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Performance assessment of arctic tundra municipal wastewater treatment wetlands through an arctic summer

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ABSTRACT

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 onto the tundra. In this study we provide the first season long study of tundra wetland systems in the Canadian Arctic. In 2008, we studied the performance of six wetland systems used for wastewater treatment in the Kivalliq Region of Nunavut, Canada. The wetland systems studied services communities of approximately 320–2300 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. We observed average weekly percent reduction in all parameters, with deviations immediately after snow-melt and at the beginning of freeze-up. For the six parameters monitored we observed reductions of 47–94% $cBOD_5$, 57–96% COD, 39–98% TSS, >99% TC, >99% *E. coli*, 84–99% NH_3-N and 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 systems to act as sinks and transformers, acknowledging that mechanistic assessments will be required to identify primary processes involved in the treatment of Arctic wastewater.

1. 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 and Duhaime, 1998; Ritter, 2007). Many communities in Nunavut use the tundra to treat wastewater either continuously discharging from detention lagoons or facultative lakes (Wootton et al., 2008; Yates et al., 2010).

Tundra treatment systems 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. As a result they are often referred to as treatment wetlands in the minimal extant literature and in regulatory documents (see Nunavut Water Board, 2008, 2009a,b, 2010a,b,c; Kadlec and Johnson, 2008). For the purpose of this study we refer to the treatment systems as wetlands, which is consistent with the terminology used by the regulatory bodies in Arctic Canada.

The wetland's pre-treatment counterparts, facultative lakes, are natural lakes or ponds where wastewater is directly discharged into for preliminary and primary treatment. These systems act similar to engineered facultative lagoons, which are also common throughout the Canadian Arctic (Johnson and 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

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common and preferred approach in the Canadian Arctic because the high capital investment, operation costs, and the requirement of a specialized labor 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 and Jenssen, 2002; Kadlec and 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 and 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 and 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 less stringently 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 3 years, whereas a 5 year research period was granted for the northern territories (Northwest Territories, Nunavut, Yukon and regions above the 54th 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, natural wetland treatment systems in Nunavut have not been extensively monitored until this study. Our objective 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; comment on the potential mechanisms responsible for treating wastewater in these heterogeneous Arctic systems. This study will help determine whether the current systems can remove wastewater contaminants to proposed regulatory standards for Canadian municipal wastewater. Our study is also the first season long monitoring initiative of Arctic tundra wastewater treatment wetlands.

2. Materials and methods

2.1. Site descriptions

Six natural treatment wetlands were studied in the Kivalliq Region of the Nunavut Territory, Canada. We studied systems in the Hamlets of Arviat, Baker Lake, Chesterfield Inlet, Coral Harbour, Repulse Bay and Whale Cove (Fig. 1).

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 and Whale Cove), while others received wastewater directly or with minimal pretreatment (Baker Lake, Chesterfield Inlet and Repulse Bay). All of the systems we studied were heterogeneous landscapes, with various amounts of dilution because of surface water, percent cover of different plant communities. 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 h for analysis.

2.1.1. 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 2318 (Statistics Canada, 2010). 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 of wastewater is by the community's 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. Approximately 235 m^3/day is discharged into the lagoon. Wastewater continuously exfiltrates from the lagoon berm flows into the adjacent wetland; actual loading rate of the wetland is not known. 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 78 000 m^2 (Fig. 2).

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 1.0 m 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.

2.1.2. Baker Lake 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. In 2010 the population was recorded as 1872 (Statistics Canada, 2010). The mean

Fig. 1. Map of Canada showing location of communities studied (Map Credit: Noreen Goodliff).

January temperature is −32.3 °C and the mean July temperature is 11.4 °C, with an average annual temperature of −11.8 °C. The annual rainfall is 156.7 mm while the annual snowfall is 130 cm (Environment Canada, 2010).

