

International Polar Year Research Project
Constructed Wetlands for
Wastewater Treatment in the Arctic

Research Proposal



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1. Introduction

As Arctic communities evolve and populations become more concentrated and urbanized (Figures 1 and 2), there is a growing need to develop environmentally sustainable technologies and resource management practices. The Canada-wide Strategy for the Management of Municipal Wastewater Effluent calls for implementation of secondary level treatment of municipal sewage across Canada, including the North. Wastewater and water treatment methods are a particular challenge for Northern communities. Disparities exist between Southern/urban populations and Northern/Inuit/remote communities, particularly in access to safe water treatment methods. Current wastewater treatment systems are rudimentary in the North because of constraints caused by remoteness, climate, and socioeconomic factors. Territorial governments and Hamlets, typically with very small resident populations, cannot afford millions of dollars in capital investments required for modern sewage treatment facilities. Additionally, conventional systems are often too complicated for effective operation and maintenance in this region. Specifically, community capacity and the availability of skilled labour is limited, and logistical constraints exist because of remoteness and the short construction season. To address these problems, the technologies suitable for northern applications need to be simple in operation, effective in performance and economical in use. Under these environmental, socio-political and economic conditions, constructed wetlands have been demonstrated as a viable wastewater treatment technology option. This project will develop engineering and technological solutions using constructed wetlands to assist Northern communities to adapt to growing populations and associated public sanitation and related health issues.

Constructed wetlands are capable of treating agricultural, municipal and industrial wastewaters as well as landfill leachate with high efficiency. Long-term studies carried out in France (Merlin et al., 2002), Italy (Conte et al., 2001) and Sweden (Jenssen et al., 2005) showed the treatment efficiency for organic matter as >80%, pathogen removal at almost 100% and nutrients reduction at almost 60%. Capital costs, operation and maintenance costs have been shown to be significantly less than conventional sewage treatment plants (EPA, 2000). Treatment wetlands have

the potential to be effective and economical wastewater treatment solution for communities in Arctic Canada.





Figure 1 Igaluit

Figure 2 Rankin Inlet

One of the major concerns with the operation of treatment wetlands in an Arctic environment is the influence of environmental conditions, most notably temperature. Research has shown subsurface flow wetlands to be effective in cold climates where treatment occurs below the ground surface, allowing bacterial communities to be insulated from cold air temperatures (Wittgren and Maehlum, 1997). Lagoon systems or natural wetlands are in use in the Canadian Arctic region for the treatment of municipal wastewater. Johnson and Wilson (1999) listed constructed lagoon, constructed lagoon and wetlands, mechanical system, natural lake, natural lake and wetland, trench and wetlands as wastewater treatment systems working in Nunavut. The performance from these treatment wetlands need to be studied to assess efficacy and for exploring and experimenting alternative treatment options.

As part of International Polar Year activities, researchers at the Centre for Alternative Wastewater Treatment, Fleming College will be undertaking the following activities:

- Studying the performance and efficacy of existing natural wetland treatment systems in six communities in Nunavut;
- 2) Studying the functioning of engineered constructed wetland systems in an Arctic environment:
- 3) Examining the chemical, and microbial processes occurring in treatment wetlands in cold climates;

4) Collaborating with the United Nations Environment Programme (UNEP) to create software that can model treatment wetlands in cold climates and serve as a design tool for use in the Canadian Arctic and other cold climate regions throughout the world.

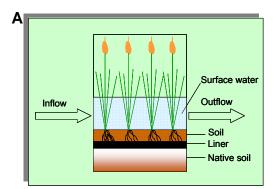
Pilot-scale constructed wetland systems will be developed and built in Nunavut in 2008. The research activities at the CAWT will focus on arriving at a prototype design specific to Arctic needs. Pilot scale systems to test these designs will then be built in communities in the Canadian Arctic while involving communities, scientists, local groups and individuals. These pilot systems will be monitored locally and publicized, encouraging community stewardship of water resources and further initiatives. This project also includes a significant training component through the hiring and training of northern technicians to monitor the systems, through targeted community oriented workshops and training of highly qualified personnel. Legacies of this project will include:

- 1) Original research on efficacy and functioning of treatment wetlands in extreme cold environments:
- 2) Validated technological designs and recommendations for regulators and operators;
- 3) Wetland design software prepared in collaboration with the UNEP International Environmental Technology Centre (IETC);
- 4) Training of local community members and community engagement and awareness-building regarding public sanitation issues;
- 5) Training of highly qualified personnel including graduate students and technicians;
- 6) Through a partnership with local governments and Inuit organizations, a dedicated analytical laboratory in the Kivalliq region of Nunavut allowing for continued accredited analyses of wastewater samples as required by regulations;
- 7) Compliance with forthcoming new federal regulations on municipal wastewater effluent;
- 8) Overall enhanced community capacity in public sanitation and public health protection.

2. Constructed Wetlands: Basic Concept

Constructed wetlands or treatment wetlands have been in use since the 1970s throughout the world as an effective wastewater treatment system. They are passive, onsite or off-site systems that mimic natural wetlands in treating wastewater. They can be shallow ponds or subsurface flow beds with aquatic plants that rely on physical, chemical and biological processes for the treatment of wastewater (EPA, 1999). Treatment wetlands are typically one of two types: (1) free water surface flow systems (FWSF) (Figure 3A), or (2) vegetative submerged beds (VSB) or subsurface flow systems (Figure 3B).

Both designs consist of beds planted with emergent aquatic vegetation underlain by an impermeable membrane. The water flows above the soil/substrate in FWSF--a common treatment method in North America. In a VSB wetland, the wastewater flows through the soil or porous media. VSB are widely used in Europe and in cold countries. VSB can be further classified into horizontal or vertical subsurface flow systems according to the direction of flow of the influent wastewater. Primarily because of the differences in oxygen saturation, there are trade-offs in performance between horizontal and vertical flow systems. Horizontal VSB systems are more effective at treating organic matter than nutrients compared to vertical VSB.



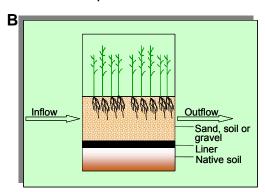


Figure 3 Constructed Wetland Types. A, free water surface flow systems (FWSF); B, vegetative submerged bed (VSB). Source: Knight (1990) and Merz (2000)

As wastewater flows through the inlet into the substrate material in a horizontal subsurface flow system, it comes into contact with a matrix of plant rhizomes, soil

and microorganisms wherein physical, chemical and microbiological degradation and transformation of contaminants occurs. Organic matter is decomposed microbiologically, nitrogen is nitrified/denitrified, phosphorus is fixed in the soils, and pathogens are eliminated via natural die-off, predation and sedimentation (Kadlec and Knight, 1996; Brix, 1993; Vymazal et al., 1998). The plants and microorganisms play a vital role in treatment wetlands.

