34	579
1	14-Jul-08	0.12	0.6	3.7	NA	3	3.30	8.99	719
2	14-Jul-08	<0.015	<0.1	0.12	NA	0.04	0.12	8.27	437
1	21-Jul-08	0.41	<0.1	14.5	11.86	5.9	2.84	7.93	869
2	21-Jul-08	<0.015	<0.1	0.05	2.98	<0.02	0.11	8.42	531
1	28-Jul-08	0.064	3.6	15.4	49.54	15.6	12.72	7.18	986
2	28-Jul-08	<0.015	<0.1	0.18	6.75	0.2	0.16	8.2	688
1	7-Aug-08	0.052	<0.1	17.2	17.48	6.6	4.57	7.51	969
2	7-Aug-08	<0.015	0.3	0.09	NA	0.3	0.16	7	625
1	11-Aug-08	0.023	<0.1	24.3	35.48	10.6	5.71	7.33	1051
2	11-Aug-08	<0.015	<0.1	0.08	2.09	0.04	0.11	8.33	634
1	18-Aug-08	0.046	<0.1	29.64	15.88	8.2	4.40	7.33	946
2	18-Aug-08	<0.015	0.1	0.261	0.48	<0.02	0.20	8.1	531
1	25-Aug-08	0.034	0.3	21.4	22.76	8.9	5.38	7.49	822
2	25-Aug-08	<0.015	0.1	<0.02	2.62	0.03	0.21	8.22	455
1	2-Sep-08	0.051	<0.1	11.1	14.10	5.4	3.75	8.34	790
2	2-Sep-08	<0.015	0.1	0.12	2.51	0.48	0.26	7.98	192.7
1	10-Sep-08	0.049	0.2	10	14.20	5.4	4.08	8.69	818
2	10-Sep-08	<0.015	0.2	2.06	NA	0.04	0.16	7.73	594
1	24-Sep-08	0.058	<0.1	13.5	13.54	4.1	2.02	7.55	737.0
2	24-Sep-08	<0.015	0.1	<0.02	3.17	0.08	0.39	7.75	487.0

Table 18. Repulse Bay baseline study raw data Part 1 of 2.

Sample	Date of Collection	Total Coliforms (cfu/100mls)	E.coli (cfu/100mls)	COD (mg/L)	CBOD5 (mg/L)	DO (mg/L)	TSS (mg/1 L)	POM (as %)
1	7/4/2008	>121200000	6600000	596	536.44	0.17	146	NA
2	7/4/2008	10600	800	137	77.58	9.94	84	NA
1	7/7/2008	2.42E+08	6900000	580	1021.9	0.96	64	NA
2	7/7/2008	NA	NA	87.1	18.45	10.36	33	NA
1	7/14/2008	1600000	<300000	571	164.48	6.02	660	5.6
2	7/14/2008	32	<12	102	13.64	9.5	22.4	58.0
1	7/21/2008	>48480000	5420000	653	420.48	0.42	920	7.8
2	7/21/2008	22	<6	171	22.42	7.32	44	52.3
1	7/28/2008	>121200000	7050000	262	247.88	1.02	96	43.7
2	7/28/2008	177	5	71	30.01	6.93	35	65.7
1	8/11/2008	65400000	7600000	174	219	0.74	13	NA
2	8/11/2008	>2424	3	41.2	17	8.69	16	NA
1	8/18/2008	>242400000	53400000	250	276.12	0.74	0	NA
2	8/18/2008	32	20	52.1	34.41	9.66	0	NA
1	8/25/2008	2.35E+08	3200000	330	423.73	1.1	12.5	NA
2	8/25/2008	>4848	700	27.4	11.81	11.66	81	NA
1	9/2/2008	>484800000	22000000	542	235	0.89	22.5	NA
2	9/2/2008	876	76	19.6	12.68	10.68	1	0.0
1	9/10/2008	6.78E+08	20800000	467	338.63	0.99	6	16.7
2	9/10/2008	112	<12	18.9	18.89	11.19	17.5	0.0
1	9/24/2008	98800000	22000000	524	355.13	0.95	34	17.6
2	9/24/2008	236	<12	54	21.49	15.69	9	44.4

Table 19. Repulse Bay baseline study raw data Part 2 of 2.

