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Derivation of treatment rate constants for an arctic tundra wetland receiving primary treated municipal wastewater

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ABSTRACT

Tundra wetlands receive primary treated municipal wastewater in many communities in the Canadian Arctic and have demonstrated the ability to improve water quality. The kinetics of treatment within these wetlands has not been previously characterized which contributes to uncertainties in performance expectations. A case study was conducted on a tundra wetland area receiving primary treated municipal wastewater in Coral Harbour, Nunavut, Canada. The objectives of the study were to: (i) develop a tanks-in-series (TIS) performance model to determine first order areal rate constants (k) for a tundra wetland treatment area; and (ii) compare the rate constants to published literature on treatment wetlands operating in more temperate climates. This study serves as a proof of concept and initial derivation of rate constants characteristic of a tundra wetland treatment area. A TIS performance model was modified to account for external hydrologic contributions. Tracer studies, hydraulic measurements, and water quality data were used to parameterize the model and fit first order rate constants for several wastewater parameters. Dilution from the external hydrologic contributions from the watershed of the wetland accounted for approximately 33% of the contaminant reductions observed. The fitted k values normalized to 20 °C, and percentiles compared to literature, ranged from: 4.4–120 m/y (5th-70th) for $CBOD_5$; 78 –887 m/y (40th–90th) for *E. coli*; 2.7 20 m/y (10th–60th) for TN; and 12–64 m/y (40th–80th) for TAN. In general, rate constants for this arctic tundra wetland were comparable to low rate constants derived from wetlands operating in non-arctic climates.

1. Introduction

There are unique challenges associated with municipal wastewater treatment in communities situated in Canada's Far North (Government of Canada, 2012; CCME, 2009). These challenges stem from the remote and often difficult to access geographic locations of many communities; extreme cold climate operating conditions; chronic shortage of skilled operators; high capital cost and limited resources for the construction and maintenance of infrastructure; increasing populations; and anticipated changes to permafrost due to climate change (Hayward et al., 2014; Gunnarsdóttir et al., 2013; Yates et al., 2012; Doku and Heinke, 1993). Many communities in the arctic and sub-arctic regions of Canada discharge effluent to un-engineered tundra wetlands directly, or following treatment in wastewater stabilization ponds (WSPs) (Hayward et al., 2014; Yates et al., 2012; Krkosek et al., 2012).

Previous studies on these arctic and sub-arctic tundra receiving wetlands have demonstrated their ability to improve the water quality of municipal and domestic wastewater effluent (Hayward et al., 2014; Chouinard et al., 2014a; Yates et al., 2014, 2012; Doku and Heinke, 1995; Dubuc et al., 1986; Wright, 1974). It has been suggested that many of these wetlands were formed as a result of the influx of organic matter, nutrients and hydrological inputs from the effluent dispersal onto the tundra (Hayward et. al., 2014; Chouinard et al., 2014b). Therefore the receiving tundra wetlands are distinctly different from natural tundra wetlands. In this study, the receiving tundra wetlands are termed tundra wetland treatment areas (WTAs). The discharge of primary treated effluent into these wetland systems provides the benefits of further polishing the effluent prior to discharge into sensitive freshwater, estuarine, and marine receiving environments (Hayward et al., 2014; Doku and Heinke, 1993).

However, to date studies conducted on arctic tundra WTAs have not included the data necessary to parameterize quantitative treatment performance models (Hayward et al., 2014). It is

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extremely challenging to collect the simultaneously measured hydraulic and water quality datasets that are required to parameterize performance models due to the remote location of the communities in Nunavut, travel logistics, personnel and sample holding time limitations. Therefore the sample size of coupled hydraulic and water quality datasets are restricted. In general, there is limited information on the hydrodynamics and pollutant removal rates occurring in natural wetlands (Stern et al., 2001). Currently, there are few published materials on the reaction rates, best management practices, and modeling tools for use in design of treatment wetlands in the arctic (Chouinard et al., 2014a).