During the study period the community discharged 167 m^3/day of wastewater into a small detention pond (~60 m^2). Wastewater continuously overtopped or exfiltrated through the berm walls of the detention pond and into the adjacent wetland system. The treatment wetland of this community is a sub-basin of a larger watershed draining into Baker Lake. Wastewater flows through a series of ponds and small lakes connected via surface flow wetlands. Following the complex of ponds and sedge wetlands, wastewater flows in a distinct stream channel before discharging into a final large lake. Gravels from glacial till are dominant through portions of the wetland (soil depth is 0.12–0.30 m). Large mats of settled solids from the influent cover the area outside the holding cell (Fig. 3).

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 throughout the wetland. 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* becomes prevalent at the bottom of the system.

2.1.3. Chesterfield Inlet (Igluligaarjuk) Treatment Wetland (63°20′N, 90°42′W)

The Hamlet of Chesterfield Inlet (63°N, 90°W) is located in the Kivalliq Region of Nunavut, Canada. The treatment wetland in this community services approximately 313 residents (Statistics Canada, 2010). The average annual temperature is −11 °C, and mean summer temperature of 9.4 °C (Environment Canada, 2010).

The wetland is located in a shallow depression in the landscape, with an approximate area of 50 000 m^2 and a length of 720 m, with a minimum width of 58 m and a maximum width of 225 m 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 wastewater before it enters the wetland. Treated wastewater discharges into Hudson Bay's Chesterfield Inlet (Fig. 4).

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.

2.1.4. 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 834 (Statistics Canada, 2010).

The climate of Coral Harbour has a mean January temperature is −30 °C, mean July temperature is 9.3 °C (Environment Canada, 2010). Annual rainfall is 155.2 mm, annual snowfall is 133.5 cm (Environment Canada, 2010).

Sewage is collected by the community'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

Fig. 2. Aerial photograph and outline of Arviat lagoons and treatment wetland. General flow direction is depicted by blue arrows. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

Fig. 4. Aerial photograph and outline of the Chesterfield Inlet wetland and the depression where wastewater was discharged during the time of study. Blue arrows depict the direction of wastewater flow through the wetland. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

width ranges from 100 to 160 m, on very gradual slope (<1%). It is estimated that 95 m^3/day is discharged into the lagoon; actual discharge into the wetland is unknown given uncontrolled continuous subsurface exfiltration of the lagoon into the wetland (Fig. 5).

The Coral Harbour treatment wetland was located on a sand-silt plain. Very little organic soils are present throughout the site. 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.

Fig. 3. Aerial photograph and outline of Baker Lake holding cell and treatment wetland. Flow of wastewater is depicted by blue arrows. The extent of surface water can be observed. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

Fig. 5. Aerial photograph and outline of Coral Harbour's facultative ponds and treatment wetland. General flow direction is depicted by blue arrows. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