Sample	Date of Collection	Nitrite (mg/L as NO2-N)	Nitrate (mg/L as N03-N)	Ammonia-N (mg/L as NH3-N)	TKN (mg/L as N)	Phosphate (mg/L as PO4)	Total Phosphorus (mg/L as P)	pH	Cond. (uS)
1	7/4/2008	0.072	<0.1	80.4	NA	23.1	9.9	7.63	1117
2	7/4/2008	0.13	<0.1	4.2	NA	3.15	2.4	10.22	262
1	7/7/2008	0.06	<0.1	62.2	NA	20.4	8.4	7.69	1036
2	7/7/2008	0.144	0.1	3.5	NA	3.46	1.7	9.86	268
1	7/14/2008	0.062	<0.1	3.2	NA	4.6	3.8	7.68	740
2	7/14/2008	0.17	0.3	0.9	NA	3.38	1.6	9.62	281
1	7/21/2008	0.04	<0.1	87.6	4.18	28.6	11.4	7.9	1301
2	7/21/2008	0.04	<0.1	0.09	NA	2.32	1.3	9.98	291
1	7/28/2008	0.05	<0.1	69	41.82	19.1	10.8	7.74	1449
2	7/28/2008	0.023	<0.1	0.86	15	2.76	1.9	9.74	306
1	8/11/2008	0.024	0.2	34.1	NA	6.5	6.0	7.45	1068
2	8/11/2008	0.121	0.4	1.2	NA	0.74	0.9	9.1	398
1	8/18/2008	0.058	<0.1	142.8	33	24.7	9.4	8.05	1218
2	8/18/2008	0.116	0.2	0.21	7.63	0.26	0.7	9.56	415
1	8/25/2008	0.046	0.2	73.2	77.7	24.6	11.4	7.8	1087
2	8/25/2008	0.062	0.3	2.96	8.6	0.57	0.5	8.08	350
1	9/2/2008	0.04	<0.1	84.6	74.42	26.4	11.4	7.62	1189
2	9/2/2008	0.063	0.3	3.7	5.8	0.58	0.5	7.88	445
1	9/10/2008	0.04	0.1	67	17.12	21.1	10.1	7.5	1175
2	9/10/2008	0.077	0.3	3.8	NA	0.52	3.4	8.26	486
1	9/24/2008	1.36	0.4	70.4	65.62	22.5	8.4	7.53	1081
2	9/24/2008	0.072	0.9	3.12	9.04	0.18	0.1	9.24	441

Table 20. Whale Cove baseline study raw data Part 1 of 2.

Sample	Date of Collection	Total Coliforms (cfu/100mls)	E.coli (cfu/100mls)	COD (mg/L)	CBOD5 (mg/L)	DO (mg/L)	TSS (mg/1 L)	POM (as %)
1	6/27/2008	>242400	31700	191	805.8	11.57	44	NA
2	6/27/2008	69400	12700	187	271.15	12.28	87	NA
3	6/27/2008	25	<15	28.6	174.13	10.87	13	NA
1	7/2/2008	>2424000	2424000	206	121.6	5.75	123	NA
2	7/2/2008	28000	2500	199	44.98	7.87	88	NA
3	7/2/2008	65	11	22.4	8	10.17	4	NA
1	7/7/2008	4520000	660000	178	29.93	7.7	70	NA
2	7/7/2008	>242400	35000	169	26.05	8.15	67	NA
3	7/7/2008	13	<3	28.5	3.03	10.27	28	NA
1	7/14/2008	1880000	80000	121	31.77	9.31	22.9	21.83406
2	7/14/2008	>484800	5000	121	15.79	9.68	17.6	79.54545
3	7/14/2008	46	13	35	4.83	10.4	3	33.33333
1	7/21/2008	690000	<30000	146	77.16	9.72	16.25	86.15385
2	7/21/2008	187600	3200	142	16.24	10.03	52.9	49.14934
3	7/21/2008	62	5	61.2	7.03	10.21	126	38.09524
1	7/28/2008	450000	40000	104	54.09	7.9	14	64.28571
2	7/28/2008	293500	12500	101	16.08	8.99	12	50
3	7/28/2008	694	52	13.7	5.66	10.48	1	100
1	8/7/2008	NA	NA	NA	19.62	NA	0	NA
2	8/7/2008	NA	NA	NA	6.96	NA	0	NA
3	8/7/2008	NA	NA	NA	3.22	NA	0	NA
1	8/13/2008	52000	22000	97.3	21.29	9.49	27.5	NA
2	8/13/2008	9600	3000	95.8	15.89	10.12	9	NA
3	8/13/2008	52	13	55	8.35	10.99	12	NA
1	8/21/2008	173600	14400	113	16.92	11.08	11	NA
2	8/21/2008	121200	3250	103	17.86	11.05	2	NA
3	8/21/2008	510	52	30.9	8.69	11.94	16	NA
1	8/25/2008	6500	1500	117	13.37	9.78	2	NA
2	8/25/2008	1300	300	118	13.73	10.31	11.25	NA
3	8/25/2008	92	22	18	7.88	11.13	2	NA
1	9/2/2008	15600	3200	118	12.45	9.92	2	50
2	9/2/2008	3640	1240	121	13.88	10.18	0	0
3	9/2/2008	240	19	16.1	11.01	10.95	0	0
1	9/10/2008	2000	1200	110	9.63	10.26	5	100
2	9/10/2008	>48480	7240	116	14.94	10.38	2	100
3	9/10/2008	280	102	18.2	9.57	11.82	6	100

1	9/24/2008	106800	15200	124	29.31	10.98	9	33.33333
2	9/24/2008	28000	5200	127	17.58	10.99	4	75
3	9/24/2008	375	123	146	8.32	11.46	5	60

Table 21. Whale Cove baseline study raw data Part 2 of 2.