3. Constructed Wetlands in Cold Climates

The FWSW and VSB have been in wide application in cold temperate climates in Canada, Alaska and northern USA, Scandinavia, eastern Europe, Russia and northeastern China, where the coldest month has a mean temperature below -3°C and the warmest a mean above 10°C (Wittgren and Maehlum, 1997). The sub-surface flow systems have been extensively used in Scandinavian countries with promising results. Maehlum et al. (1995) studied two Norwegian multistage systems consisting of aerobic pre-treatment followed by constructed wetlands (CW). The study indicated treatment process nearly the same during winter and summer seasons with high removal of organic matter and nutrients. Maehlum and Jenssen (2003) also studied a number of long-term functioning systems in Norway that treated domestic wastewater with an area of 6 to 350 m², depth of 0.9 to 1 m, person equivalents of 10 to 15, flow rate of 2 m³/d, hydraulic loading rate of 0.6 to 18 cm/d, hydraulic retention time of 1.3 to 30 d and vegetation consisting of *Phragmites* and *Typha*. The study showed high removal efficiencies of organic matter and suspended solids.

In an unpublished study of treatment wetlands at the Centre for Alternative Wastewater Treatment, a constructed wetland of 56 m² treating human wastewater at a rate of 14 to 16 m³ day⁻¹ in average minimum air temperatures of -11°C (minimum temperature -29.3°C) achieved the following mean water quality results in the final effluent:

TSS 2.8 mg/L

NH3-N <0.001 mg/L

CBOD₅ <5.0 mg/L

E. coli99.69% reductionTotal coliform99.79% reduction

In Arctic conditions, minimum temperatures are much lower and wetlands would be expected to freeze. However, summer temperatures in the Arctic are well within the operational range for treatment wetlands where the warmest month may have a mean temperature of 10°C.

When considering treatment in cold climates, some climate dependent processes, such as ice formation and its implication on hydraulic performance, hydrology and hydraulic issues and thermal consequences for biologically and microbiologically mediated treatment processes (Wittgren and Maehlum, 1997) should be researched for effective design and operation. The thermal regime of the subsurface flow wetland is complex due to various layers in the system: saturated medium, unsaturated medium in overlaid layers, plant litter, snow and ice, and in the Arctic, permafrost. Hence, available background data on thermal conductivity in combination with site specific weather and wastewater data will make reliable predictions possible (Maehlum and Jenssen, 2003) for constructed wetlands. The rate constants used in design of cold climate treatment wetlands will be also be studied to allow for effective application. Temperature is one of the driving factors associated with the performance of constructed wetlands and is highly variable over daily, seasonal and latitudinal gradients. Plant and microbial activity, community selection, and most notably nitrogen cycling will be sensitive to seasonal and temperature shifts (Kadlec and Knight, 1996; Werker et al., 2002). The adaptation of a microbial community to the climatic region or even season may be an explanation for cold climate wetlands showing less temperature dependence than laboratory incubations (Wittgren and Maehlum, 1997; Werker et. al., 2001). The optimal temperature for maximum microbial activity may vary depending on the interactive factors such as hydraulic loading, effluent quality, vegetation, soil and substrate within the wetland (Kadlec and Reddy, 2001).

Temperature, however, may be only a moderate predictor of seasonal performance. There might be a coupling effect of factors such as plant growth, flow rate, loading rate, residence time and dissolved oxygen availability for an effective performance. The effect of plant species selection on CW performance is likely to be important in regions subjected to extended periods of low temperatures and plant dormancy (Stein and Hook, 2005). Overall wetland performance will therefore be assessed

using as many variables as possible, including climate, hydrology, soil, vegetation, design and wastewater treatment parameters.

Normally, performance of wetlands is high during high temperature and active plant growth. A study by Stein and Hook (2005) showed the effects of plants on performance as greatest during the coldest periods, during dormancy, implying that plant species selection may be more important to cold-season than to warm-season performance. They also suggested that effects of temperature and oxygen transfer are not readily separable because both factors respond to seasonal cycles and because effects of one can offset the other.

Temperature profiles do not vary significantly across the width of the beds, while they can vary with length and depth, and daily variations of temperature gradients do not produce significant changes in effluent quality in case of temperate climatic condition (Garcia et al., 2003).

There are conflicting opinions as to the presence or absence of temperature dependence in the removal of BOD within treatment wetlands (Werker et al., 2001). Studies by Kadlec and Reddy (2001) and Akratos and Tsihrintzis (2007) showed minimal influence of temperature on BOD removal and a more significant influence on nitrogen removal. Hill et al. (2003) found marked decline in the efficiency of BOD in insulated wetland beds where temperature fell below -23°C for several weeks at a time. Will it show similar results the case of Canadian Arctic region?

Nitrification reduces concentration of ammonia nitrogen in the treatment wetland by conversion into nitrates, a two-step process mediated by the nitrifiers *Nitrosomonas* and *Nitrobacter*. The nitrifier growth rate is related to the nitrification rate, and temperature plays a significant role in the maximization of the nitrifier growth rate. Nitrifiers increase significantly at higher water temperatures and decrease at lower water temperatures. Denitrifying bacteria are more abundant than nitrifiers in subsurface flow wetlands. Hence, temperature significantly affects the rate of nitrification and denitrification in treatment systems (Kadlec and Knight, 1996). Vymazal et al. (2003) found the number of bacteria (total coliform, fecal coliforms and fecal streptococci) in out-flowing water to be lower in winter as compared to summer.

The seasonal effect was not observed within the first few meters of the bed where the reduction of bacteria occurred. Kern (2003) also found lower numbers of nitrifying and faecal coliform bacteria during the winter treatment of dairy farm wastewater at a mean temperature of 3.1°C. Will the nitrification and denitrification processes slow down in cold temperature? How effective will be the removal of pathogens in cold temperature?