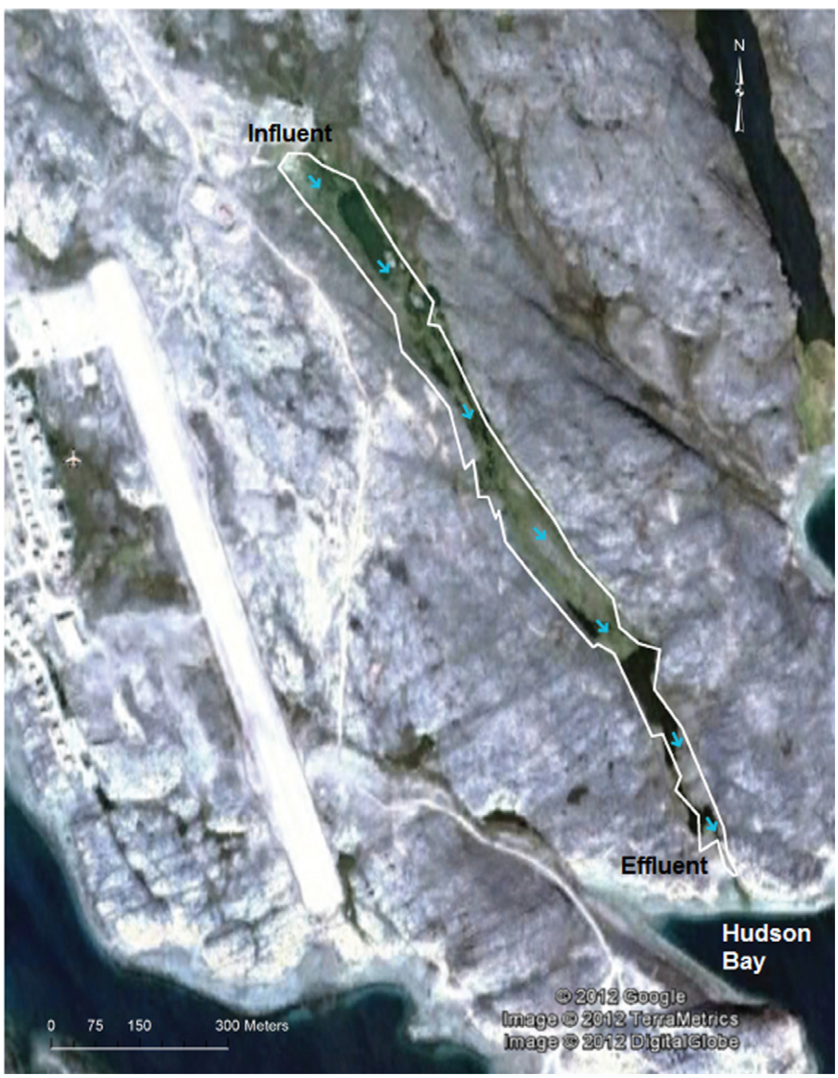

Fig. 6. Aerial photograph and outline of the Repulse Bay wetland and the depression where wastewater is discharged. Blue arrows depict the direction of wastewater flow through the wetland. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

2.1.5. 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 945 (Statistics Canada, 2010). 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 community's sewage trucks. The sewage dumpsite is located 1 km from 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 and 90 m, with a total wetland area of 95 000 m^2, and a slope of approximately 2%. It is estimated based on the community discharges approximately 60 m^3/day of wastewater is discharged into the wetland. No lagoon currently exists at the site. Wastewater is discharged into a shallow natural depression (Fig. 6).

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.

2.1.6. Whale Cove Treatment Wetland (62°11′N, 92°35′W)

Whale Cove is located on the western shores of Hudson Bay. Its population has a population of 407 (Statistics Canada, 2010). Climate normals are not maintained for this community. Its closest neighbor community where weather data is maintained is Rankin Inlet, which has a yearly average temperature of −11 °C (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. It is estimated based on the community's water use that approximately 28 m^3/day of wastewater is discharged into the facultative lake. The effluent continuously discharges into a tundra wetland before discharging into Hudson Bay (Fig. 7).

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 to 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. 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. 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 point of discharge. 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. *Carex aquatilis*,

