Cambridge Bay Wetland Planning Study

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Introduction

This report presents an estimate of wetland water quality improvement performance based on the current lagoon design and anticipated population patterns for the community of Cambridge Bay, Nunavut. The configuration of the Cambridge Bay system includes retaining wastewater in winter in primary and secondary lagoons (**Figure 1**). The volume of these lagoons is 120,000 m^3. The current discharge from the community is 225 m^3/d, and that is expected to increase to 330 m^3/d by the year 2025. The nominal detention times are therefore 533 days under current flows, and 365 days for year 2025 flows.

It is proposed that the lagoon discharges will be directed to constructed wetlands, which will convey and further treat the water before final discharge to the north arm of Cambridge Bay. The 2.93 ha wetland will be constructed by berming the flow path from the lagoons to the sea, and excavating as necessary to remove existing features as needed (**Figure 2**). In particular, a scrap metal pile will be removed to another location, and an existing berm will be relocated. The discharge from the lagoons through the wetland is proposed to be continuous during the summer season, of approximately three months duration. At a 45 cm operating depth, the wetland will provide 14 days detention at the current flows delivered during the summer, and 10 days detention at future flows.

Treatment in the wetland is expected to be the result of a number of processes, such as settling, filtration, and bacterial action. These are aided by the presence of wetland vegetation, which is expected to be relatively sparse. However, such vegetation does now exist in the depression ponds within the proposed wetland footprint.

As an estimate of treatment potential, it is assumed that lagoon treatment will occur in the unfrozen lagoons, and that the combined meltwater and warm weather flows will have TSS and CBOD of approximately 50 and 30 mg/L respectively at current flows, and 75 and 50 mg/L at the 2025 flows. Total phosphorus is anticipated to be approximately 2.5 mg/L, and total nitrogen about 16 mg/L. The basis for these estimates is water quality measured in samples taken in June 1998, June 2006, and August 2007.

The discharge season is assumed to be the three month unfrozen period, during which the water temperatures are estimated to average 5.4°C, with a range of only from 2 – 8 °C (Environment Canada, 2005). That period will see flows from the frozen wastewater and lagoons, accompanied by melting and seepage phenomena. Stored water released during the warm season will make room for the next cold season's deliveries to the lagoons. The warm season flow to the wetlands will average approximately 894 m^3/d, or about four times the daily rate of generation, under current conditions. Warm season flows to the wetlands will increase to 1311 m^3/d in the year 2025.

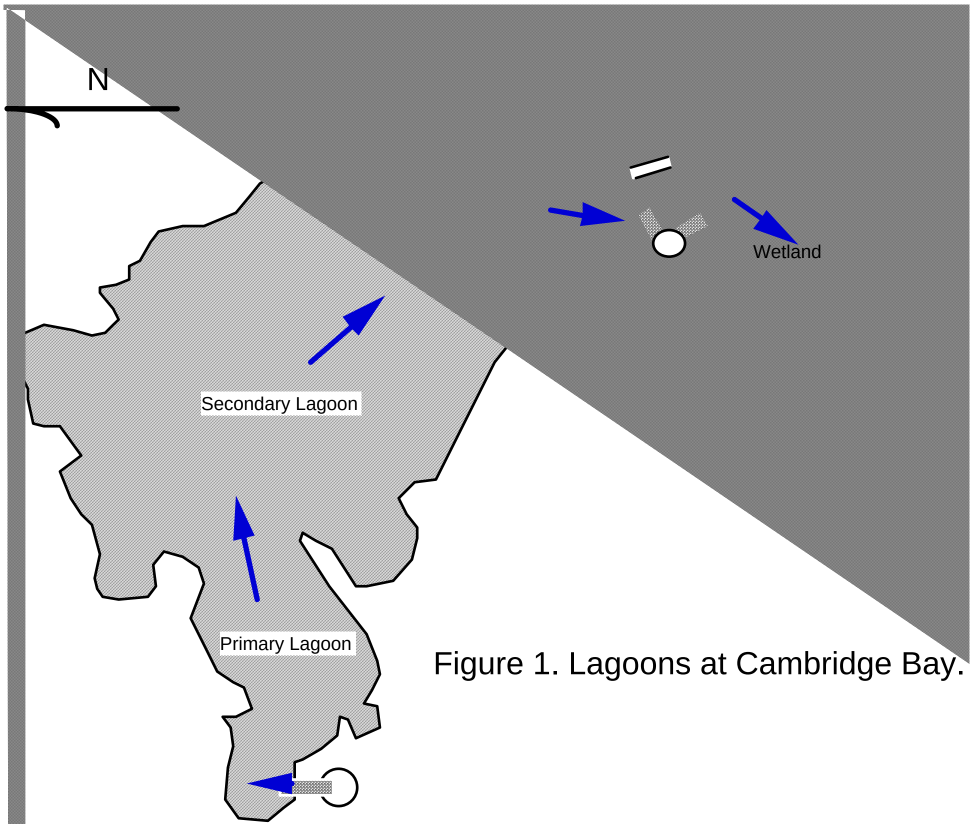

Figure 1. Lagoons at Cambridge Bay.

Figure 1. Lagoons at Cambridge Bay

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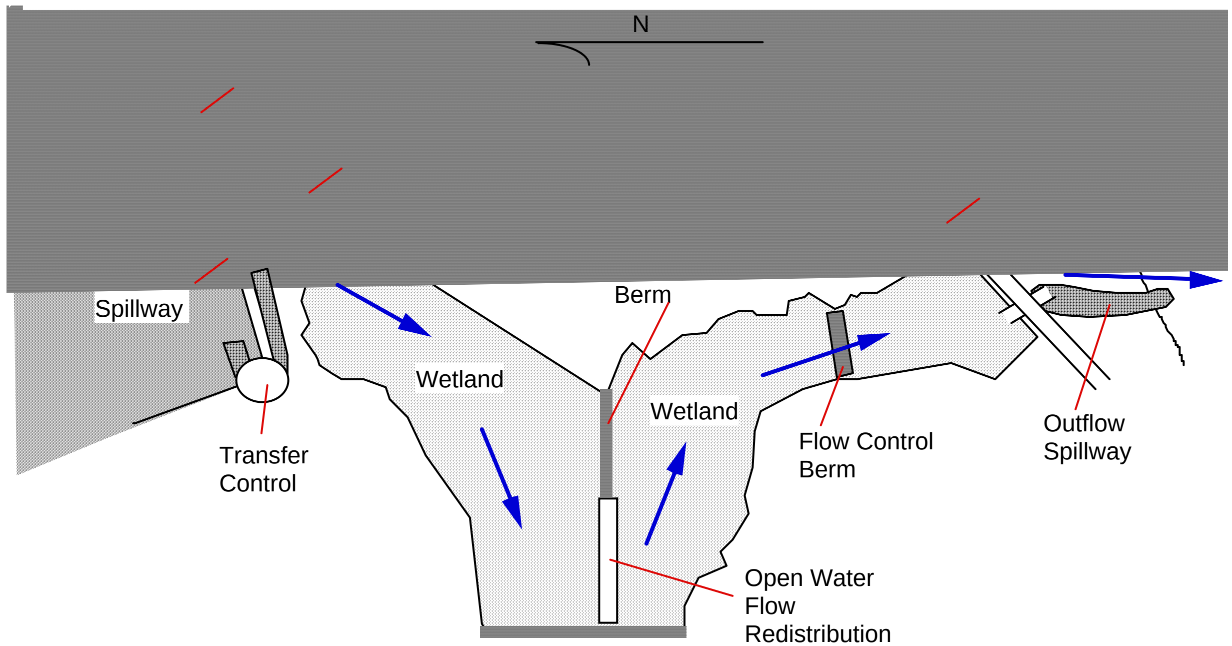

Figure 2. Proposed treatment wetland.

Figure 1. Lagoons at Cambridge Bay

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Wetland Forecasting Procedure

Three principal themes have been prevalent in the history of constructed treatment wetland design: consideration of the pollutant and hydraulic loadings, first order removal models, and regression equations. The strategy advocated here is to utilize the existing data sets to maximum advantage, while retaining as much simplicity as possible. The strategy used here attempts to salvage the good features of past work, and to improve upon past methods as much as data can support. The strategy is not simpler than previous methods, because it includes more pieces; that is, it is an integrated rational approach to forecasting. The calculations are implemented via spreadsheets on a desktop computer, because of the level of detail in the procedure.

The key features of the forecasting procedure are:

Basis:

1. Set inlet concentrations
2. Set inflow and seepage
3. Determine rain, evapotranspiration (ET), temperature
4. Select wetland area

Parameter Selection and Calculation:

5. Select rate constants and seasonality
6. Select detention time distribution (DTD) (hydraulic) efficiency = P value (Select compartmentalization).

