Assessment of Arctic Community Wastewater Impacts on Marine Benthic Invertebrates

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List of Abbreviations

%	Percent
$CBOD_5$	Five-day Carbonaceous Biochemical Oxygen Demand
CCME	Canadian Council of Ministers of the Environment
DO	Dissolved Oxygen
EEM	Environmental Effects Monitoring
km	Kilometer
L	Litre
m	metre
mg	Milligram
MPN	Most Probable Number
N	Nitrogen
NH3-N	Un-ionized Ammonia
NRI	Nunavut Research Institute
NSERC	Natural Science and Engineering Research Council of Canada
P	Phosphorus
Pop	Population
TN	Total Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solid
WSER	Wastewater Systems Effluent Regulation
WSP	Wastewater Stabilization Pond

Summary

This study sought to understand the performance of arctic treatment systems and the impact of wastewater effluent on benthic invertebrate communities in arctic receiving water habitats. Effluent quality and benthic impacts were monitored in the receiving water of five communities across Nunavut that differed in the type and level of treatment achieved by wastewater infrastructure, the volume of effluent and receiving water mixing environment. We detected minimal impacts to benthic communities (<225 m linear distance from the effluent source) in four out of the five communities (Grise Fiord, Kugaaruk, Pond Inlet, and Pangnirtung), where the population was < 2,000 people. In these small communities impacts were characterized by increases or decreases in species richness, diversity, evenness, and density, and some differences in benthic species composition. This was in contrast to benthic sediments in Iqaluit (population 6699), which were devoid of benthic fauna up to 580 m from the effluent source in response to sediment anoxia. Variation in benthic community response between sampling locations was attributed primarily to differences in effluent volume, with effluent quality and receiving water hydrodynamics playing secondary roles. The results of this study will help to inform the development of northern specific treatment performance standards which will aid in prioritizing community wastewater system upgrades in arctic communities.

Why did we do this research?

The Canadian Council of Ministers of the Environment developed the Municipal Wastewater Effluent Strategy in 2009 (CCME, 2009). The Strategy aims to provide a harmonized national framework for managing wastewater; however, it was identified that the Far North, due to its extreme climatic conditions and remoteness, would require careful consideration in order to produce a viable means to improve human and environmental health protection. The North was therefore given a 5-year window to conduct research in order to develop feasible standards and an approach that will protect human and environmental health.

Environment Canada passed the Wastewater Systems Effluent Regulations (WSER) in June of 2012 (Government of Canada, 2012), which incorporate some of the concepts of the CCME strategy. A risk-based framework was used to specify timelines, between 10 and 30 years, for individual systems to meet the new national effluent standards. The WSER do not as yet apply to regions in Canada's far north (Nunavut, the Northwest Territories, and northern regions of Quebec and Newfoundland and Labrador); these regions were provided a 5-year window to conduct research to inform northern specific effluent criteria, and establish appropriate risk assessment criteria.

The WSER applies to all municipal wastewater systems that discharge greater than 100 cubic metres per day, which based on water use in Nunavut of approximately 100 litres per capita per day (Heinke et al., 1991), corresponds to a community population of approximately 1000.

The effluent quality standards set out in the WSER are:

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

In an earlier draft of the WSER, in addition to effluent quality standards, there was a requirement for environmental effects monitoring (EEM). The proposed EEM process included the quantification of mixing zones, water quality sampling in the receiving water and both benthic invertebrate and fish population sampling in order to ensure adequate protection of environmental health. Although EEM is not included in the WSER, it provides a framework for determining site-specific receiving water risks, and could provide value in establishing site-specific discharge requirements for remote northern communities.

Benthic invertebrates are organisms that live on or in the sediments of rivers, streams and lakes. Benthic invertebrates are often used as biological indicators as they are easy to sample, have low mobility and are highly affected by their environment. Benthic communities also play important roles in the processing of organic matter and recycling of nutrients, so shifts in benthic community composition can cause changes in ecosystem functioning.[2] The presence and absence of different species is an indication of the level of organic enrichment in the sediments and potential resulting effects to the ecosystem. Figure 1 below shows the relationship between community composition and level of organic pollution, showing that at high levels of pollution, the diversity of organisms decreases while the number of organisms may increase.