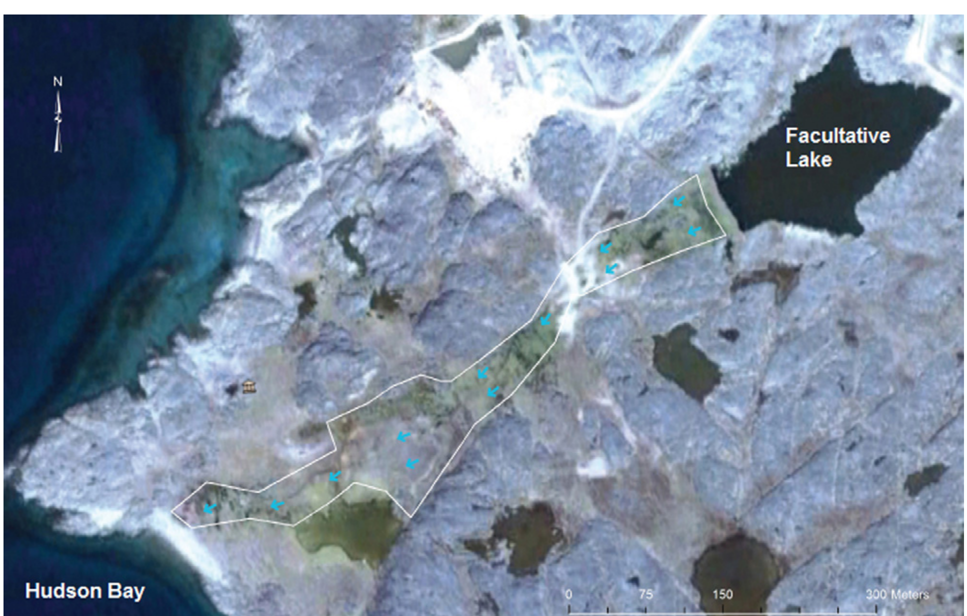

Fig. 7. Aerial photograph and outline of Whale Cove's facultative lake and treatment wetland. General flow direction is depicted by blue arrows. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

Table 1
Mean influent and effluent data, with percent concentration change from six tundra treatment wetlands studied in Nunavut.

Arviat

Volume discharged (235 m^3/day)	Influent concentration				Effluent concentration				% Change	*t*-Test (paired) *n* = 11
	Mean	Standard Deviation	Max	Min	Mean	Standard Deviation	Max	Min		
$cBOD_5$ (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 (cfu/100 ml)	29 500	18 600	60 000	10 000	898	1350	4510	4	97	0.000
TC (cfu/100 ml)	633 000	543 000	162 000	110 000	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. (°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				% Change	*t*-Test (paired) *n* = 13
	Mean	Standard deviation	Max	Min	Mean	Standard deviation	Max	Min		
$cBOD_5$ (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 (cfu/100 ml)	16 400 000	1 670 000	68 500 000	3 200 000	14	14	52	3	>99	0.002
TC (cfu/100 ml)	306 000 00	262 000 00	96 900 000	2 420 000	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. (°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				Effluent concentration				% Change	*t*-Test (paired) *n* = 12
	Mean	Standard deviation	Max	Min	Mean	Standard deviation	Max	Min		
$cBOD_5$ (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 (cfu/100 ml)	1 390 000	2 670 000	9 400 000	60 000	87	182	600	3	>99	0.064
TC (cfu/100 ml)	57 100 000	74 500 000	242 400 000	300 000	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. (°C)	6.6	2.7	16.3	0.5	6.2	2.9	13	0.5	–	–

Table 1 (*Continued*)

Coral Harbour

Discharge volume (96 m^3/day)	Influent concentration				Effluent concentration				% Change	*t*-Test (paired) *n* = 14
	Mean	Standard deviation	Max	Min	Mean	Standard deviation	Max	Min		
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 (cfu/100 ml)	37 000	55 600	150 000	600	168	339	1200	3	100	0.029
TC (cfu/100 ml)	4 950 000	9 860 000	27 400 000	9500	6960	21 800	79 400	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. (°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				Effluent concentration				% Change	*t*-Test (paired) *n* = 11
	Mean	Standard deviation	Max	Min	Mean	Standard deviation	Max	Min		
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 (cfu/100 ml)	14 100 000	15 100 000	53 400 000	300 000	165	310	800	3	100	0.008
TC (cfu/100 ml)	2 130 000 000	204 000 000	678 000 000	1 600 000	1940	3420	10 600	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. (°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				Effluent concentration				% Change	*t*-Test (paired) *n* = 13
	Mean	Standard deviation	Max	Min	Mean	Standard deviation	Max	Min		
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 (cfu/100 ml)	7590	9500	35 000	300	36	39	123	3	100	0.009
TC (cfu/100 ml)	126 000	149 000	484 800	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. (°C)	8.2	6.6	24.9	0.5	10.7	6.1	22.2	0.3	–	–