Constraint Checks:

7. Set estimated growth cycle
8. Check biogeochemical cycles for consistency
9. Check constraints (hydraulic and chemical)
10. Check loading graph for intersystem comparison.

Water Budget

The annual water budget forms the basis for a first approach to understanding pollutant reductions and the area required. Under the assumption of a constant water level, the flows out of the wetland may be computed from the inflow and the meteorological data. Some infiltration is assumed here, if leakage is present in the wetland. The relevant equations are:

$$Q_{out} = Q_{in} + A \cdot (P - ET - I) \quad (1)$$

or

$$q_{out} = q_{in} + (P - ET - I) \quad (2)$$

where A = wetland area, m^2

ET	=	evapotranspiration rate, m/d
I	=	infiltration rate, m/d
P	=	precipitation rate, m/d
q	=	hydraulic loading rate, m/d
Q	=	flow rate, m^3/d

The inlet hydraulic loading will be increased by rainfall (ca. 2.1 mm/d in the discharge season) (Environment Canada, 2005), and decreased by evapotranspiration (ca 1.5 mm/d, Engstrom et al, 2006). These amounts are important if the wetland is to have a very low hydraulic loading, or correspondingly, a long detention time. However, the hydraulic loading from the lagoons is expected to be far greater than these atmospheric additions and subtractions, at 3.0 – 4.5 cm/d. The ratio = $(P\text{-}ET)/q_i$ is the atmospheric augmentation, which is only 1 – 2 % for the proposed Cambridge Bay wetlands.

The pollutant mass balances will be conducted on a cells-in-series basis. Results of the overall water mass balance are apportioned to the cells according the chosen number of tanks in series (PTIS), which is presumed to be three, the average of tracer testing results of a large number of wetlands. For the first unit in the series:

$$Q_1 = Q_{in} + A_1(P - ET - I) \qquad (3)$$

where:	A_1	=	area of tank number 1, m^2
	Q_1	=	flow rate out of tank 1, m^3/d

Flows are thus computed sequentially, from inlet to outlet, for the number of tanks chosen (PTIS = 3). This value is conservative for Cambridge Bay, because deep zones and interior berms are proposed to improve the hydraulic efficiency.

Flow Rates

The flow from the community is expected to be 225 m^3/d, for a total of 82,220 m^3/yr. This flow is augmented by about 30,000 m^3/yr of precipitation accumulated in the drainage area of the lagoons, but summer ET losses are about the same (Engstrom et al, 2006). The total water leaving the area of the two lagoons is thus taken to be 82,220 m^3/yr, which is discharged over the period of 92 days. Thus the average flow to the wetlands is 894 m^3/d during discharge under current conditions, and 1,311 m^3/d for 2025 conditions.

Seepage is expected to be negligible, because of the hard rock base of the region, presumably including the wetland.

Pollutant Mass Balances

Water passes through P tanks in series, and loses contaminant in each. For the case of no water losses or gains, the steady flow contaminant mass balance for the j^{th} tank is:

$$(QC_{j-1} - QC_j) = kA(C_j - C^*) \qquad (4)$$

where	Cj	=	concentration in and leaving tank "j", gm/m^3
	C*	=	background concentration, gm/m^3

k = removal rate constant, m/d (or with unit conversion, m/yr)

For the entire sequence of tanks, these mass balances combine to:

$$\frac{(C - C^*)}{(C_0 - C^*)} = \left(1 + \frac{k\tau}{Ph}\right)^{-P} \qquad (5)$$

where C_o = concentration entering the wetland, gm/m^3

h = water depth, m

P = number of tanks in series, PTIS

τ = nominal detention time, d

Note that there are two reaction parameters in this model: the rate constant "k" and the hydraulic parameter "P." However, wetlands typically have inputs of rain, and outputs of evaporation and infiltration. Therefore, the flows are not spatially uniform, and a tank to tank calculation must be invoked. Also note that for very large P-values, this model becomes the exponential, plug flow model of Kadlec and Knight (1996).

The tanks in series model is then carried forward via a sequential calculation of pollutant concentrations for each "tank" in the chosen hydraulic model.

A first order areal model with rate constant k is selected, with a wetland background concentration C* as necessary. The pollutant mass balance for the first of the wetland segments, designated by subscript "1", for steady state, non-uniform flow is:

$$Q_1C_1 = Q_{in}C_{in} - I \cdot A_1C_1 - \alpha ETA_1C_1 - k \cdot A_1 \cdot (C_1 - C^*) \qquad (6)$$

In this simple version, rainfall has been assumed to have a zero pollutant concentration, but it is easy to add an atmospheric input of the pollutant if it exists. Infiltration is assumed to occur at the outlet concentration. Transpiration flow of the contaminant has been included. Combining (3) with (6) gives the concentration exiting hypothetical segment number one:

$$C_1 = \frac{Q_{in}C_{in} + k \cdot A_1 \cdot C^*}{Q_1 + (\alpha ET) \cdot A_1 + I \cdot A_1 + k \cdot A_1} \qquad (7)$$

or

$$C_1 = \frac{q_{in}C_{in} + k \cdot C^*}{q_1 + (\alpha ET) + I + k} \qquad (8)$$

Note that the hydraulic loading rates in (8) are the tank loading rates, not the system loadings. This computation is then repeated sequentially for the remaining segments, in each case using the outlet concentrations and flows from the preceding unit. The wetland outlet concentration is that exiting from the final hypothetical segment.

The additional input data requirements for the pollutant mass balances are:

1. Input concentration (C_{in});
2. Background concentration (C*);
3. Transpiration fraction (β);
4. Rate coefficient (k).

Inlet Concentrations

The wastewater from the community has high strength, due to the restricted use of water. However, water reaching the wetlands will have that strength greatly reduced, due to extended lagoon treatment. The inlet concentrations in **Tables 1** and **2** are estimated from data taken in prior years at the lagoon discharge.

Background Concentrations

Wetland systems are dominated by plants (autotrophs), which act as primary producers of biomass. However, wetlands also include communities of microbes (heterotrophs) and higher animals, which act as grazers and reduce plant biomass. Most wetlands support more producers than consumers, resulting in a net surplus of plant biomass. This excess material is typically buried as peat or exported from the wetland. The net export results in an internal release of particulate and dissolved biomass to the water column, which is measured as non-zero levels of BOD, TSS, TN, and TP. These wetland background concentrations are typically denoted by the term C*. Enriched wetland ecosystems (such as those treating wastewater) are likely to produce higher background concentrations. The background concentrations in **Tables 1** and **2** are estimated from the literature.

Transpiration

The fraction of water loss due to transpiration is assumed to be 20%. This flow draws water into the root zone for enhanced treatment.

Contaminant Removal Rate Coefficients

The rate coefficients used to calculate estimated removals vary from substance to substance. The mechanisms and chosen values are discussed in this section.

Suspended Solids

A major function performed by wetland ecosystems is the removal of suspended sediments from water moving through the wetland. These removals are the end result of a complicated set of internal processes, including the production of transportable solids by the wetland biota. Low water velocities, coupled with the presence of litter on the wetland bottom, promote fallout and trapping of solid materials. This transfer of suspended solids from the water to the wetland sediment bed has important consequences both for the quality of the water and the properties and function of the wetland ecosystem.

A wetland processes sediments and suspended solids in a number of ways. After the suspended material reaches the wetland, it joins large amounts of internally-generated suspendable materials, and both are transported across the wetland. Sedimentation and trapping, and resuspension, occur en route, as does "generation" of suspended material by activities both above and below the water surface. Chemical reactions may cause the formation of solids that can deposit. Algal and plant debris may form at one location and deposit downgradient in the wetland. Thus it is clear that the TSS leaving a treatment wetland of moderate to long detention is more reflective of generation and resuspension than of unsettled incoming solids.