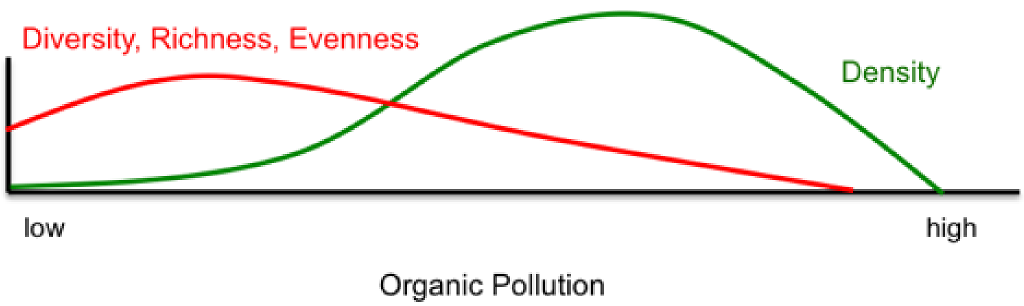

FIGURE 1. THEORETICAL MODEL OF COMMUNITY RESPONSE TO ORGANIC ENRICHMENT (MODIFIED FROM PEARSON & ROSENBERG 1978).

The response of benthic marine and freshwater communities to enrichment from municipal wastewater effluent has been well documented in temperate regions,[2,5,6] but there is a lack of published studies that have examined the effects of wastewater on benthic communities in polar habitats.

This study focused on examining benthic invertebrates in sediments in marine environments in five communities across Nunavut, Canada (Grise Fiord, Kugaaruk, Pangnirtung, Pond Inlet, and Iqaluit) to assess and understand the scale (distance from shore) and magnitude (overall effect on benthic community measures) of the impact of existing community wastewater effluent on the receiving environment.

What did we do?

Study Locations

The impact of community wastewater effluent on benthic communities was assessed in five locations across Nunavut (Figure 2). Wastewater generated by these communities consists primarily of residential wastewater, there are minimal industrial wastewater inputs. In the majority of the communities water and wastewater is distributed and collected from homes using pumper trucks; water consumption in these communities is relatively low at 90 L/person/day[7]. Several communities, however, use specially designed piped water systems, and have water consumption rates on the order of 250 L/person/day[7].

FIGURE 2. MAP OF THE FIVE STUDY SITE LOCATIONS.

Community location and population, annual volume of wastewater, the method used to treat wastewater, and characteristics of the receiving environment at each site, are shown in Table 1. In Grise Fiord, Kugaaruk, and Pond Inlet wastewater is continuously trucked from individual households to a waste stabilization pond (WSP). This wastewater is stored throughout the winter months (September – June). The WSP is then decanted at some point during the summer season, when the WSP and receiving water are not ice-covered. In Grise Fiord and Kugaaruk, the WSP effluent is further treated in natural tundra wetlands before reaching the marine environment. In Pangnirtung, wastewater is trucked to a mechanical treatment plant that is currently operated as an activated sludge system. The City of Iqaluit has an insulated piped water and wastewater system that services approximately 85% of the population with the remaining 15% serviced using pumper trucks. The plant in Iqaluit achieves preliminary wastewater treatment, using a Salnes Filter, before discharge. In both Pangnirtung and Iqaluit, effluent is continuously discharged to the receiving environment throughout the year. The population of each community is provided in Table 1, and details of effluent quality are presented in the results and discussion.

TABLE 1. CHARACTERISTICS OF WASTEWATER TREATMENT SYSTEMS AND RECEIVING WATER ENVIRONMENT AT EACH SAMPLING LOCATION; "POP" IS POPULATION SIZE, "WSP" IS WASTEWATER STABILIZATION POND.

Location	Population	Annual wastewater volume (m^3/yr)	Treatment type	Decant timing	System effluent sampling location	Receiving environment	Max tidal range (m)	Exposed sediment at low tide
Kugaaruk 68°20'29.04"N, 90°14'25.80"W	771	25,330	WSP and wetland	Annual – end of summer	End of wetland	Small bay	3	10 m rocky intertidal area
Pond Inlet **7**2°42'00.42"N 77°57'30.72"W	1549	80,880	WSP	Annual - end of summer	End of discharge channel	Open marine	2.5	<5 m rocky intertidal area
Grise Fiord 76°25'3.01"N 82°53'38.00"W	130	4,270	WSP and wetland	Annual - end of summer	End of wetland	Fiord mouth	3.7	200 m sandy sediment
Pangnirtung 66°08'47.61"N, 65°42'04.38"W	1425	46,810	Mechanical treatment (activated sludge)	Continuous - year round	End of discharge pipe	Fiord	6.9	200 m sandy sediment
Iqaluit 63°44'40.09"N 68°31'01.08"W	6699	552,600	Preliminary treatment (bulk solids removal)	Continuous - year round	End of discharge pipe	Large bay	11	1 km sandy sediment