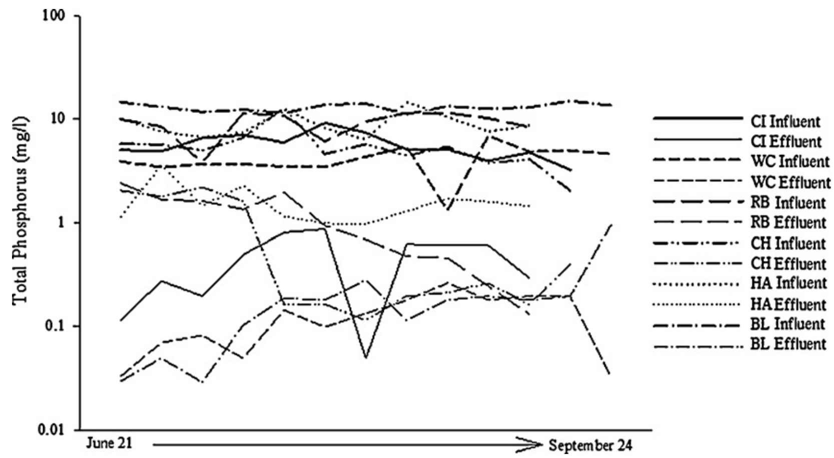

Fig. 8. Time series comparison of total phosphorus influent and effluent concentrations of the six treatment wetland studied.

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.

2.2. Data collection

We collected weekly samples from six treatment wetlands between June 21st and September 24th, 2008 which approximates the historical ice-free period of the year (9–12 weeks); June 10–15 to September 5–20 (Maxwell, 1981). Samples were transported in coolers to a laboratory in Rankin Inlet and analyzed within 24 h of collection for time sensitive analysis of parameter (e.g. $cBOD_5$, and pathogens) following Standard Methods for Wastewater.

At each of the six wetlands we obtained samples (500 mL each) from the point of 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 (Government of Canada, 2010). Other sampled parameters include dissolved oxygen, total coliforms, *Escherichia coli*, total phosphorus and chemical oxygen demand. Temperature was recorded continuously over the ice-free period, with Onset Temperature logging tidbits situated in the surface water of the influent and effluent streams; obtaining readings at 0.5 h intervals.

Sampling at the influent and effluent is considered the minimum required sampling for wastewater treatment facilities (Kadlec and 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 24-h 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.

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

We used a paired *t*-test ($p < 0.05$) 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 was collected in 2009 for Baker Lake only.

3. Results

Raw wastewater was directly discharged into the wetlands or lagoons via tanker trucks. We 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

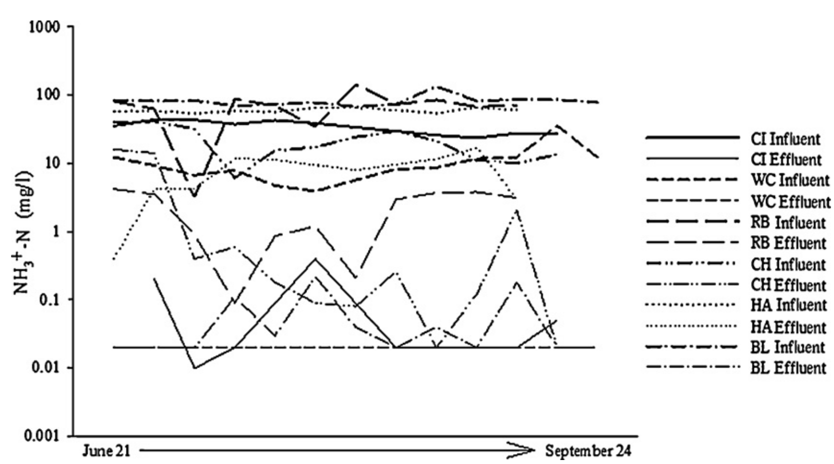

Fig. 9. Time series comparison of NH_3-N influent and effluent concentrations of the six treatment wetland studied.