Sample	Date of Collection	Nitrite (mg/L as NO2-N)	Nitrate (mg/L as N03-N)	Ammonia-N (mg/L as NH3-N)	TKN (mg/L as N)	Phosphate (mg/L as PO4)	Total Phosphorus (mg/L as P)	pH	Cond. (uS)
1	6/27/2008	0.19	<0.1	12.2	NA	9.3	3.931202	9.07	626
2	6/27/2008	0.214	<0.1	11.4	NA	9.05	3.865954	9.22	613
3	6/27/2008	<0.015	0.3	0.02	NA	0.04	0.032624	7.72	474
1	7/2/2008	0.234	<0.1	9.3	NA	9.2	3.980138	9.09	615
2	7/2/2008	0.282	0.1	7.8	NA	8.75	3.425529	9.32	593
3	7/2/2008	<0.015	0.1	<0.02	NA	0.03	0.069489	7.49	502
1	7/7/2008	0.294	<0.1	6.7	NA	9.7	3.882266	8.88	616
2	7/7/2008	0.35	0.2	5.7	NA	9.25	3.637586	7.75	534
3	7/7/2008	<0.015	<0.1	<0.02	NA	0.02	0.08156	7.62	531
1	7/14/2008	0.18	0.3	7.9	NA	10.5	3.490777	7.92	656
2	7/14/2008	0.19	0.3	7.3	NA	10.35	3.653898	8.03	648
3	7/14/2008	<0.015	0.1	0.02	NA	0.02	0.048936	7.51	575
1	7/21/2008	0.302	0.2	4.7	23.5	9.8	3.686522	8.97	631
2	7/21/2008	0.352	0.5	4.2	8.4	9.3	3.458153	9.12	624
3	7/21/2008	<0.015	<0.1	<0.02	NA	<0.02	0.143546	7.9	602
1	7/28/2008	0.254	0.4	3.9	80	10	4.078011	7.89	616
2	7/28/2008	0.257	0.4	3.8	1.32	10.5	3.425529	7.93	614
3	7/28/2008	<0.015	0.1	0.02	NA	0.06	0.097872	7.85	478
1	8/7/2008	NA	NA	NA	NA	10.7	NA	NA	NA
2	8/7/2008	NA	NA	NA	NA	10.8	NA	NA	NA
3	8/7/2008	NA	NA	NA	NA	0.02	NA	NA	NA
1	8/13/2008	0.056	0.2	8.2	78	10.9	4.730492	7.39	645
2	8/13/2008	0.071	0.2	7.8	5.997	11.1	5.382974	7.61	651
3	8/13/2008	<0.015	0.1	<0.02	1.054	0.04	0.179432	7.97	520
1	8/21/2008	0.047	<0.1	8.6	NA	17.7	0.260993	7.47	649
2	8/21/2008	0.058	0.1	9.8	NA	13.65	1.304963	7.55	669
3	8/21/2008	<0.015	<0.1	<0.02	NA	0.2	0.260993	7.74	546
1	8/25/2008	0.039	0.2	11.7	11.24	12.35	6.198576	7.47	614
2	8/25/2008	0.031	0.2	11.6	7.89	12.2	6.851058	7.52	618
3	8/25/2008	<0.015	0.1	<0.02	3.636	0.03	0.179432	7.64	322
1	9/2/2008	0.067	0.3	12.3	27.72	12.8	4.763117	7.54	691
2	9/2/2008	0.076	<0.1	12.2	3.77	13	4.828365	7.52	684

3	9/2/2008	<0.015	<0.1	0.02	0.388	0.06	0.195745	7.84	429
1	9/10/2008	0.091	0.2	35.6	88.16	12.8	4.991485	7.53	734
2	9/10/2008	0.093	0.2	13.5	5.9	13.1	4.926237	7.54	728
3	9/10/2008	<0.015	0.1	<0.02	6.082	0.02	0.195745	7.71	548
1	9/24/2008	0.229	1.8	12.2	NA	12.7	4.763117	7.83	707
2	9/24/2008	0.235	1.6	12.4	NA	12.9	4.567372	7.74	708
3	9/24/2008	<0.015	0.2	<0.02	NA	0.12	0.032624	8.04	619