Table 1. Performance calculation sheet, FWS wetland
Cambridge Bay
Nunavut
Uniform Discharge

With P & ET, N TIS

N = 3 RTD Parameter

T = 5.4 C
I = 0.00 cm/day
P = 0.21 cm/day
ET = 0.14 cm/day
Trans = 0.03 cm/day 0.200 =T/ET
a = 0.07 Augmentation
Ieff = 0.10 m/yr Effective Leakage
y = 1.00 Fraction NH4-N Nitrified

1609 pe
140 L/pe d 82220 m3/yr
92 d

Design Flow, m3/d Q = 894 m3/d 0.236 mgd

		TSS	CBOD	TP	Org-N	NH4-N	NOx-N	TN	TKN	FC
Influent Concentration, mg/L	Ci =	50	30	2.50	5.00	10.00	0.50	15.50	15.00	1,000
Influent Loadings, kg/ha/day		15.3	9.2	0.76	1.5	3.1	0.2	4.7	4.6	
Permit Effluent Conc., mg/l	Ce =									
Permitted Load to Receiving Water, kg/day										
Max Month/Annual Factor										
Design Target Conc., mg/L	Cd =	25.0	25.0							
Wetland Background Limit, mg/l	C* =	10.0	5.0	0.002	1.50	0.00	0.00	1.50		50
Areal Rate Constant, 20 C, m/y	k20 =	50	20	2	10	8	27	15		83
Temperature Factor	q =	1.000	1.000	1.000	1.000	1.050	1.100	1.060		1.000
Areal Rate Constant, m/y	k =	50	20	2	10	4	7	6		83

Porosity = 0.95 HRT = 13.8 days Area = 315,248 ft2
Bed Depth = 0.45 m HLR in = 3.05 cm/d 7 acres
HLR out = 3.12 cm/d 2.93 ha

		TSS	CBOD	TP	Org-N	NH4-N	NOx-N	TN	TKN	FC
Calculated Effluent Concentrations , mg/l	Co =	12.5	11.1	2.08	3.1	8.6	2.7	14.3	11.7	72
Effluent Loadings, kg/ha/day		3.92	3.46	0.65	0.96	2.68	0.83	4.47	3.64	
Effluent Loadings, kg/day		11	10	2	3	8	2	13	11	

Table 1. Performance Calculation Sheet, FWS Wetland

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Table 2. Performance calculation sheet, FWS wetland
Cambridge Bay
Nunavut
Uniform Discharge, Future

With P & ET, N TIS

N = 3 RTD Parameter

T =	5.4	C
I =	0.00	cm/day
P =	0.21	cm/day
ET =	0.14	cm/day
Trans =	0.03	cm/day — 0.200 =T/ET
a =	0.07	Augmentation
Ieff =	0.10	m/yr — Effective Leakage
y =	1.00	Fraction NH4-N Nitrified

2360 pe
140 L/pe d — 120596 m3/yr
92 d

Design Flow, m3/d — Q = 1,311 m3/d — 0.346 mgd

		TSS	CBOD	TP	Org-N	NH4-N	NOx-N	TN	TKN	FC
Influent Concentration, mg/L	Ci =	75	50	2.50	5.00	10.00	0.50	15.50	15.00	1,000
Influent Loadings, kg/ha/day		33.6	22.4	1.12	2.2	4.5	0.2	6.9	6.7	
Permit Effluent Conc., mg/l	Ce =									
Permitted Load to Receiving Water, kg/day										
Max Month/Annual Factor										
Design Target Conc., mg/L	Cd =	25.0	25.0							
Wetland Background Limit, mg/l	C* =	10.0	5.0	0.002	1.50	0.00	0.00	1.50		50
Areal Rate Constant, 20 C, m/y	k20 =	50	20	2	10	8	27	15		83
Temperature Factor	q =	1.000	1.000	1.000	1.000	1.050	1.100	1.060		1.000
Areal Rate Constant, m/y	k =	50	20	2	10	4	7	6		83

Porosity =	0.95		HRT =	9.5	days	Area = 315,248 ft2
Bed Depth =	0.45	m	HLR in =	4.47	cm/d	7 acres
			HLR out =	4.55	cm/d	2.93 ha

		TSS	CBOD	TP	Org-N	NH4-N	NOx-N	TN	TKN	FC
Calculated Effluent Concentrations , mg/l	Co =	17.8	21.0	2.20	3.5	9.2	2.2	14.8	12.6	98
Effluent Loadings, kg/ha/day		8.11	9.56	1.00	1.59	4.16	0.98	6.73	5.75	
Effluent Loadings, kg/day		24	28	3	5	12	3	20	17	

Table 2. Performance Calculation Sheet, FWS Wetland

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Accordingly, the estimated k-value for TSS has been chosen as 50 m/yr, with no effect of water temperature. In any case, the water temperature in the wetlands is expected to range only from 2 – 8 °C, with a mean discharge season value of 5.4°C. This rate coefficient is sufficiently high to drive the wastewater TSS down close to the background value of 10 mg/L.

Carbonaceous Biochemical Oxygen Demand

Carbon compounds interact strongly with wetland ecosystems. The carbon cycle in wetlands is vigorous and typically provides carbon exports from the wetland to receiving ecosystems. Many internal wetland processes are fueled by carbon imports and by the carbon formed from decomposition processes.

Treatment wetlands frequently receive large external supplies of carbon in the added wastewater. Any of several measures of carbon content may be made, with Carbonaceous Biochemical Oxygen Demand ($CBOD_5$) being the parameter of inteest for Cambridge Bay. Degradable carbon compounds are rapidly utilized in wetland carbon processes. At the same time, a variety of wetland decomposition processes produce available carbon. The balance between uptake and production provides the carbon exports. In general, the amounts of carbon cycled in the wetland are comparable to the quantities added in domestic wastewater. The wetland cycle of growth, death, and partial decomposition uses atmospheric carbon, and produces gases, dissolved organics, and solids. Decomposition involves the sugars, starches and low molecular weight celluloses in the dead plant material. Gaseous products include methane and regenerated carbon dioxide. A spectrum of soluble large organic molecules, collectively termed humic substances, are released into the water. The solid residual of plant decomposition is peat or organic sediment, which originated as celluloses and lignins in the plants. These wetland soil organics are broadly classified as fulvic material, humic material, and humin.

The P-k-C* first order model can readily account for observations, for appropriate values of parameters. There are four levels of inlet concentration to be considered: tertiary ($0 < Ci < 30$ mg/L); secondary ($30 < Ci < 100$ mg/L); primary ($100 < Ci < 200$ mg/L); and "super" ($Ci > 200$ mg/L). The Cambridge Bay situation is expected to be in the second group, with moderate incoming $CBOD_5$. At moderate strength, the k-values for $CBOD_5$ are relatively high, with a median value of 41 m/yr for 77 wetland datasets. Further, temperature effects have been found to be minimal. For purposes of forecasting, k = 30 m/yr has been selected, which is the 40th percentile of the distribution across wetlands (Kadlec and Wallace, 2008). This rate coefficient is sufficiently high to drive the wastewater $CBOD_5$ down to 9 mg/L under current conditions, and 16 mg/L for future flows in 2025.

Nitrogen

Nitrogen compounds are among the principal constituents of concern in wastewater because of their role in eutrophication, their effect on the oxygen content of receiving waters, and their toxicity to aquatic invertebrate and vertebrate species. These compounds also augment plant growth, which in turn stimulates the biogeochemical cycles of the wetland. The most important inorganic forms of nitrogen in wetlands treating municipal or domestic wastewater are ammonia (NH_4^+) and oxidized nitrogen (NO_2^- and NO_3^-). Nitrogen is also invariably present in wetlands in organic forms. Both dissolved and particulate forms may be present, but in most cases there is little particulate nitrogen in settled wetland surface waters.

Organic Nitrogen

Wastewaters contain varying amounts of organic nitrogen, depending upon the source. Nitrogen in domestic sewage is comprised of about 60% ammonia, and 40% organic nitrogen. Lagoon effluents may retain approximately the same proportions while reducing total nitrogen. For Cambridge Bay, it has been assumed that there are 5 mg/L of organic nitrogen that survive passage through the two lagoons, compared to 10 mg/L of ammonia nitrogen, the later based on limited data from the existing lagoons.

Ammonification is the biological transformation of organic nitrogen to ammonia and is the first step in mineralization of organic nitrogen. This process occurs both aerobically and anaerobically, and releases ammonia from dead and decaying cells and tissues. Kinetically, ammonification proceeds more rapidly than nitrification, thus creating the potential for increasing ammonia concentrations along the flow-path of a wetland and requiring design for nitrogen removal to be include both ammonification and the slower nitrification process. The ammonification process does not proceed to completion in wetlands, although the removal of ammonia can go to completion for long enough detention. There is an organic nitrogen background concentration which may consist of irreducible residuals, or be due to return fluxes of organic nitrogen from decomposing solids, which is typically 1.5 mg/L.

The median net period-of-record removal rate for 54 FWS systems receiving more than 5 mg/L of organic N is 97 g/m^2•yr. The median k-value for organic nitrogen is 17.3 m/yr, but the range is wide. The 10^{th} to 90^{th} percentile range is 3.6 – 39.9 m/yr. For purposes of forecasting, k = 10 m/yr has been selected, which is the 25^{th} percentile of the distribution across wetlands (Kadlec and Wallace, 2008). There appears to be little or no temperature dependence of organic nitrogen k-values.

Ammonia Nitrogen

Ammonia is an intermediate in the sequential processing of nitrogen in treatment wetlands, which is produced by ammonification of organic nitrogen, and reduced by aerobic and possibly anaerobic ammonia oxidation processes. Because of toxicity of free ammonia in receiving aquatic ecosystems, this nitrogen species is often singled out for regulation. Free ammonia depends upon water temperature as well as total dissolved ammonia.