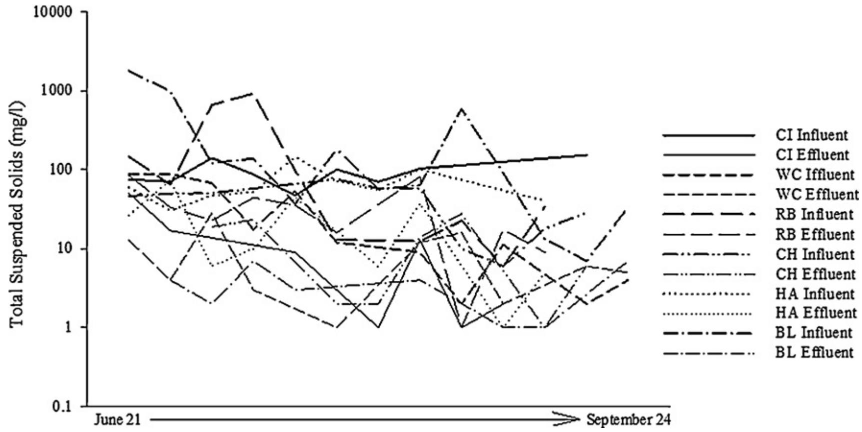

Fig. 10. Time series comparison of TSS influent and effluent concentrations of the six treatment wetland studied.

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 1).

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 (Figs. 8 and 9). TSS was especially variable (Fig. 10). In systems where wastewater was diluted in stream and small water bodies, TSS reductions 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 (Figs. 11 and 12). In cases where percent removal was low for COD and $cBOD_5$, actual concentration of influent into the wetland was low, due to pretreatment 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 continually discharging into the adjacent wetland and Coral Harbour 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 (Fig. 11).

Natural background concentrations of parameters were also observed from an adjacent, discrete reference wetland (Table 2). 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. However, it is important to note that Baker Lake tundra wetland is composed of a series of small ponds connected by surface water flow paths which dilute the wastewater entering the system. Systems with more surface water flow also obtained high levels of dissolved oxygen; although all achieved concentrations of greater than 8 mg/L on average in the effluent (Fig. 13).

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 (Figs. 14 and 15). Other studies have also reported high background concentrations of pathogens and other

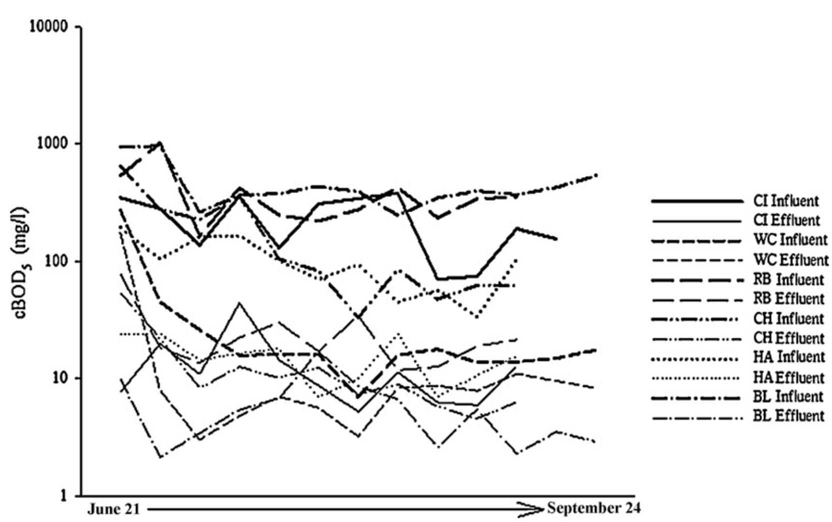

Fig. 11. Time series comparison of $cBOD_5$ influent and effluent concentrations of the six treatment wetland studied.