Water Quality Sampling

Grab samples were collected of the system effluent (effluent entering the receiving water) for all locations between 2010 and 2013. Approximately 3 L of sample water was collected at each sample point in sterilized and rinsed clear plastic sample bottles. Samples were stored, cooled and transported by aircraft for analysis at the Dalhousie University Northern Water Quality Laboratory located at the Nunavut Research Institute (NRI) in Iqaluit, Nunavut.

Benthic Invertebrate Sampling

In each sampling location, benthic communities were sampled in the receiving environment as well as at a reference site where no or minimal human impacts are expected. The term "location" is used here to refer to the geographic location (e.g. Grise Fiord) while the term "site" is used to refer to the receiving or reference sites in each location. Reference sites were selected to have similar site conditions as the receiving water site, and were 2.5-5.0 km from the effluent discharge point. For sites that do not have continual discharges, sampling was conducted during decant events, which would represent worst-case scenarios in terms of exposure of benthic communities to wastewater effluent. A photograph of field staff conducting benthic sampling in Grise Fiord in 2011 is shown below in Figure 3.

FIGURE 3. CWRS FIELD STAFF PERFORMING BENTHIC SAMPLING IN GRISE FIORD IN 2011.

Sampling details, including the number of samples, and position of each sample relative to shore, and sampling method used at each site are shown in Table 2. Site-specific differences in tidal range and sediment type prevented uniform sampling protocols across sites. Three of the five locations had tidal flats with soft-sediments that were exposed at low tide (Grise Fiord, Pangnirtung, and Iqaluit), and were sampled to the maximum offshore extent possible during a single low tide cycle. The remaining two locations (Pond Inlet and Kugaaruk) had low tidal ranges that did not expose soft-sediments in the near shore, so these locations were sampled from a boat.

In the laboratory, invertebrates were sorted from each sample, identified to the lowest taxonomic level possible, and counted.

TABLE 2. SUMMARY OF BENTHIC COMMUNITY SAMPLING METHODS

Location/Site	Distances sampled from shore or effluent source	Total # of samples	Sampling method
Grise Fiord			
Receiving	20,50,150,200	40	Hand core
Reference	20,50,150	30	
Kugaaruk			
Receiving	70,100,150,200	24	Petite Ponar Grab
Reference	70,100,150,200	24	
Pangnirtung			
Receiving	75,125,175,225	40	Hand core
Reference	75,125,175,225	40	
Pond Inlet			
Receiving	0,25,75,100, 125	16	Petite Ponar Grab
Reference	0,25,75,100	12	
Iqaluit			
Receiving	125, 290, 400,450, 520, 580, 675, 830, 950, 1076,	10	Hand core
Reference	60,125,180,225,290, 400,450,520,580,	9	

Sediment Metrics

At each sampling location, sediment samples were collected for measures of sediment porosity, organic content, chlorophyll concentration, and grain size distribution. In Kugaaruk, Pangnirtung, and Pond Inlet sediment hypoxia was also measured from photographs. Sediment hypoxia is the depth at which the sediments no longer have oxygen, which can be determined by the sediments changing color from brown to gray/black as shown in Figure 4 below. Photographs were ranked on a scale from 1 (no discoloration of sediments) to 5 (discoloration of sediments throughout) independently by two observers. Ranks were averaged across the two observers for later analysis.

FIGURE 4. PHOTOGRAPH SHOWING THE TRANSITION TO SEDIMENT ANOXIA IN PANGNIRTUNG.

What did we find?

Wastewater Effluent Water Quality

Samples were taken over the course of the treatment seasons in 2010 – 2013, and values provided in Table 3 are averages of all data. The five systems have varying effluent water qualities, and 4 of the 5 sites would not meet the effluent criteria of the WSER due to high $CBOD_5$ and TSS values.

TABLE 3. SUMMARY OF AVERAGE WASTEWATER SYSTEM EFFLUENT QUALITY FROM THE STUDY LOCATIONS FROM SAMPLES TAKEN DURING THE TREATMENT SEASONS FROM 2010 - 2013.