4. Role of Temperature on Design of Constructed Wetlands

The water in natural swamps and marshes often does not freeze in winter in temperate regions due to presence of insulating layer of snow. The standing dead vegetation is an effective snow trap that collects drifting and falling snow. If very cold temperature precedes snow accumulation, ice may form. In densely vegetated wetlands, the plant stems hold the ice layer in place. If the water levels subsequently drop, an air gap can form under the ice. This insulation of air, snow and ice is sufficient allow wetland to winter water flow (Kadlec and Knight, 1996). The volume available for flow will be reduced as the ice layer thickens. The constriction of flow beneath the ice layer leads to subsequent flooding, freezing and hydraulic failure. Operating a wetland with a higher water level at the time of freezing is beneficial as it creates space for both water and air beneath the ice (Wittgren and Maehlum, 1997). Kadlec and Knight (1996) pointed out that the insulation provided by snow, ice, mulch and air gaps is enough to prevent water from freezing under north temperate conditions. To be effective, insulation must be uniform in coverage, which requires that it be designed as an integral part of the wetland system (Wallace et. al, 2001). In the Arctic, conditions are very different from southern Canada or the Northern USA. Permafrost, limited snowfall or snow accumulation, lack of woody vegetation and extreme cold temperatures likely result in wetlands freezing solid and/or extremely diminished flow. However, wetlands and lagoons may continue to be effective outside of the normal summer growing season, particularly into the fall and early winter. At this time, the top layers of frozen soil and vegetation and accumulated snow may insulate lower layers above the permafrost, allowing microbial activity to continue. This is also likely to be the case in sewage lagoons.

5. Design Models

Constructed wetlands are designed for the treatment of wastewater parameters BOD, COD, suspended solids (SS), nitrogen compounds, phosphorus compounds, heavy metals, and pathogenic organisms (Kadlec and Knight, 1996; Reed et al., 1995). Both models use a first-order kinetics-based uptake model. First-order kinetics means that the rate of removal of a particular pollutant is directly proportional to the remaining concentration at any point within the wetland cell. Although the flow in constructed wetlands is generally intermediate between plug-flow and completely mixed, the first-order model with plug-flow assumptions provides a conservative design estimate (Knight et al., 2000).

Reed et al. (1995) incorporate flow rate, wetland depth, wetland porosity, a temperature-based rate constant, and inflow and outflow concentrations. The rate constant used in this approach is a function of depth and porosity of the wetlands. Kadlec and Knight (1996) refer to their model as the k–C* model. The model incorporates the hydraulic loading rate, concentrations into and out of the wetlands, and a temperature-based rate constant. They also include a background concentration parameter (C*). Their rate constant differs from Reed et al. (1995) in that depth and porosity are not included in the calculation (Stone et al., 2004).

One of the limitations of the Kadlec and Knight approach is that, as the required effluent concentration approaches the minimum pollutant concentration, their predicted area for the treatment increases exponentially, leading to over-estimates of the required area in cases near the pollutant concentration limit (Jorgensen et al., 2007).

Kadlec and Knight (1996) present the area-based first-order plug-flow design model as:

$$\ln\left[\frac{C_{out} - C^*}{C_{in} - C^*}\right] = -\frac{K_T}{q} \tag{1}$$

where C^* is the background concentration (mg/L) and KT is the rate constant adjusted for temperature (m/day).

The hydraulic loading rate (q) is defined as:

$$q = \frac{Q_{in}}{A} \tag{2}$$

where, Q_{in} is the inflow (m³/day) and A is the wetland surface area (m²).

The rate constant (K_T) is defined as:

$$K_T = K_{20} \theta^{(T-20)} \tag{3}$$

where K_{20} is the rate constant at 20°C (m/day), θ is dimensionless temperature coefficient, and T is temperature (°C). This equation is a modification of the Arrhenius relationship which gives the temperature effects on the removal rate constants.

$$K_T = K_R \theta^{(T - T_R)} \tag{4}$$

where K_T is the rate constant at a specified temperature T (day⁻¹), K_R the rate constant at a reference temperature T_R (day⁻¹), T the temperature (°C), T_R the reference temperature (°C), and θ the dimensionless temperature coefficient.

Values of K_R (typically as K_{20}) and θ for constructed wetlands vary widely in published reports. For subsurface flow (SSF) systems, Reed et al. (1995) suggested that $K_{20} = 1.104 \text{ day}^{-1}$ and $\theta = 1.06$, and Kadlec (1997) reported $0.30 \le K_{20} \le 6.11 \text{ day}^{-1}$ with a weighted mean of 1.96 for subsurface system BOD removal. Provided that C^* is constant across temperatures, values of θ greater than unity indicate a positive relationship between temperature and organic matter removal, while values less than unity indicate that the removal rate increases as temperature decreases (Stein et al., 2006). The rate constants for the case of Arctic climates need to studied and investigated.

The Alberta Environment Model (AENV) is based on the Kadlec and Knight model and is normally used for the design of treatment wetlands in the Canadian sub-Arctic. The rate constant used for the design is 20° C; however, average temperatures during the decant months are usually between 5 and 10° C (Kent and Morakinyo, 2005). The modification on the AENV model was carried out assuming the linear relationship between rate constant (k) and the reference temperature. According to Kadlec and Reddy (2001), typical rate constant versus temperature plots show a great deal of scatter and a slight downward trend with increasing temperature in free

water surface systems. This rate constant variation with temperature needs to be studied for an effective application in the northern climate.

6. Research Objectives

The short term objectives are outlined as follows:

- To study performance and efficacy of existing natural wetland treatment systems in six communities in Nunavut
- To study the functioning of engineered constructed wetland treatment systems in the Arctic environment
- To examine the chemical and microbial processes occurring in treatment wetlands in cold climates and develop design models and recommendations for use in the Canadian Arctic

The long term objectives are as follows:

- To train local people in monitoring and operation of natural and engineered treatment systems
- To collect baseline date available for policy formulation regarding creation of treatment and effluent discharge standards

7. Research Questions

- 1) What are the environmental characteristics where the natural wetlands are located?
- 2) What are the characteristics of the wastewater found in each community?
- 3) What are the characteristics (physical, biological, hydrological, chemical) of natural wetlands (and lagoons) in the Kivalliq region used for treatment of wastewater?
- 4) How well do the wetlands function in the treatment of wastewater and what are the performance differences between wetlands?
- 5) What are the characteristics of treatment performance within wetlands? Where does treatment occur across the breadth, length, and depth of wetlands?
- 6) How will low temperatures affect the performance of BOD, TSS, nitrification, denitrification and pathogen removal processes?
- 7) How will temporal variations (daily, seasonally) in temperature affect the performance of treatment wetlands?
- 8) How will plant species and community composition affect the removal of pollutants and how will vegetation differences respond to temperature effects?

9) What is the optimal rate constant for designing wetlands for Arctic climates? And what kind of modification is needed in the AENV model for the design of cold climate treatment wetlands in the Canadian Arctic?