When the TN loading to the wetland is less than the growth requirements of the plants and algae by a considerable margin, the removal of TN is very likely to be mediated by the growth and decay of biomass. As a rough guideline, this situation occurs for TN loading less than approximately 120 gN/m^2•yr. In the Cambridge Bay situation, plant growth requirements are insignificant compared to the ammonia loading of about 1,600 gN/m^2•yr, and the processing of ammonia is likely to be entirely due to microbial functions.

The median net period-of-record removal rate for 118 systems receiving more than 1 mg/L ammonia N is 127 g/m^2•yr. The value C* = 0.0 mg/L is used, and the remaining model parameter is the k-value. Calibration included ammonification (production) and nitrification (destruction), as well as return of organic nitrogen from the decomposition of biomass. The median annual rate constant was k= 14.7 m/yr. The 10^{th} to 90^{th} percentile range is 4.7 – 85.6 m/yr. For purposes of forecasting, k_{20} = 8 m/yr has been selected, which is the 25^{th} percentile of the distribution across wetlands (Kadlec and Wallace, 2008). There is a significant temperature dependence of ammonia k-values, with a theta value of 1.05. Therefore, at the mean water temperature of 5.4°C, the rate coefficient for ammonia is , k = 4 m/yr.

Oxidized Nitrogen

Nitrate is potentially tied quite closely to the process of nitrification in wetlands that receive both ammonia and oxidized nitrogen, because incoming nitrate loads may be supplemented by produced nitrate. For wetlands which receive and reduce large amounts of organic and ammonia nitrogen, the inferred denitrification is much different from the net loss or gain of nitrate from inflow to outflow. Nitrate is entirely consumable in treatment wetlands. The value for C* is zero, because no investigation has shown a lower limit to the reduction of nitrate.

Seventy-two nitrate-dominated wetlands were calibrated for k. The median annual rate constant was k_{NN} = 26.5 m/yr, while the average was k_{NN} = 30.0 m/yr. The 10^{th} to 90^{th} percentile range is 9.6 – 54.4 m/yr (Kadlec and Wallace, 2008). For purposes of forecasting, k_{20} = 27 m/yr has been selected, which is the 50^{th} percentile of the distribution across wetlands (Kadlec and Wallace, 2008). There is a significant temperature dependence of nitrate k-values; thus even on an average annual basis, temperature or season may be an important determinant of the rate constant, and these factors are thus responsible for the some of the intersystem variability in annual k-values. The median theta value for 20 wetlands was 1.10 (Kadlec and Wallace, 2008). Therefore, at the mean water temperature of 5.4°C, the rate coefficient for nitrate is k = 7 m/yr. Oxidized nitrogen is forecast to increase slightly in the treatment wetland.

Phosphorus

Treatment wetlands are capable of phosphorus (P) removal from wastewaters, on both short-term and long-term bases. Phosphorus is a nutrient required for plant growth, and is frequently a limiting factor for vegetative productivity. P-cycling in wetlands may be visualized as consisting of several compartments: water, plants, microbiota, litter, and soil. There are three principal categories of P removal processes in wetlands: sorption, utilization to build a bigger biomass compartment, and storage as newly created, refractory residuals (burial). The first two are transitory processes, and the corresponding capacities are used up. The third, accretion of new materials with structural phosphorus, is sustainable. There is a misconception that wetlands provide phosphorus removal only through sorption processes on existing soils. It is true that most soils do have sorptive capacity for phosphorus, but this storage is soon saturated under any increase in phosphorus loading. There are two direct effects of vegetation on phosphorus processing and removal in treatment wetlands:

1. The plant growth cycle seasonally stores and releases P, thus providing a “flywheel” effect for a P removal time series.

2. The creation of new, stable residuals, which accrete in the wetland. These residuals contain phosphorus as part of their structure, and hence accretion represents a burial process for P.

Despite the apparent complexity of the several removal mechanisms, data analysis shows that relatively simple equations can describe the sustainable processes. Profiles of phosphorus concentration within wetlands typically show a decreasing trend that approaches the background concentration asymptote if the wetland is large enough. Global first order removal rates characterize such removal profiles, but do not incorporate any biotic features. Results across systems are given here, for measured P-values, or for the mean of those (P = 3.4) when not measured. The value C* = 0.002 mg/L is used, and the remaining model parameter is the k-value, selected to fit the model. Across 282 wetlands, the median annual rate constant was k = 10.0 m/yr. The 10^{th} to 90^{th} percentile range is 1.4 – 60 m/yr. (Kadlec and Wallace, 2008). For purposes of forecasting, k_{20} = 2 m/yr has been selected, which is the 15^{th} percentile of the distribution across wetlands (Kadlec and Wallace, 2008). This low value is selected because of the perceived low amount of biological activity in the Cambridge Bay wetland. There appears to be little or no temperature dependence of phosphorus k-values.

Pathogens

Pathogens are present in untreated domestic wastewaters. Wetlands have been found to reduce pathogen populations with varying but significant degrees of effectiveness. Bacteria, protozoa, helminths and viruses typically do not survive longer than about 30 days in freshwater environments, and about 50 days in soil environments. Similar survivals might therefore be predicted for wetlands, but there are many site-specific factors and processes which may materially increase or decrease survival. Ultraviolet radiation is a potent agent for killing bacteria. Most bacteria are food for nematodes, rotifers and protozoa. Among these, rotifers and flagellated and ciliated protozoa have been implicated as important contributors to the reduction of bacteria in treatment wetlands. A measurable proportion of wastewater microorganisms are found either associated with particulates, or as aggregates of many organisms, and are removed by particulate settling and trapping.

First-order models have been used to describe reduction of indicator bacterial populations in lagoons and wetlands. Data from 28 FWS systems, totaling 47 wetland-years, was used to estimate fecal coliform k-values for a presumed C* = 50/100ml. These systems were selected for having at least 1,000/ 100ml inlet FC, thus eliminating systems with low incoming FC. Because the critically-important PTIS values were not known, PTIS = 3 (a modest degree of departure from both plug flow and complete mixing), was used. The resulting annual median k-values was 83 m/yr. There are not pronounced seasonal effects or temperature effects for fecal coliform removal in the FWS treatment wetland datasets that are currently available. Until more wetland data becomes available, it is recommended that global wetland fecal coliform reduction be regarded as independent of temperature and season.

Summary of Estimated Wetland Water Quality Improvement

The presumed 3 hectares of lower wetland in the flow path of the effluent, if at a mean depth of 30 cm, would provide about two weeks detention in the wetland. Removal rate coefficients have been assumed to be at the low end of the probability distribution for nutrients, $CBOD_5$ and TSS; and these have been further reduced according to estimates of temperature effects caused by the 5.4°C water. The workbooks given in the Appendix show the expected removals for current and future conditions, and their relation to the data from other systems, and the implications for nutrient cycling. The forecasts for water quality at the downstream end of the wetland are given in **Table 3**.

Wetland Cycles

Carbon, phosphorus and nitrogen are all cycled by the wetland ecosystem. It is prudent to examine whether the assigned rates lead to a reasonable set of ecosystem uptakes, releases and burials (Appendix). These rely upon estimates of the amounts of biomass and nutrient contents, and so are not precise. The analyses are based upon estimates of what the ecosystem will be like. Such estimates cannot be precise, and consequently the analysis is “order-of-magnitude” only. The intent is to gain some insight into the relative importance of wetland processes. Only current conditions are discussed here, however the future condition information is in the Appendix.

Table 3. Expected Water Quality into and out of the Treatment Wetland at Cambridge Bay

		Current Conditions		2025 Conditions	
		From Lagoons	Wetland Outlet	From Lagoons	Wetland Outlet
TSS	mg/L	50	13	75	18
BOD	mg/L	30	9	50	16
TP	mg/L	2.5	2.1	2.5	2.2
Org-N	mg/L	5	3.1	5	3.5
NH4-N	mg/L	10	9	10	9
NOx-N	mg/L	0.5	2.7	0.5	2.2
TN	mg/L	15.5	14	15.5	15
TKN	mg/L	15	12	15	13
FC	#/100ml	1,000	70	1,000	100

Carbon Cycling

The growth, death and decomposition processes are referred to as part of the wetland carbon cycle, but more than carbon is involved. However, most vegetation and other wetland organisms are about 40% carbon, so either dry biomass or carbon serves to track the amount of material involved. Carbon itself is withdrawn from atmospheric sources, as carbon dioxide for photosynthesis. Likewise, carbon is returned to the atmosphere as methane from anaerobic mechanisms, or carbon dioxide from oxidative processes (respiration included). The important estimation quantities are:

- Annual growth rate, g/m2•yr (standing crop phytomass = necromass + biomass times turnovers per year)
- Annual burial fraction (undecomposable residual fraction)

The assumption is made that nutrients taken up, but not buried as accretion, are returned to the water column of the FWS wetland. For nitrogen, this is a maximum estimate, because microbial processes in above-water tissues can transfer nitrogen to the atmosphere without entering the water. These phytomass quantities, together with phytomass nutrient content (% or mg/kg) allow checks on the empirical removal calculations. The wetland carbon cycle is also critical to observed performance, as it relates to sediment oxygen demand and to the carbon supply for denitrification. The implied supply constraints of this carbon cycle are examined in the constraint check section.