	$CBOD_5$ (mg/L)	TSS (mg/L)	NH_3-N (mg/L)	E coli (log MPN/100 mL)	TN (mg N/L)	TP (mg P/L)	pH	DO (mg/L)
Kugaaruk	12	3	0.42	3.7	53	4.4	7.5	4.5
Pond Inlet	47	77	1.85	6.9	80	5.4	8.2	15.1
Grise Fiord	75	280	0.52	2.4	12	1.7	8.0	11.6
Pangnirtung	104	253	0.80	5.8	66	8.9	7.8	7.5
Iqaluit	620	310	0.30	8.0	39	10.5	7.6	-

$CBOD_5$ – 5-day Carbonaceous biochemical oxygen demand
TSS – Total suspended solids
NH_3-N – Ammonia as nitrogen
MPN – Most probable number
TN – Total Nitrogen
TP – Total Phosphorus
DO – Dissolved Oxygen

Impacts of Effluent on Benthic Invertebrate Communities

Benthic invertebrate communities in all study locations showed a response to sediment enrichment by wastewater effluent. A summary of the results is provided in Figure 5.

	Grise Fiord	Kugaaruk	Pangnirtung	Pond Inlet	Iqaluit
Chlorophyll	↑		↑	↑	↑
Organic Content	↑			↓	↑
Density	↑		↑	↓	↓
Diversity	↓		↑		↓
Richness		↓	↑	↓	↓
Evenness	↓				↓
Community Composition	≠	≠	≠	≠	≠
Ecological Quality	↓	↓			↓
Scale of Impact (m)	20-150	70-100	75-225	0-75	580

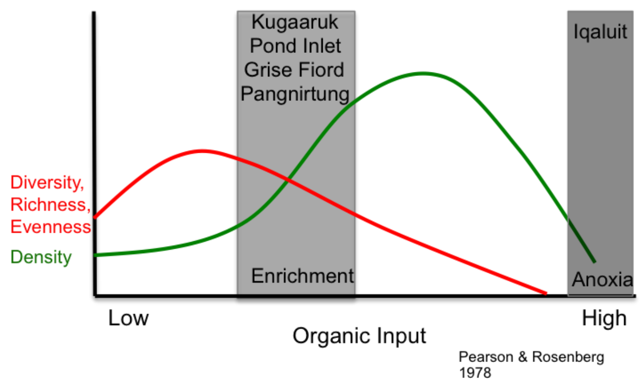

FIGURE 5. SUMMARY OF DIFFERENCES IN SEDIMENT METRICS (CHLOROPHYLL AND ORGANIC CONTENT), COMMUNITY METRICS (RICHNESS, EVENNESS, DIVERSITY, DENSITY), COMMUNITY COMPOSITION, AND ECOLOGICAL QUALITY AT THE RECEIVING WATER SITE RELATIVE TO THE REFERENCE SITE. ARROWS INDICATE THE DIRECTION OF THE RELATIONSHIP (E.G. UPWARD ARROW MEANS A HIGHER VALUE AT THE RECEIVING WATER SITE THAN THE REFERENCE SITE), A ≠ INDICATES WHERE DIFFERENCES IN COMMUNITY COMPOSITION BETWEEN SITES WERE OBSERVED IN PERMANOVA, AND A BLANK CELL DENOTES NO SIGNIFICANT DIFFERENCE. ALSO SHOWN IS THE CONCEPTUALIZED (APPROXIMATE) PLACEMENT OF EACH SAMPLING LOCATION ALONG A GRADIENT OF ENRICHMENT ACCORDING TO THE MODEL PUT FORTH BY PEARSON & ROSENBURG (1978).

Higher sediment chlorophyll and organic content in the receiving water relative to the reference site indicated sediment enrichment at Grise Fiord, Pond Inlet, Iqaluit, and Pangnirtung. This effect was not observed in Kugaaruk, which had the highest quality effluent of all the locations sampled.

The response of benthic communities to wastewater effluent in locations with lower populations, and thus lower effluent volumes (Grise Fiord, Kugaaruk, Pangnirtung, and Pond Inlet) was characterized by a slight increase or decrease in species richness, evenness, diversity, and density in the receiving water. In these locations, significant differences were also observed in the overall community composition between the receiving water and reference sites. Somewhat lower ecological quality values in the receiving water relative to the reference site in the near shore at some locations also indicated that wastewater is affecting benthic communities (Figure 6), and differences were generally associated with an increase in density of pollution tolerant benthic species.[3,13] According to the model put forth by Pearson & Rosenburg,[3] (Figure 5) these results provide evidence that the benthic invertebrate communities in Grise Fiord, Kugaaruk, Pond Inlet, and Pangnirtung were being mildly enriched by wastewater effluent on the scale of 20 – 225 m from shore (Figure 5).