8. Research Areas

Six communities--Arviat, Whale Cove, Chesterfield Inlet, Baker Lake, Coral Harbour, Repulse Bay--located in Kivalliq region of Nunavut, Canada have been selected as study sites (Figures 4 to 7). They lie in the mid-Arctic wetland region (Figure 8) characterised by short cool summers, long cold winters, very low precipitation and the presence of permafrost. The wetlands found in these areas are mostly fens and salt marshes and the dominant vegetation found are *Carex* sp., *Eriophorum* sp., lichen and mosses (Tarnocai and Zoltai, 1988).

The communities range in size from 332 (Chestefield Inlet) to 2358 (Rankin Inlet). Table 1 describes the communities and wastewater treatment systems currently in place.



Figure 4 Chesterfield Inlet Treatment Wetland



Figure 5 Whale Cove Treatment Wetland





Figure 6 Baker Lake Treatment Wetland



Figure 7 Arviat Treatment Wetland

Table 1 Study Site Characteristics Source: Wootton et al., 2008

	Chesterfield Inlet	Whale Cove	Repulse Bay	Coral Harbour	Baker Lake	Arviat	Rankin Inlet
Latitude	63°20'20"N	62°10'14"N	66°31'59"N	64°7'59"N	64°19'9"N	61°6'29"N	62°49'0"N
Longitude	90°42'5"W	92°34'40"W	86°15'0"W	83°10'0"W	96°1'14"W	94°3'29"W	92°4'59"W
Population in 2006	332	353	748	769	1728	2060	2358
Water source	First Lake	Fish Lake	Nuviq Luktujuq Lake	Rock-blast reservoir; Post River	Baker Lake	Wolf Creek	Steel reservoir; Nipissar Lake
Annual quantity of water use licensed	20,000 m ³	30,000 m ³	24,000 m ³	35,000 m ³	n/a	81,000 m ³	400,000 m ³
Annual quantity water used	11,379 m ³ (2003), 17,248 m ³ (projected 2008)	n/a	22,000 m ³	40,000 m ³ (size of reservoir)	64,693 m³ (2005)	64,871 m ³	n/a
Sewage collection	Trucked	Trucked	Trucked	Trucked	Trucked	Trucked	95% piped (collection by HDPE mains), 5% trucked
Annual quantity of wastewater	unknown	unknown	22,000 m ³	unknown	62824 m³	64,871m ³	Unknown
Treatment system	Natural depression (holding cell), exfiltrates into natural wetland area	Facultative lagoon and treatment wetland	Natural wetlands	Natural wetlands, small pond	Holding cell, exfiltrates through series of wetland and pond areas (200 m wetland, Lagoon Lake, 300 m wetland, Finger Lake, 1000 m wetland, Airplane Lake, Garbage Creek, final discharge into Baker Lake)	Engineered lagoon, exfiltrates into natural wetland area	Treatment plant (wastewter pumped by 2 lift stations through a 1 mm mesh drum screen), outfall 450 m into Prairie Bay, depth of 10 m. Screenings landfilled
Number of cells	One (holding cell)	One	n/a	n/a	Four (one holding cell, three ponds along wetland flow path)	One	n/a
Discharge type	Continuous	Continuous	Continuous	Continuous	Continuous	Continuous	Continuous
Lagoon retention time	Very limited	Not confirmed	Very limited	unknown	Very limited	unknown	n/a
Lagoon capacity and dimensions	n/a	15,000 m ³	None	n/a	n/a	55,000 m ³	n/a

	Chesterfield Inlet	Whale Cove	Repulse Bay	Coral Harbour	Baker Lake	Arviat	Rankin Inlet
Location relative to community	3.1 km W	0.7 km SW	1.4 km E	3.6 km N	1.4 km N	2.8 km	n/a
Wetland area and flow path	165,000 m ² area; 900 m flow path	700 m flow path	64,000 m ² area; 1400 m flow path	70,000 m ² area; 1150 m flow path to small pond area	97,000 m ² area; 2100 m flow path	200 m flow path	N/A
Receiving body	Hudson Bay	Hudson Bay	Hudson Bay	Hudson Bay	Baker Lake	Hudson Bay	Hudson Bay
Maximum effluent fecal coliforms	1x10 ⁴ CFU/dI	1x10 ⁶ CFU/dl	1x10 ⁴ CFU/dI	1x10 ⁶ CFU/dI	n/a	1x10⁴ CFU/dl	1x10 ⁶ CFU/dI
Maximum effluent BOD5	80 mg/L	120 mg/L	80 mg/L	120 mg/L	n/a	80 mg/L	120 mg/L
Maximum effluent total suspended solids	100 mg/L	180 mg/L	100 mg/L	180 mg/L	n/a	100 mg/L	180 mg/L
Maximum effluent pH	Between 6 and 9	Between 6 and 9	Between 6 and 9	Between 6 and 9	n/a	Between 6 and 9	Between 6 and 9
Oil and grease requirement	No visible sheen	No visible sheen	No visible sheen	No visible sheen	n/a	No visible sheen	No visible sheen
Acute toxicity requirement	No requirements	No requirements	n/a	n/a	Not specified	Not specified	Not specified
Raw sewage volume monitoring stations	CHE-3, raw sewage at truck offload point	Not specified	REP-3, raw sewage at truck offload point	Not specified	Not specified	ARV-3, raw sewage at truck offload point	Not specified
Effluent quality monitoring stations	CHE-4, final discharge point	WHA-3, final discharge point	REP-4, final discharge point	COR-3, final discharge point	BAK-2, inflow into Airplane Lake (compliance testing point); BAK-3, outlet of Airplane Lake	ARV-4, final discharge point	GRA-3, discharge from sewage treatment plant
Volume monitoring requirements	CHE-3, monthly and annual measurement	Monthly and annual quantity of raw sewage	REP-3, monthly and annual quantity of raw sewage	Monthly and annual quantity of raw sewage	n/a	ARV-3, monthly and annual measurement of quantities of raw sewage	GRA-3, monthly and annual quantity of raw sewage
Effluent quality monitoring frequency	CHE-4, monthly May to Aug inclusive	WHA-3, monthly May to Aug inclusive	REP-4, monthly May to Aug inclusive	COR-3, monthly May to Aug inclusive	May-Aug ARV2, ARV-4	May-Aug ARV2, ARV-4	May-Aug GRA-3