The estimates for Cambridge Bay for the current condition are given in **Figure 3**. The maximum standing stock of vegetation is assumed to be 500 g/m^2 for each of above and below ground plant parts. Additionally, there is presumed to be 200 g/m^2 of micro-scale biota, including bacteria, algae, and similar. The turnover of the above ground material is in the growing period of about three months, but roots are assumed to turn over more slowly, over a period of two years. Nutrient contents are assigned in accordance with a large body of observations, from warmer climates. About 25% of the biomass is assumed to be undecomposed. This carbon cycle is much smaller than would be observed in a warmer climate for similar water conditions, by about a factor of four or five.

Phosphorus Cycling

For phosphorus, the calculated removal is represented as a large uptake, in major part balanced by the return of soluble P from decomposition. For a stable ecosystem past startup, the net P removal associated with the k-rate calculation is assigned to accretion. Sorption and building of biomass not considered sinks for phosphorus.

Figure 4 shows the estimate of the phosphorus cycle in the wetland for the current condition. Because the nutrient concentrations are high (2.5 mg/L P and 15.5 mg/L TN), it is anticipated that the nutrient rich condition will prevail. The biogeochemical cycle removes 16 gP/m^2•yr from the water column, a large fraction of the loading to the wetland of 27.8 gP/m^2•yr. The k-rate calculations indicate that 4.7 gP/m^2•yr are removed, and hence it is deduced that (16.0 – 4.7) = 11.3 gP/m^2•yr are returned to the water from decomposition and leaching of the biomass. The removal to accretion is thus 4.7/16.0 = 29% of the biomass uptake. These uptakes and returns involve above ground plant parts, below ground plant parts and microbes and algae.

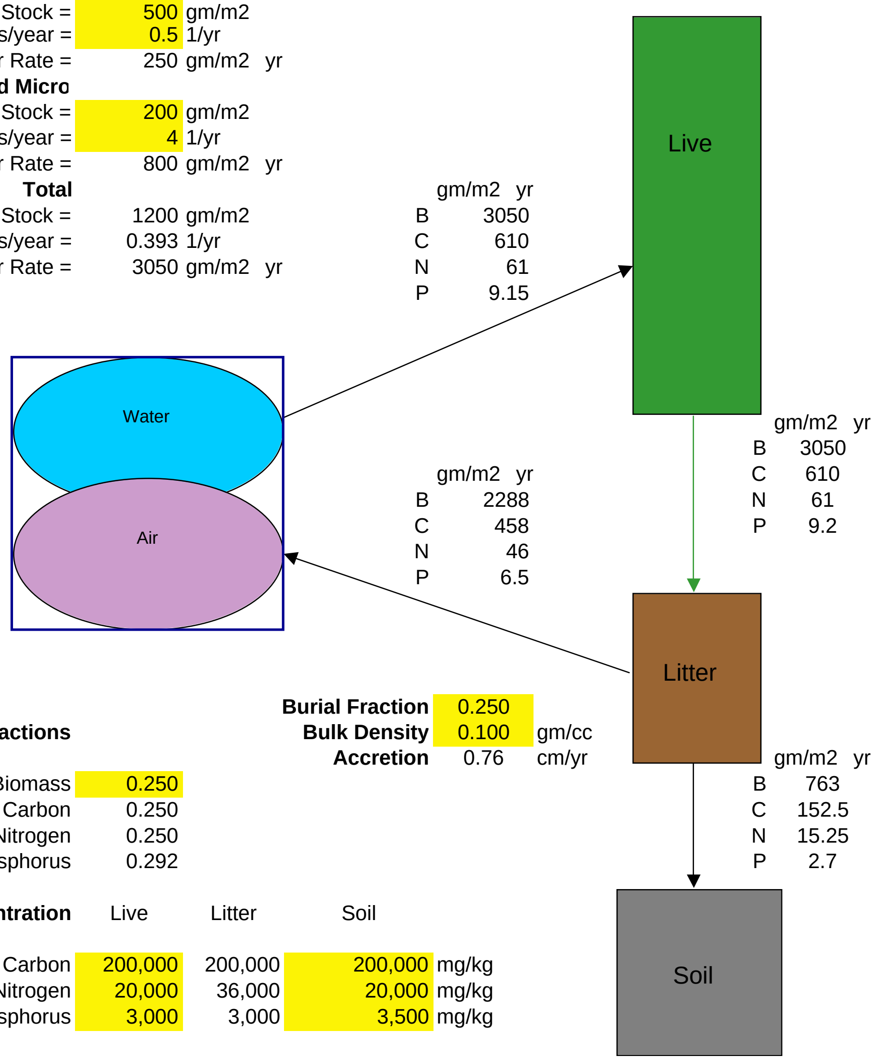
Nitrogen Cycling

For nitrogen, a more complex situation occurs as a result of the multiple speciation of water column nitrogen. The water column contains organic, ammonium and nitrate nitrogen. Their interconversions are computed from the empirical k-rates. The biogeochemical cycle is linked in a manner analogous to phosphorus, but with abstraction from both the ammonium and nitrate pools in the water, and return from both the ammonium and organic pools in the water. This allocation recognizes a split of plant uptake between ammonium and nitrate, and the fact that decomposition processes produce organic nitrogen. The nitrogen content in accreting sediments is known from extensive data from treatment wetlands to range from ca. 1.0 to 2.5 % dry weight. A higher value would be associated with nutrient-rich systems. Again, because the k-rate calculations are independent of the cycle calculation, there is one degree of freedom, which for nitrogen is taken to be an assumed percentage of the cycled nitrogen that is buried in accreting sediments. A nitrogen deficit may be assumed to be supplied by fixation, a process known to occur in N-deficient wetland environments.

As indicated in **Figure 5** for the current condition, the incoming nitrogen is presumed to be mostly organic (5 mg/L) and ammonia (10 mg/L), comprising almost all of the 15.5 mg/L of TN. The nitrogen loading to the wetland is high and places the system in the category of a microbial system. It is therefore expected that the biogeochemical cycling of nitrogen will not play an important role in the overall reduction. The required nitrogen to build the annually cycled biomass is 61 gN/m^2•yr, which is 35% of the nitrogen loading (**Figure 5**). The ultimate fate of removed nitrogen in the forecast is apportioned to accretion (27%) and denitrification (71%).

Figure 3. Carbon processing.

Aboveground Macro		
Standing Stock =	500	gm/m2
Turnovers/year =	4	1/yr
Turnover Rate =	2000	gm/m2 yr
Belowground Macro		
Standing Stock =	500	gm/m2
Turnovers/year =	0.5	1/yr
Turnover Rate =	250	gm/m2 yr
Aboveground Micro		
Standing Stock =	200	gm/m2
Turnovers/year =	4	1/yr
Turnover Rate =	800	gm/m2 yr
Total		
Standing Stock =	1200	gm/m2
Turnovers/year =	0.393	1/yr
Turnover Rate =	3050	gm/m2 yr



Burial Fractions	
Biomass	0.250
Carbon	0.250
Nitrogen	0.250
Phosphorus	0.292

Concentration	Live	Litter	Soil	
Carbon	200,000	200,000	200,000	mg/kg
Nitrogen	20,000	36,000	20,000	mg/kg
Phosphorus	3,000	3,000	3,500	mg/kg