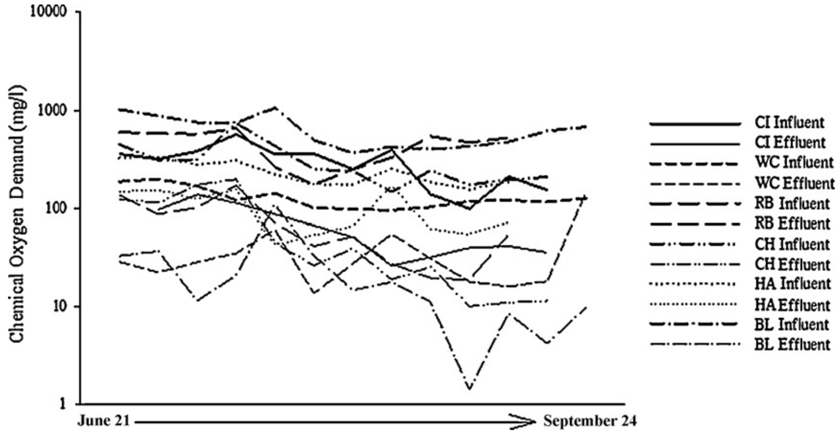

Fig. 12. Time series comparison of COD influent and effluent concentrations of the six treatment wetland studied.

Table 2
A comparison between reference water quality values for adjacent nearby natural wetlands and treatment wetland effluent.

Parameters	Wetland											
	Arviat		Baker Lake		Chesterfield Inlet		Coral Harbour		Repulse Bay		Whale Cove	
	Background	Effluent	Background	Effluent	Background	Effluent	Background	Effluent	Background	Effluent	Background	Effluent
$cBOD_5$ (mg/L)	6	16	2	6	3	14	4	14	24	25	0	21
COD (mg/L)	31.8	100	66.6	24	14.5	64.3	30.5	66.3	91	64.4	21	39.5
TSS (mg/L)	6	19.1	2	3.2	3	10.3	103	10.5	0	34.8	0.3	18
TP (mg/L)	0.15	2.3	0.07	0.2	0.02	0.4	ND	0.08	0.2	1.4	0.18	0.1
NH_3-N (mg/L)	0.14	11	0.18	0.1	0.08	0.1	0	2.8	0.012	2.8	0.02	0
E. coli (cfu/100 mL)	40	898	6	14	20	87	6	168	80	165	6	36
TC (cfu/100 ml)	615	4720	44	1100	1360	771	10	6960	12 100	1940	56	205
DO (mg/L)	11.2	9.1	9.6	8.9	10.8	11	9.9	10.6	10.9	10.1	6.6	10.9

parameters due to waterfowl (Kadlec and 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 of the communities.

4. Discussion

As aforementioned in the introduction and site descriptions, the systems studied were all physiographically distinct, with varying cover and composition of vegetation communities, presence of surface water and treatment area. It was not our intention to determine with great certainty which mechanisms are most significant in treating wastewater in the Arctic, but to draw light on the performance and potential treatment mechanisms for the parameters we addressed in these remote systems. In the following discussion we elaborate on the potential mechanisms at work in Arctic treatment wetlands acknowledging the heterogeneity of the systems.

We are yet to clearly understand 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, we suggest how wastewater treatment may be influenced

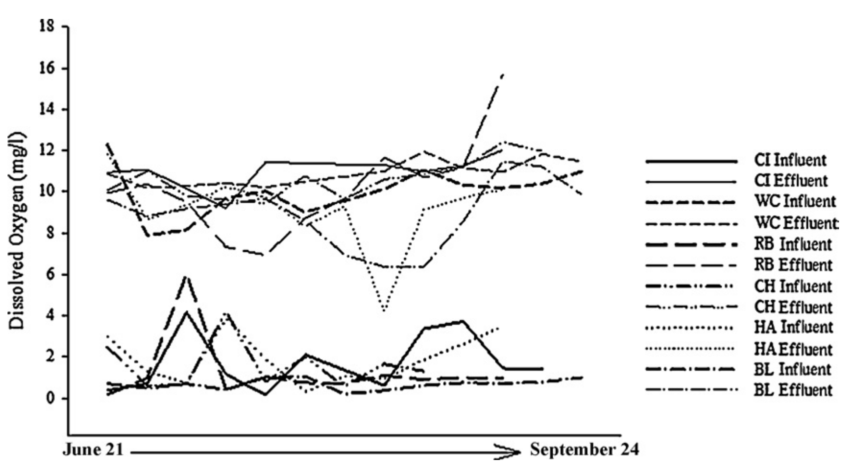

Fig. 13. Time series comparison of DO influent and effluent concentrations of the six treatment wetland studied.