	Chesterfield Inlet	Whale Cove	Repulse Bay	Coral Harbour	Baker Lake	Arviat	Rankin Inlet
Effluent quality monitoring parameters	BOD, TSS, pH, FC, NO3-NO2, conductivity, NH3-N, oil and grease (visible), sulphate, potassium, calcium, total phenols, sodium, magnesium, total arsenic, total copper, total iron, total mercury, total zinc, total chromium, total cadmium, total lead, total nickel	BOD, TSS, pH, FC, NO3-NO2, conductivity, NH3-N, oil and grease (visible), sulphate, potassium, calcium, total phenols, sodium, magnesium, total arsenic, total copper, total iron, total mercury, total zinc, total chromium, total cadmium, total lead, total nickel	BOD, TSS, pH, FC, NO3-NO2, conductivity, NH3-N, oil and grease (visible), sulphate, potassium, calcium, total phenols, sodium, magnesium, total arsenic, total copper, total iron, total mercury, total zinc, total chromium, total cadmium, total lead, total nickel	BOD, TSS, pH, FC, NO3-NO2, conductivity, NH3-N, oil and grease (visible), sulphate, potassium, calcium, total phenols, sodium, magnesium, total arsenic, total copper, total iron, total mercury, total zinc, total chromium, total cadmium, total lead, total nickel	n/a	BOD, TSS, pH, FC, NO3-NO2, conductivity, NH3-N, oil and grease (visible), sulphate, potassium, calcium, total phenols, sodium, magnesium, total arsenic, total copper, total iron, total mercury, total zinc, total chromium, total cadmium, total lead, total nickel	n/a

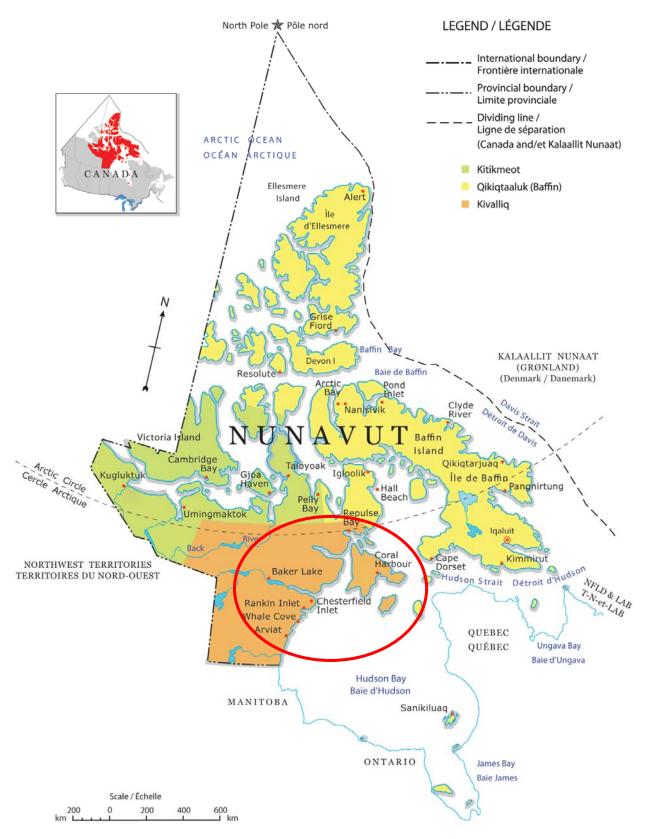


Figure 8 Map of Nunavut. Six study areas depicted: Arviat, Whale Cove, Chesterfield Inlet, Baker Lake, Coral Harbour and Repulse Bay. Source: Natural Resources Canada (2006); modified by J. Durkalec (2008)

9. Research Methodology

The research design is comprised of the following components:

- Characterisation of existing wetlands/ lagoons in six communities in the Kivalliq region of Nunavut;
- Experimental column tests under Arctic conditions in an environmental chamber at the Centre of Alternative Wastewater, Fleming College;
- Pilot-scale implementation of engineered CWs in two communities in Kivalliq;
- Calibration of a treatment wetland design model (SubWet Model).

9.1 Characterisation of existing wetlands

Natural wetlands are already used for treating wastewater in many communities in Nunavut. Fundamental comprehensive research on their efficacy and functioning is lacking. Therefore, the first component of this research will be to characterize the existing wetlands and lagoons located in six communities in Kivalliq region. Baseline monitoring will commence in June 2008 and will monitor at least two locations in each wetland: (1) where raw or pretreated wastewater enters the wetland and (2) where it is deemed to leave the wetland (Figures 9-14). Sampling will be conducted by hamlet employees where possible and by locally hired residents if necessary. Frequency will be weekly starting in June continuing into the fall. A laboratory will be established in Rankin Inlet, allowing samples to be analysed within 24 hours. Parameters will be measured as per Tables 2 and 3.

Table 2 Wastewater Analyses for Existing Treatment Wetlands

Physical parameters	Chemical parameters	Microbiological parameters
• pH	 Ammonia 	• E. coli
 Temperature 	 Nitrate 	 Total Coliform
 Conductivity 	 Nitrite 	
 Total suspended 	TKN	
solids	 Particulate Organic P 	
 Particulate Organic 	 Particulate Organic N 	
Matter	 Total Phosphorus 	
 Turbidity 	• COD	
 Dissolved oxygen 	 CBOD₅ 	

Table 3 Baseline Summer Monitoring Program

Sampling locations

Sampli	ng locations			
	Weekly for 12 weeks June-September 2 X 500 mL bottles per location	Quantity jars	Volume (mL)	Total (mL)
Baker L	ake			
1	Holding cell - raw wastewater	2	500	1000
·	Lagoon Lake where influent from wetland enters	_		
2	lake	2	500	1000
3	Finger Lake - where effluent leaves Finger lake Airplane Lake - where influent from stream enters	2	500	1000
4	Airplane Lake Final Effluent location in stream where effluent	2	500	1000
5	enters Baker Lake	2	500	1000
	Weekly Total	10		5000
Arviat				
1	Raw Effluent entering lagoon	2	500	1000
2	Where Effluent seeps from lagoon into wetland	2	500	1000
3	Final Effluent location TBD SNP	2	500	1000
	Weekly Total	6		3000
Whale (Cove			
1	Raw Effluent entering lagoon	2	500	1000
2	Where Effluent seeps from lagoon into wetland	2	500	1000
3	Final Effluent location above ocean SNP	2	500	1000
	Weekly Total	6		3000
	rfield Inlet			
1	Raw Effluent at dump off location	2	500	1000
2	Final Effluent location SNP point marked by sign	2	500	1000
	Weekly Total	4		2000
Repuls	-			40.55
1	Raw Effluent at dump off location	2	500	1000
2	Final Effluent location above ocean SNP	2	500	1000
	Weekly Total	4		2000
Coral H		•	5 00	4000
1	Where Effluent seeps from lagoon into wetland	2	500	1000
2	Final Effluent location SNP	2	500	1000
		4		2000
Totals		34		17000