Figure 3. Carbon Processing

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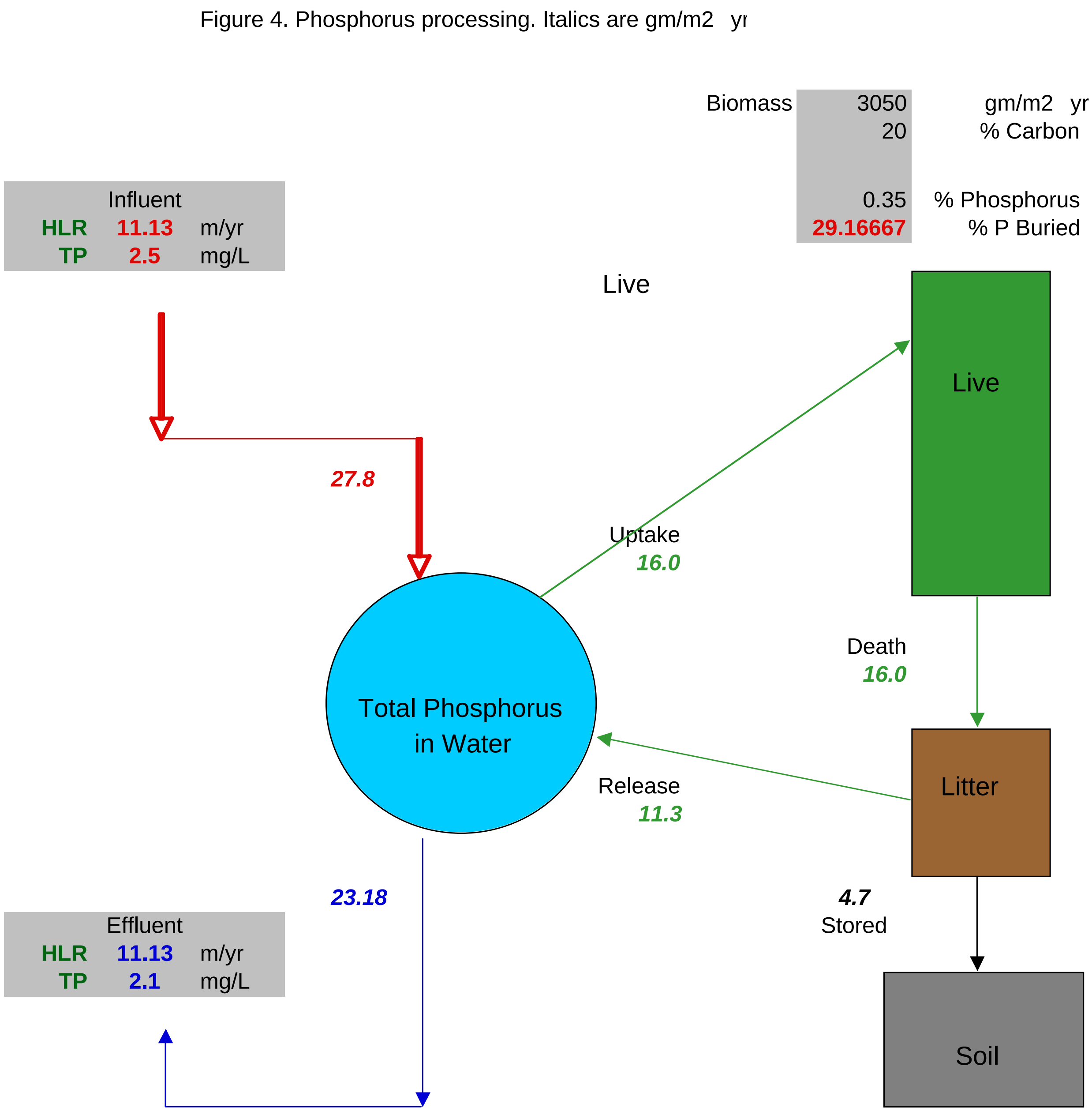

Figure 4. Phosphorus Processing

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Figure 5. Nitrogen processing. Italics are gm/m2 yr

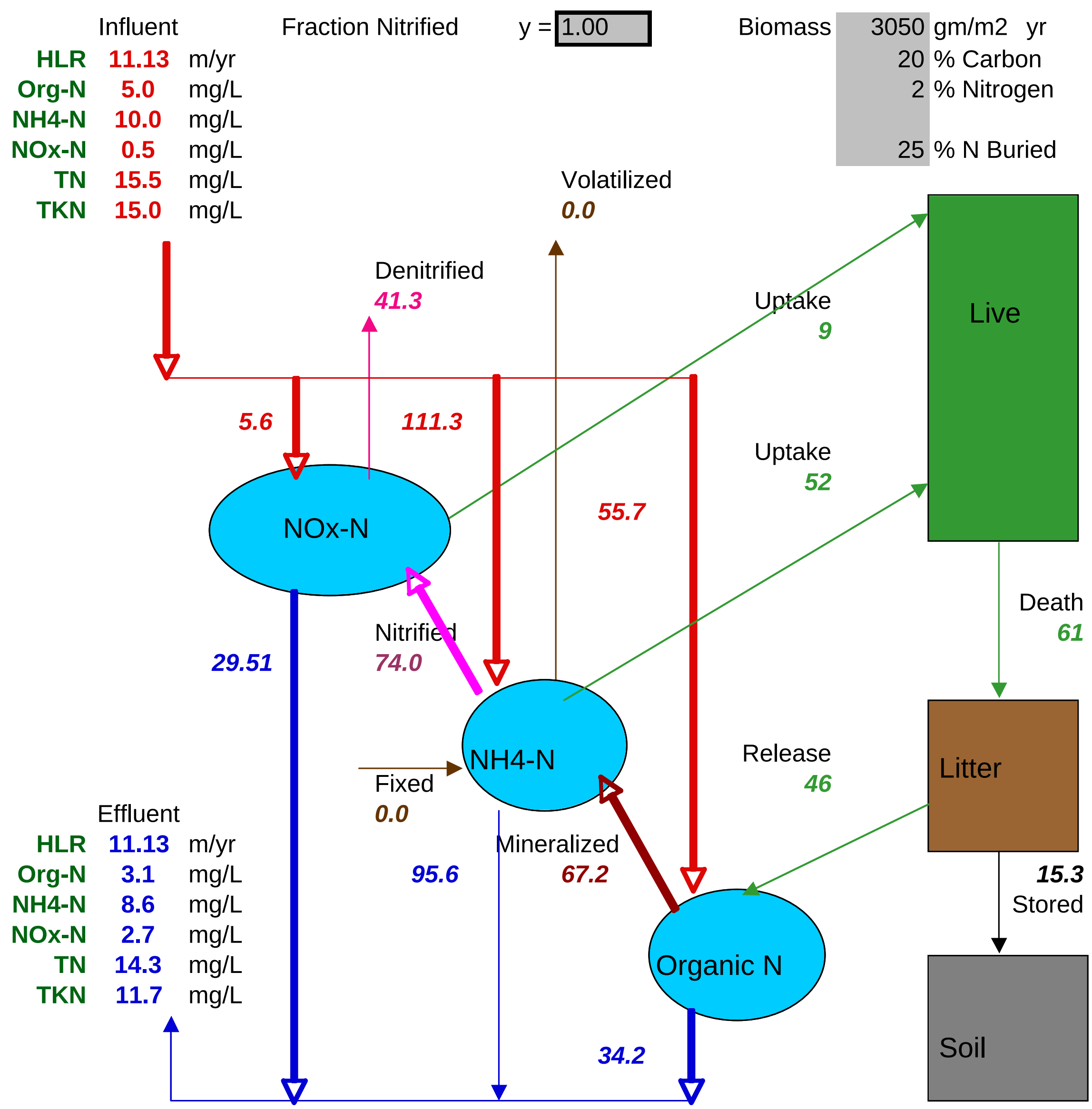

Figure 5. Nitrogen Processing

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Supply Constraints

Traditional chemistry assumptions indicate a requirement for carbon to support heterotrophic denitrification, and an oxygen requirement to support nitrification. The oxygen requirements for the predicted performance are calculated. Removal of $CBOD_5$ (0.65 $gO/m^2•d$) and nitrification (0.87 $gO/m^2•d$) exert only a slight oxygen demand, which would easily be supplied by atmospheric reaeration. The predicted denitrification requires an estimated 44 $gC/m^2•yr$, which is easily supplied by the 238 $gC/m^2•yr$ of the $CBOD_5$ removed. The vegetation will produce an even greater amount of carbon via decomposition, and thus the carbon supply is more than adequate to fuel denitrification.

Inter-System Comparisons

Loading graphs allow inter-system comparisons for common constituents. These are a plot of the wetland outlet concentration (mg/L) versus the constituent loading to the wetland (kg/ha•d or g/m2•d). Figures 6 - 9 show the position of the Cambridge Bay forecast with respect to the performance of a large number of operating treatment wetlands.