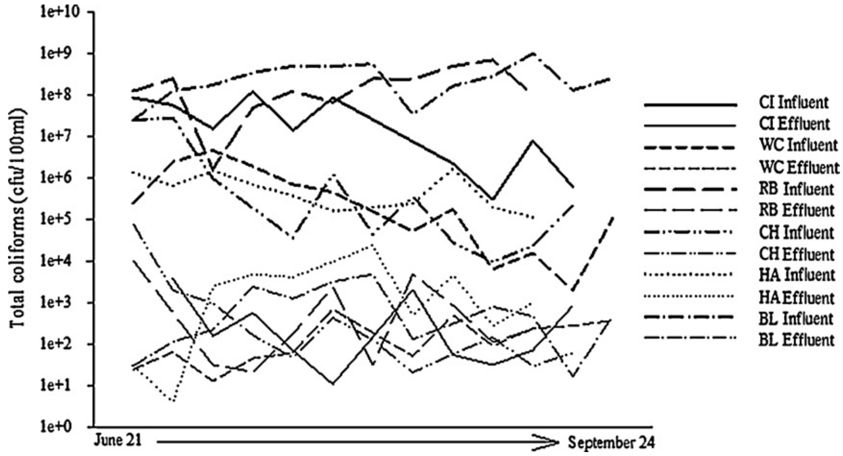

Fig. 14. Time series comparison of total coliforms influent and effluent concentrations of the six treatment wetland studied.

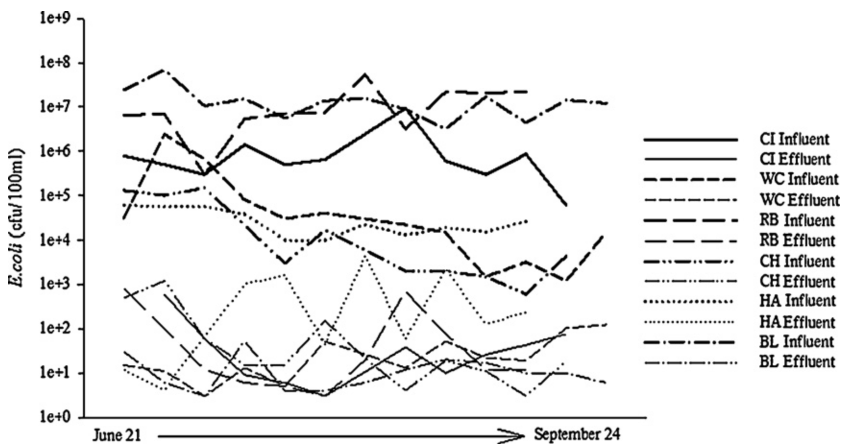

Fig. 15. Time series comparison of *E. coli* influent and effluent concentrations of the six treatment wetland studied.

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 and 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. $-17\,^{\circ}$C to $-32\,^{\circ}$C between November and May) no significant biological 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 we 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 we 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 and 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 has 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 $-5\,^{\circ}$C. Hobbie and Chapin (1996) also suggested that microbial activity may be able to uptake nutrients in soils at temperatures as low as $-5\,^{\circ}$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 we 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 5 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 °C (Hammer and 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 °C BOD removal rate was 27.2% and 46.8% for NH_3-N (Hammer and 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 °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 and Johnson (2008) calculated (BOD 9 mg/L and TSS 13 mg/L), are comparable to what we 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 and 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 and Douglas, 2007).

5. 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 should be to store wastewater over the winter period would be an appropriate management strategy to prevent spring freshet containing large volumes of frozen wastewater. However, we suggest these lagoons should be designed as continuous flow exfiltrating systems, which slowly decant into throughout the summer months. Reason being, the wetlands will be able to sustain performance with lower and longer sustained loading rates, than with an annual end of summer decant when most plants have already begun to senesce. Since the time of study, Chesterfield Inlet and Baker Lake have both received larger lagoons as part of their treatment systems.

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