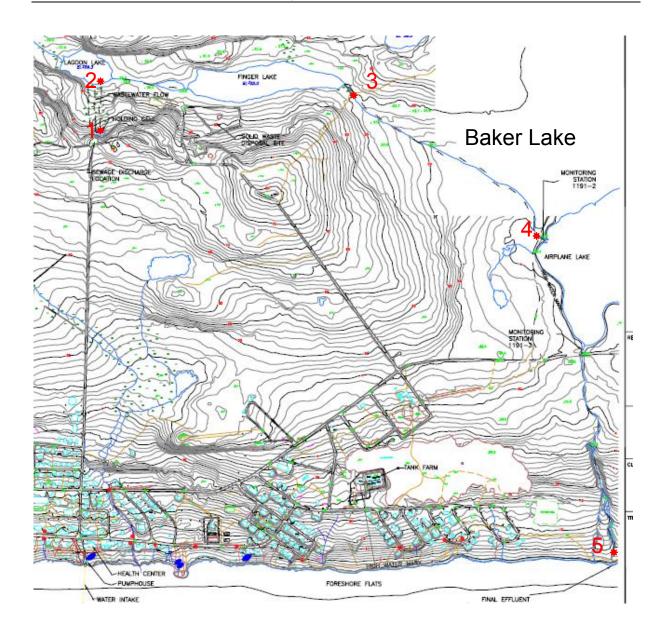


Figure 9 Baseline Monitoring Locations for Baker Lake



Figure 10 Baseline Monitoring Locations for Arviat

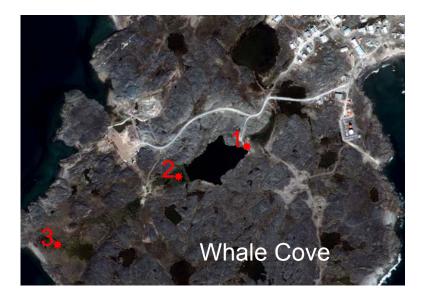


Figure 11 Baseline Monitoring Locations for Whale Cove



Figure 12 Baseline Monitoring Locations for Chesterfield Inlet

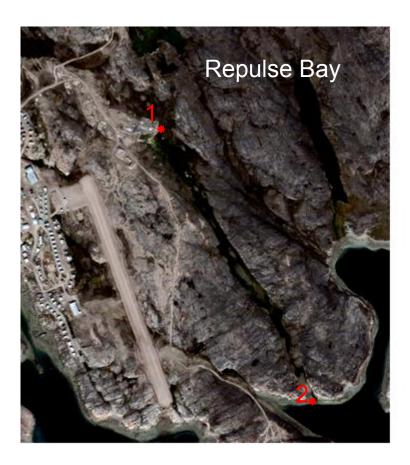


Figure 13 Baseline Monitoring Locations for Repulse Bay



Figure 14 Baseline Monitoring Locations for Coral Harbour

In addition to baseline monitoring which will provide information on efficacy during the growing seasons, an intensive comprehensive survey of each wetland will be conducted in order to understand internal wetland dynamics and the mechanisms of treatment.

Preliminary Procedures

Maps acquisition, Field walk and Grid establishment

- The first activity will be to walk around the wetland to survey topographical details, vegetation, soil, and hydrologic patterns and to establish the wetland boundary. Available photographs, satellite imagery, soil surveys and any other pertinent data will be used in this approach. Any area with one or more wetland indicators (hydric soil or vegetation or hydrology) will be flagged or marked on topographic maps. The information from other data sources such as watershed and drainage details from topographic maps will also aid in characterizing particular area of interest.
- Depending upon size of wetland or lagoon, a grid system with a number of points will be established by walking or pacing ranging from 100 x 100 m or 50 x 50 m or 30 x 30 m (approx. 100 x 100 ft). A GPS device as well as flags or plastic tapes will be used to document location of samples on the field. The sampling points will be referenced to landmarks or other reference points where possible. Also, it is desirable to pace from given sample point to adjacent examples and evaluate whether the grid system is square. This will determine if individual points are out of position and hence facilitate correction of misplaced points (Lyon, 1993). The boundaries of the wetland or lagoon will also be made on a topographic map. At each sampling point or grid, detailed information on wetland topography, soil, hydrology, plants and wastewater will be collected.

Specific Procedures

Hydrology, Soil and Vegetation

- To evaluate wetland hydrology and subsurface conditions, a soil sample will be taken at the grid sampling site with a soil corer. The sampling hole will be deep enough to evaluate the top 18 inches (0.45 m) of the soil. The physical analyses of the site relating to air temperature, water temperature, permafrost condition and water depth will be noted.
- Soil samples found at each sample point will be preserved to later identify features such as soil texture, soil levels and soil colours. The peat content and general soil characteristics will be described. The soil evaluation will be carried out checking Munsell Colour charts for colour value and chroma. Soil samples will be taken for chemical analyses and grain size measurements in the laboratory.
- The sample hole will be observed for standing water or seepage of water into the hole from the bottom or from the sides. A seepage test will be conducted by timing the rate of water infiltration. The origin of water in the wetland, i.e., through ground water, stream water, lake water or fresh water sources will be estimated. The associated water body will be described. Soils will be examined for gleying where very wet soils have specific coloration and odours resulting from very anaerobic conditions producing sulphur or methane odours. Hydric soils often develop certain colour and characteristics because they have spent long periods flooded and thus under anaerobic conditions and are mostly black in colour (Mitsch and Jorgensen, 2004). Hydrological indicators of the surrounding landscape will be recorded. At each sampling point, flood markings and debris lines, shallow root systems, wet or poorly decomposed plant material and adjacent stream courses will be noted. Changes in vegetation, layers of undecomposed leaves and/or absence of plant growth compared to adjacent areas will also be noted.
- The vegetation types that are either grass, rush, moss, lichen, floating species, submerged species or non-vegetated sites will be inspected and the percentage of their cover will be calculated through a visual inspection. Also, the species will be identified. A description of the sample sites with reference to the exposure

(minimum, moderate and severe), homogeneity (continuous, discontinuous, patchy, and rare) and micro relief (plane, convex, concave, hummocky, undulating, or other pattern) of the site will be recorded.