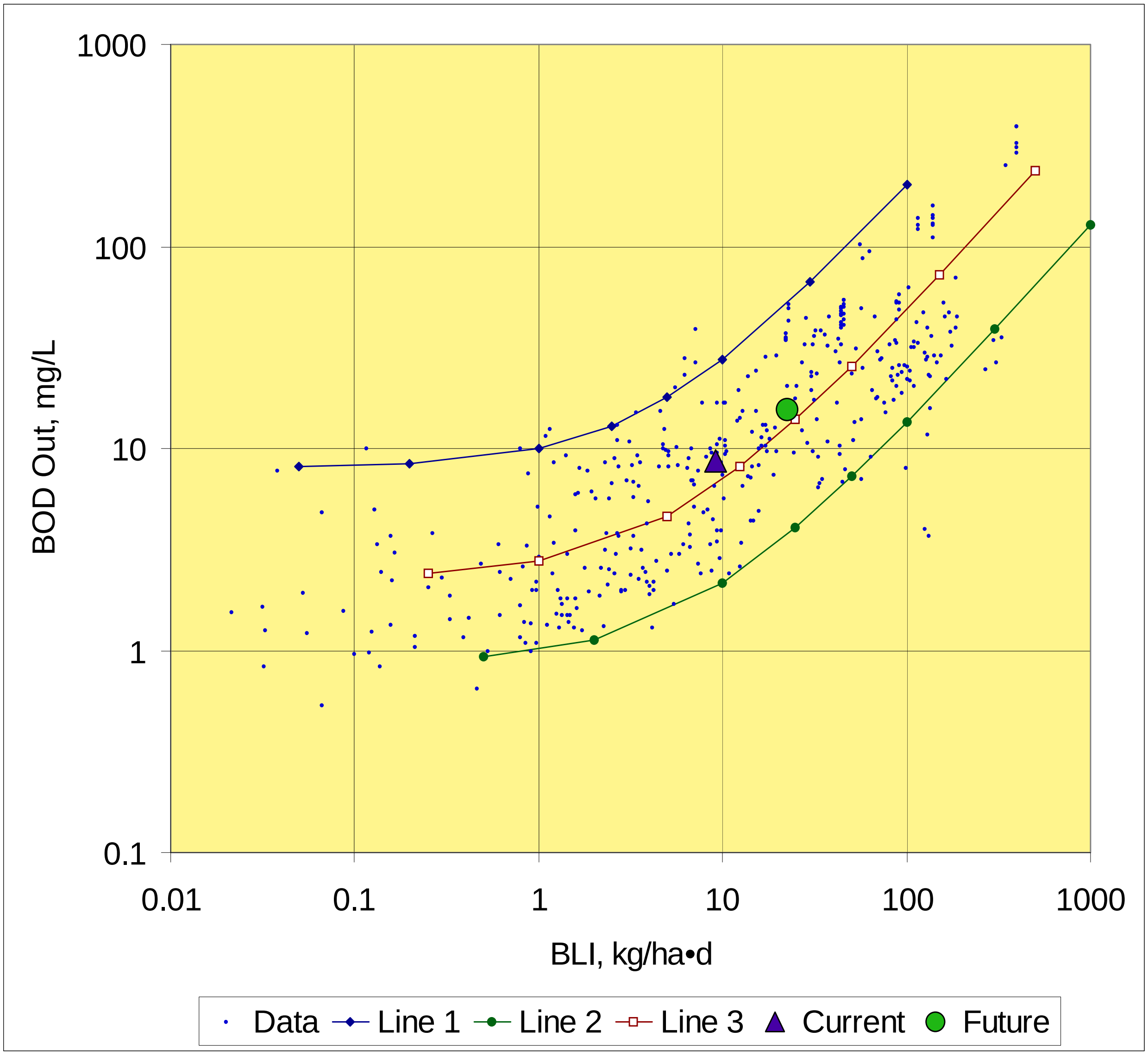
BOD and TSS

The removal of these contaminants relies upon particulate settling and microbial activity by the general class of heterotrophic bacteria, as well as algal activity. Settling and trapping are known to be effective during all seasons and water temperatures. Bacteria are known to be effective in cold climates, and therefore there is no perceived penalty for the far northern site. The removal rate constants have been selected to produce average removals, and therefore the predicted performance is close to the central tendency of behavior of the comparison systems (**Figures 6** and **7**).

Nitrogen and Phosphorus

The reduction of nitrogen in the wetland relies upon autotrophic nitrification to form oxidized nitrogen, and then upon heterotrophic denitrification. The nitrifying microbes are known to exhibit a rather slow build-up of populations, and are very sensitive to cold temperatures. Denitrifiers are usually present in larger numbers, and do not have a long period for growth, but they are also very temperature sensitive. Therefore, relatively low rate coefficients have been selected for nitrogen processing. The result is that the Cambridge Bay wetland shows lower TN removals than the comparison database, which reflects more southerly, warmer conditions (**Figure 8**).

Phosphorus removal does not involve microbes as heavily as nitrogen reduction, and a good share of the removal is due to the burial of a small fraction of the plant uptake. Therefore, P removal is tuned to the size of the growth cycle, which is anticipated to be rather small for this far northern site. Accordingly, a low removal rate coefficient has been used in forecasting, which results in a performance prediction well above the majority of comparison system data (**Figure 9**).



Each of the 383 points represents an annual average for one of 136 wetlands. The lines represent upper and lower bounds, and the central tendency. The Cambridge Bay forecasts are close to the central tendency.

Figure 6. Loading Chart for BOD in Treatment Wetlands

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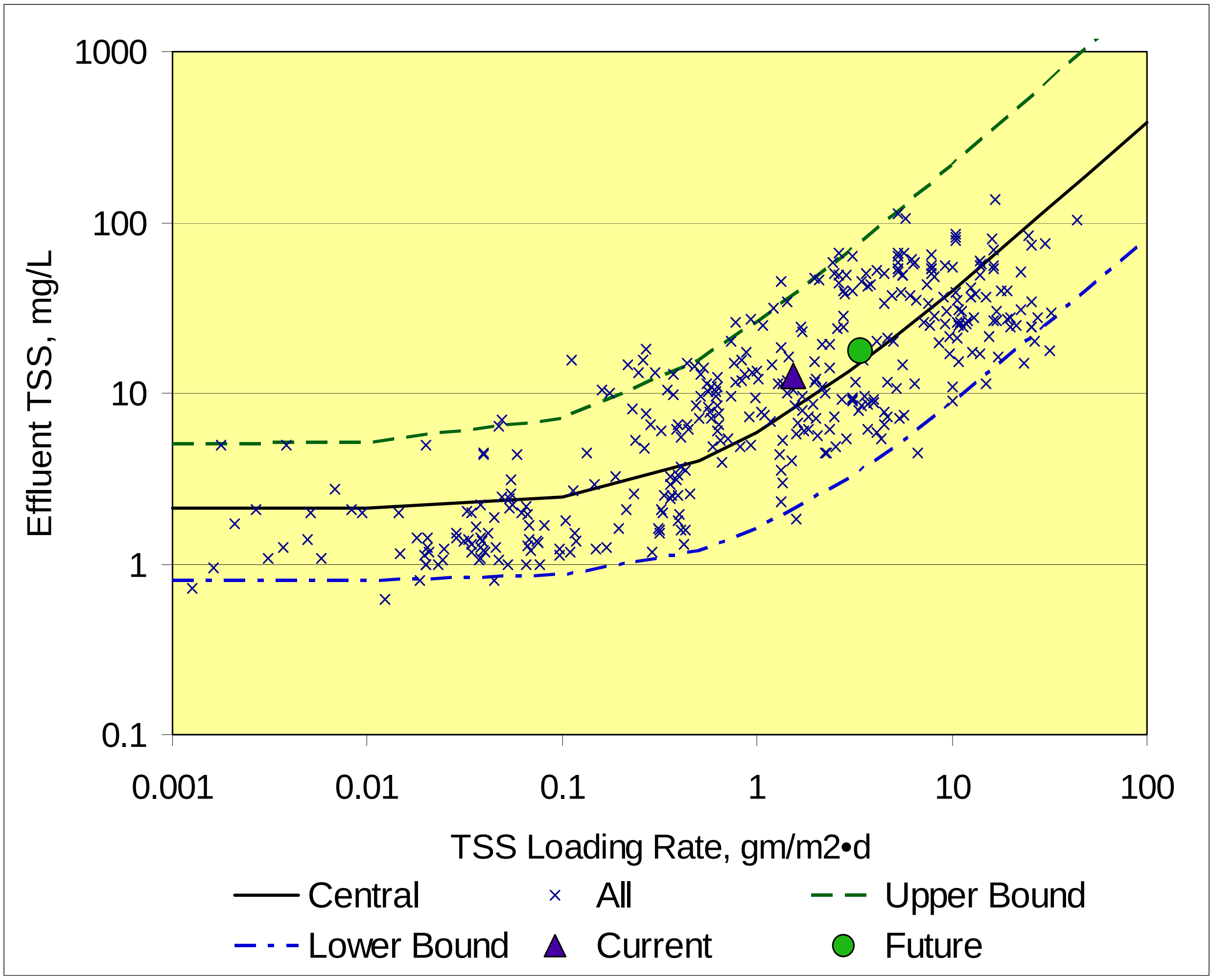

Each of the 449 points represents an annual average for one of 136 wetlands. The lines represent upper and lower bounds, and the central tendency. The Cambridge Bay forecasts are close to the central tendency.