The results from Grise Fiord, Kugaaruk, Pond Inlet and Pangnirtung differ largely from what was observed in the benthic sediments offshore of the wastewater discharge location in Iqaluit, where chlorophyll and organic enrichment of the sediments was clearly evident up to 580 m from shore. The sediments in Iqaluit had no benthic invertebrates on this same scale, and samples from the receiving water site were clearly distinct from samples at the reference site in terms of overall species composition. The absence of benthic invertebrates indicates that the sediments in Iqaluit were highly anoxic due to organic enrichment (Figure 5).[3] This effect was more severe both in magnitude and spatial extent than what was observed in Grise Fiord, Kugaaruk, Pangnirtung, and Pond Inlet.

Results from Grise Fiord, Kugaaruk, Pangnirtung, and Pond Inlet also differ from what has been observed in larger municipalities in other areas of Canada and throughout the world, where municipal wastewater effects generally occur over larger spatial scales (1-4 km from the outfall).[14-18]

The localized spatial impacts in Nunavut also appeared to be influenced by effluent quality and the hydrodynamics of the receiving environment.[15,19] Three of the locations sampled were characterized by sandy tidal flats that are exposed at low tide within the range of 200 – 1000 m from shore (Grise Fiord, Pangnirtung, Iqaluit). In Grise Fiord, where effluent volume is low, discharged annually, and effluent quality is moderate, significant community effects were generally restricted to within 50 m from shore. In contrast, significant community effects were observed in Pangnirtung up to 225 m from shore, where annual effluent volumes are higher, the discharge is continuous, and effluent quality is relatively poor. In Iqaluit, where wastewater effects were most severe, low tides expose the largest tidal flat, effluent quality is lowest, effluent volume is highest, and wastewater is discharged continuously.

In contrast, low tides in Kugaaruk and Pond Inlet do not expose benthic sediments, and effluent, discharged annually, passes through a short rocky intertidal area before entering the seawater. This may mean that benthic sediments in the near shore are less likely to