- To establish an area as wetland, three main criteria should be met: hydric soil, evidence of wetland hydrology and 50% or more of the dominant plants with a high probability of occurrance in a wetland. Failure to meet one or more of the three criterions will lead to the conclusion that the individual location is not a wetland (Lyon, 1993). Also, according to Tarnocai et al. (1988), wetlands are land saturated with water long enough to promote wetland or aquatic processes as indicated by poorly drained soils, hydrophytic vegetation and various types of biological activities that are adapted to the wet environment. These factors will be considered when characterising the wetland.
- Arctic wetlands occur in peat lands, on wet mineral terrain, on areas periodically inundated by tides and on shallow open water bodies. They are associated with Gleysolic Cryosols having water table at, near or above the surface. This study will also classify wetlands according to the associated wetland forms.
- The morphology of the wetlands will be assessed to identify different land forms (level, concave, depressional, domed or plateau). The boundary conditions of the sites will be noted and the area of the wetlands and open water will be estimated.
 The functional use of wetlands will be studied with reference to wastewater treatment lagoons, wetlands coverage, wildlife support and recreational use.

Wastewater Samples

• After the area has been identified as a wetland, wastewater samples will be collected for the intensive sampling. A total of 50 wastewater samples per study area will be collected, depending upon factors such as source of wastewater, discharge point, flow distance, and flow depth (Table 4). The transect or grid system already established will be used for this purpose. Also, water samples will be taken from the raw and receiving water bodies. Water parameters will be analysed as per Table 2. Because of the expense and labour intensity required for CBOD₅ and TKN, fewer measurements of these parameters will be made.

Table 4 Intensive Summer Monitoring Program

Sampling Locations	
Wetland locations (Arviat,	
Chesterfield, Whale Cove,	
Repulse, Coral Harbour,	300
Baker Lake) 50 each in grid	
format	
Number of Parameters	18
Number of weeks	1
Total Number of Tests	5400

9.2 Experimentation based on Arctic conditions

Studies have shown that performance of a constructed wetland depends upon a number of factors, such as microbial activity, plant growth, flow rate, dissolved oxygen and temperature. Moreover, the understanding of performance variability is the key towards improved engineering in design and operation (Werker et. al., 2002). However, there has been very limited study of the performance of treatment wetlands in Arctic conditions. To better understand the functioning of the mechanisms operating in treatment wetlands in these specific environments, ex situ experiments will be carried out at the Centre for Alternative Wastewater Treatment (CAWT) in Fleming College, Lindsay, Ontario. Studies have shown that soil microbes are capable of treatment during winter periods in a subsurface flow system. The influent wastewater that passes through the soil matrix maintains a high temperature in the substrate, aiding degradation. According to Kadlec et. al (1996), lower temperatures could favour a greater extent of aerobic metabolism due to increase in dissolved oxygen saturation concentrations. The Arctic conditions will be simulated in the environmental chamber having a growth area of 3.3 m², growth height of 203 cm, light conditions approximating Arctic conditions and temperature that could be adjusted between -20 to +35 °C +/- 0.5 °C. To test the effects of temperature, mesocosm cells approximately 1 m³ will be filled with aggregate materials similar to those found in the Kivalliq region. Sedges, grass, and forbes commonly found in Kivalliq region treatment wetlands will be planted in the mesocosm cells (subject to regulatory approvals) and influent approximating raw wastewater found in Kivalliq communities will be created using a municipal wastewater found in Lindsay, Ontario, strengthened synthetically as needed to resemble northern wastewater. Flow rates, temperature rates and insulation factors will be adjusted experimentally to assess effects of temperature on treatment efficacy and to validate/corroborate field based findings.

9.3 Pilot-scale implementation of constructed wetlands

One of the key objectives of this study is to understand the functioning of treatment wetlands in the field. This will be achieved by having a demonstration pilot-scaled constructed wetland in the hamlet of Baker Lake. Originally, pilot wetlands were proposed for several communities, but logistical and financial constraints require the focusing of efforts on a single community. The purpose of a small pilot-scaled constructed wetland is to be able to tightly control all variables--especially flow rates and the flow path through an impermeable barrier. This will allow for the testing of rate constants and design equations. The EDPM lined cells will be approximately 5 x 4 m each and will contain different aggregate materials to better represent the range of material found in the Kivalliq region (sand and gravel if available). Because of the challenges in controlling dosing experimentally and to allow for pre-treatment, an EDPM lined holding cell that is 16 m³ in size will be filled with several 4000 L truckloads and then regular truckloads of 2 per week will commence, allowing several days residency time for pre-treatment. Flow will be passive through a valve controlled pipe (operational during summer months only) and monitored with a mechanical flow meter at the beginning of each cell. A second set of cells will receive effluent treated from an upstream set of cells, thus allowing for assessment of varying strengths of waste and by adding wetland areas by varying sizes. Plants found to occur in the Baker Lake wetland will be planted inside the cells. Temperature recording devices and water quality sampling ports (lysimeters) will be evenly placed in eight locations in the pilot-scale wetland at two depths.

Table 5 BOD Removal Design: Variables

		Target	Target
		conc.=120	conc.
Parameters	Comments	mg/l	=25mg/l
load (I/truck)	1000 gallons	4000	4000
frequency/week	-	1	1
load (l/day)		571.429	571.429
Wastewater discharge Q (m³/d)	Coral Harbour (2008)	0.571	0.571
CBOD, Influent C_i (mg/l)	396.39	400	400
	CBOD= 1.16 x BOD5;		
BOD, Influent C_i (mg/l)	Brake (1998)	464	464
BOD, Effluent C _e (mg/l)	Standard	120	25

Table 6 BOD Removal Design: Reed Formula

Parameters	Comments		(BOD = 12	0 mg/l)	(1	BOD = 3	0 mg/l)
		Jan	Jan	Jul	Jan	Jan	Jul
		low	High	low	low	High	low
K_R is the first-order rate	standard, Crites,						
constant for BOD	Middlebrooks &						
removal at 20°C (/day);	Reed (2006)	1.104	1.104	1.1	1.104	1.104	1.1
T _W Mean temp(°C)		-34	-28	5	-34	-28	5
T _R Reference Temperature	e (°C)	20	20	20	20	20	20
θ_R Arrhenius constant	standard	1.06	1.06	1.06	1.06	1.06	1.06
K_T is the first-order rate co	nstant for BOD						
removal (/day);		0.047	0.067	0.459	0.047	0.067	0.459
y depth of wetland (m)	standard	0.6	0.6	0.6	0.6	0.6	0.6
<i>n</i> porosity (~0.35 to 0.4 for							
pea gravel)		0.35	0.35	0.35	0.35	0.35	0.35
As (m ²)		77.5	54.6	8.0	167.4	118.0	17.3