Figure 7. Loading Chart for TSS in Treatment Wetlands

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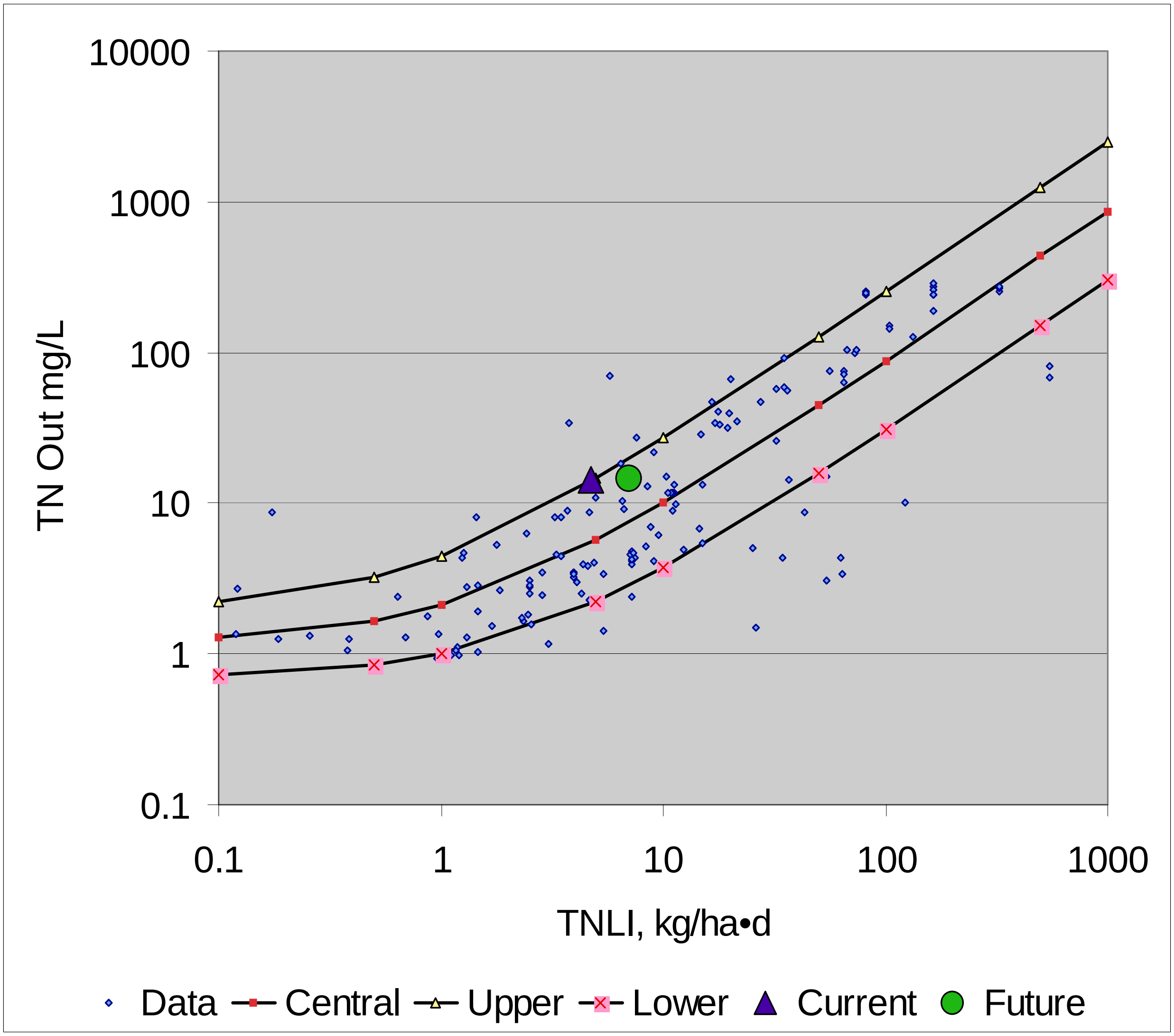

Each of the 147 points represents a period of record average. The lines represent upper and lower bounds, and the central tendency. The Cambridge Bay forecasts are well above the central tendency.

Figure 8. Loading Chart for TN in Treatment Wetlands

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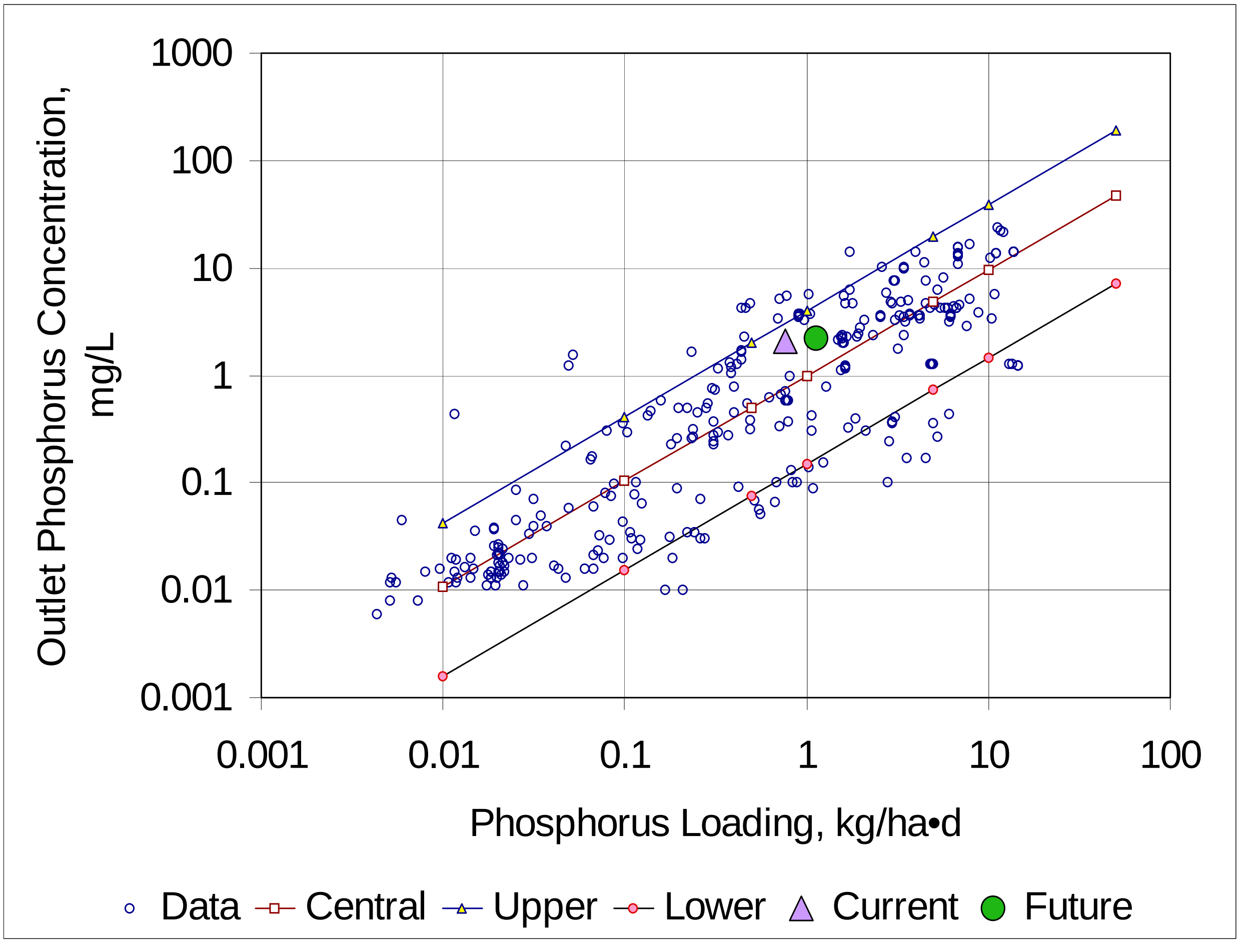

Each of the 283 points represents a period of record average. The lines represent upper and lower bounds, and the central tendency. The Cambridge Bay forecasts are somewhat above the central tendency.

Figure 9. Loading Chart for TP in Treatment Wetlands

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Discussion

The foregoing analysis has been based on a set of conservative assumptions. It is quite probable that the wetland will have a higher hydraulic efficiency, i.e., behave like more than three well-mixed units in series. The water reaching the wetland will have been subjected to very long detention in the lagoons, which will provide a good degree of water quality improvement.

Water quality improvement in the wetland has been calculated based upon a large amount of information from more southerly climates. However, the rates of biological processes have been assumed to be at the very low end of other experiences, including plant growth and nitrifier activity. Temperature coefficients have been used to reduce the rates of these processes, as indicated by the anticipated 5.4°C water temperature. The result of these assumptions is that $CBOD_5$ and TSS removal are likely to be comparable to wetlands in other climatic regions, but nutrient removal will be less. Some disinfection, or removal of pathogenic organisms is anticipated. There will be ample sunlight to promote UV disinfection in the wetland, as well as die-off due to cold temperatures. A two-log reduction (99%) is expected.

In short, the wetland will complement the proposed lagoons, and provide good water quality improvement, especially for $CBOD_5$ and TSS.

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