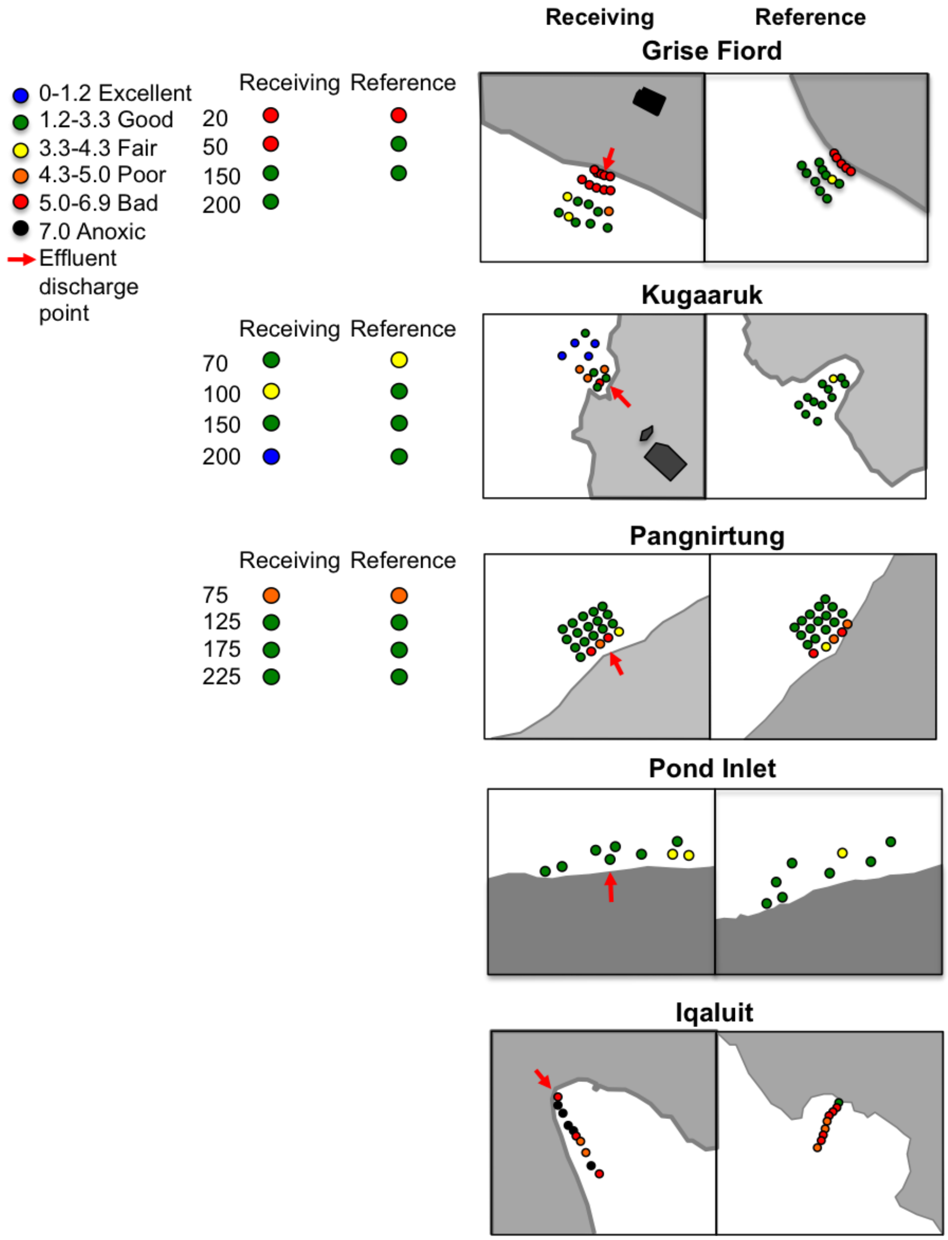

FIGURE 6. ECOLOGICAL QUALITY INDEX AT EACH SAMPLING POINT AT THE RECEIVING WATER AND REFERENCE SITES IN GRISE FIORD, KUGAARUK, PANGNIRTUNG, POND INLET, AND IQALUIT.

come into contact with wastewater effluent before it is diluted or transported offshore. Relatively high quality effluent and a small tidal range are the main factors explaining the small, and often non-significant effects of wastewater effluent in Kugaaruk. Effects to benthic communities were also minimal in Pond Inlet despite the fact that effluent quality was lower than in Kugaaruk. This is likely because effluent enters directly into an area with strong tidal currents.

What do these results mean for communities in Nunavut?

These results have important implications with respect to the management of community wastewater in small remote arctic communities. This study demonstrates that wastewater effluent is causing mild enrichment of sediments in marine aquatic habitats in the small communities (< 2,000 people) of Grise Fiord, Kugaaruk, Pangnirtung, and Pond Inlet. These effects generally occur on scales of < 200 m from the point of wastewater discharge. This was in contrast to benthic sediments in Iqaluit (pop ≈ 6699), which showed clear signs of being enriched by wastewater effluent to the point of being anoxic, and were devoid of benthic invertebrates in the vicinity (500 m) of the wastewater discharge point. An effect of this severity was not observed at any other sampling location, and strongly suggests that the total volume and duration of effluent discharge are the most important factors influencing the scale and magnitude of environmental impact. This finding is further supported by the results from the smaller communities. Despite the large range in effluent quality, ranging from very good in Kugaaruk, to poor in Pangnirtung, the scale and magnitude of impacts in the small communities were quite similar.

The findings of this study have important implications for the establishment of treatment performance standards for arctic communities. The study results suggest that for the majority of communities in Nunavut, which have populations less than 2000 people, the current level of treatment is sufficient to produce minimal impacts on the receiving water. However, based on the results from Iqaluit, it is clear that there is a point at which the volume and quality of effluent, combined with the receiving water characteristics, can produce anoxia and severe impacts in the receiving environment. This result suggests that any future community expansion or resource development projects should ensure an appropriate assessment of anticipated wastewater quality, volume and receiving water characteristics is conducted prior to development, to ensure treatment and monitoring can be implemented to minimize potential impacts. Additionally, incorporating the study results into the development of appropriate northern treatment standards will enable prioritization of existing system upgrades to help ensure that resources are allocated appropriately to minimize receiving water impacts within the financial constraints of these small remote communities.

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