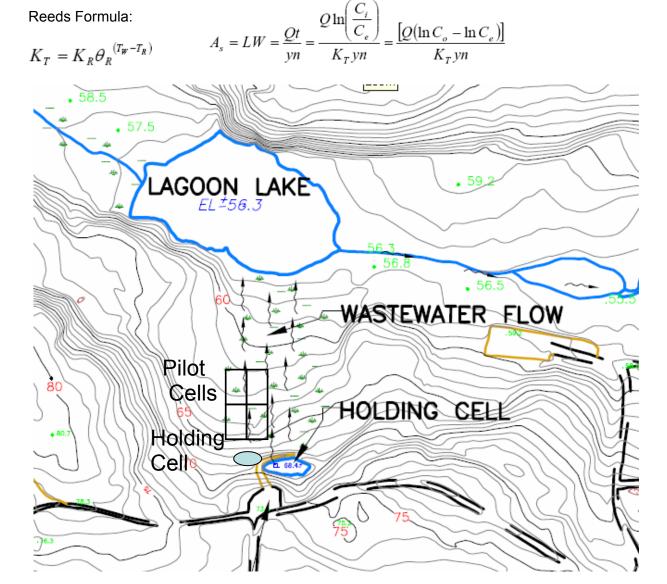


Figure 15 Location of Pilot Cells

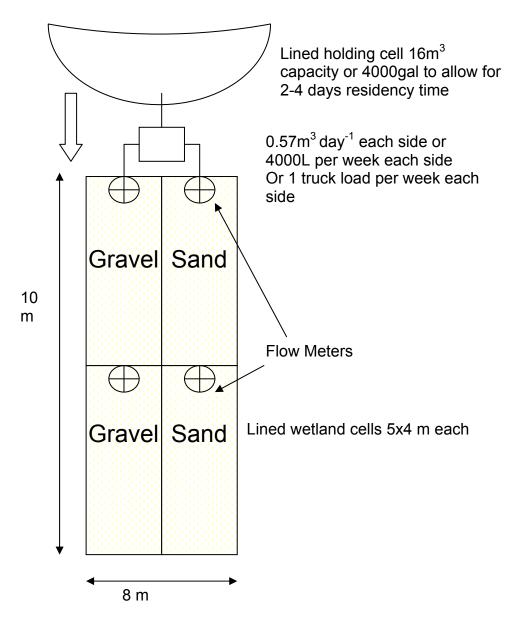


Figure 16 Details of Pilot System

The design will use available local materials, especially the substrates and plant species. Continuous monitoring will be carried out for the evaluation of the performance of these systems (Table 7 and 8).

Table 7 Pilot Site Monitoring Program

Sampling Locations	
Holding cell	1
6 lysimeters per cell	24
Bottom and top x 4 cells	24
4 Final effluent ports	4
Total Sampling Locations	29
Number of Parameters	18
Number of Weeks	10
Total Number of Tests	5220

Table 8 Pilot Site Wastewater Analyses

Physical parameters	Chemical parameters	Microbiological parameters
• pH	Ammonia	• E. coli
 Temperature 	 Nitrate 	 Total Coliform
 Conductivity 	 Nitrite 	
 Total suspended 	TKN	
solids	 Particulate Organic P 	
 Particulate Organic 	 Particulate Organic N 	
Matter	 Total Phosphorus 	
Turbidity	• COD	
 Dissolved oxygen 	 CBOD₅ 	

Monitoring will continue through 2009 and possibly 2010 pending funding. The results will be published in primary literature and made available to government and regulatory partners. This research will be used to upgrade and validate the SubWet wetland design tool and may also aid in establishment of the effluent standards by the Nunavut Water Board.

9.4 Use of SubWet Model

A model is an idealization of a real situation, in which the most important components are identified, their interactions described and used as a tool to solve problems (Jorgensen, 1986). The SubWet model from UNEP will be applied to simulate the functioning of CWs in the Arctic environment. It is used in the modelling of subsurface wetland systems. The main goal will be to calibrate the SubWet model for use in cold climate application. The baseline data accompanied by the experimental data for running the preliminary simulation, will form the backbone of this model. This work will be conducted together with Prof. Sven Eric Jorgenson (University of Copenhagen, Denmark) and Dr. Vicente Santiago from UNEP-IETC, Japan.

Models cannot work without reliable data, as shown in the ecological modelling process (Figure 17). Pre-existing data is required for the preliminary simulation of the model; hence, this is one of the objectives of carrying out the characterisation study. Specifically, the emphasis of this research will be the acquisition of primary and secondary data for the performance prediction and optimal design of CWs in Arctic

conditions. The model will take into consideration forcing functions, state variables, process equations, universal constants, and cold climate parameters for the simulation of removals of nitrogen, phosphorus and BOD₅ in mg/l and corresponding removal efficiencies. The SubWet model will be an effective tool for decision making process regarding the design of CWs.

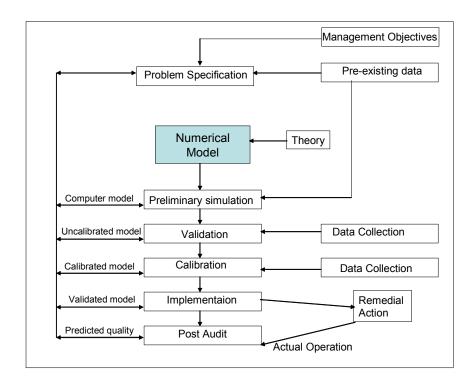


Figure 17 Ecological Modelling Process. Source: Jorgenson et. al (2007)

10. Milestones

This research will be carried out over the next three years. The time-plan is given in Table 9.

Table 9 Research Milestones

Research	Timeline
Characterization	2008 (June to Sept); continue in 2009
Experiments in CAWT	2008 (Oct) to 2009 (Feb)
Pilot CW	2008 (June- Aug); monitoring continuous in 2009
Modelling	2009
Documentation	2009 to 2010

11. Conclusion

This research will contribute significantly to solving wastewater treatment challenges in the Canadian Arctic. The characterization of existing wetlands from the study area will contribute to understanding the performance variability of the treatment systems. The design, implementation and monitoring of pilot constructed wetlands in Arctic conditions will help in furthering engineering and design knowledge for efficient resource management in communities. The in-situ experiments in CAWT will help in understanding system dynamics and provide further answers to research questions for effective application in the Arctic. The modelling and develop of a cold climate SubWet program in partnership with the UN will provide opportunities for not only scientists but for wastewater managers that are in need of effective and practical design tools.

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The Hamlets of Arviat Whale Cove Rankin Inlet Chesterfield Inlet Baker Lake Repulse Bay Coral Harbour