A breadth of literature has been produced on the design and performance modeling of engineered free water surface (FWS) constructed wetlands (CWs) (Kadlec and Wallace, 2009; U.S. EPA, 2000; Alberta Environment, 2000; U.S. EPA, 1999). However, the wetlands that receive effluent in the Canadian arctic and sub-arctic are distinctly different from CWs, due to the lack of engineered control of their hydraulics and hydrology. Many of the attributes of the northern tundra WTAs are simply a product of the natural environment; and as such their physical, hydrological and biogeochemical characteristics display extreme intersystem variability. These differences make it a necessity to modify the traditional design and performance modeling approach for treatment wetlands in the Far North.

Until recently, the most common modeling technique used to represent treatment performance was the k-C^* ideal chemical reactor model by Kadlec and Knight (1996). Where k is the first order rate constant (k-value), and C^* is the background concentration of the contaminant. Use of the model revealed that in cases, the k-C^* model produced unacceptable non-conservative design effluent concentrations, due to the inaccurate assumption of plug-flow hydraulics, and the dependency of rate constants on influent concentration, hydraulic loading rate (HLR), and hydraulic residence time (HRT) (Kadlec and Wallace, 2009; Kadlec, 2000; Carleton and Montas, 2010; Jamieson et al., 2007). However, the k-C^* model ideal chemical reactor is still recognized as one of the best design tools available, due to the breadth of data published using the model (Rousseau et al., 2004; Alberta Environment, 2000).

Non-ideal chemical reactor models are now preferred for use in design due to their ability to represent internal hydraulic behavior (Kadlec and Wallace, 2009; Carleton and Montas, 2010). The tanks-in-series (TIS) model is frequently selected for contaminant decay modeling. Kadlec and Wallace (2009) presented the TIS mass balance equation over an entire sequence of tanks as:

$$\frac{(C - C^*)}{(C_i - C^*)} = \left(1 + \frac{k\tau}{Nh}\right)^{-N} \quad (1)$$

where C is the effluent concentration, C^* is the background concentration, C_i is the influent concentration, k is the first order areal rate constant, τ is the HRT, and N is the number of TIS. A commonly applied version of this type of model is the P-k-C^* model for performance based wetland design which was developed by Kadlec and Wallace (2009). The TIS model is well suited to represent treatment within the wetlands characteristic of the Canadian Arctic due to its: (i) ability to model non-ideal hydraulics and incorporate external hydrologic influences; (ii) reasonable input data requirements; and (iii) straightforward usability which will encourage adoption in design protocols. Hayward et al. (2012) suggested that this type of model would be suitable to model tundra WTAs due to the complex hydraulic and hydrologic conditions that characterize many northern sites.

The use of process-based models is another option for modeling the treatment performance expectations of constructed wetlands. In the context of the Canadian Arctic, the SubWet 2.0 model UNEP (2014) has been used by Chouinard et al. (2014a) to model treatment performance expectations from eleven tundra WTAs in Nunavut and Northwest Territories. The SubWet 2.0 model uses 25 differential process equations and 16 rate coefficients to solve for expected effluent concentrations (Jørgensen and Fath, 2011). Chouinard et al. (2014a,b) recommended the use of SubWet 2.0 as a design tool for modeling tundra wetland treatment areas. Chouinard et al. (2014c) modified SubWet 2.0 for use in arctic climates by performing calibrations to the rate constants used in each of the process-based differential equations to produce effluent concentrations close to those measured in the field (Chouinard et al., 2014b). It is not possible to compare the rate constants that were calibrated for cold climates in the SubWet 2.0 model to the rate constants from more widely used first order models because of fundamental differences in the model assumptions including representation of the internal hydraulics, and the formulation of treatment rate expressions.

Wetland performance modeling in Canada's northern territories is not standardized and it is mostly left to designers to select the methodology. Designers typically select rate constants that have been extrapolated from treatment wetlands operated in more southern and temperate climates. For example, Kadlec (2008) used a TIS model to estimate performance expectations in a 2.9 ha tundra WTA receiving primary treated wastewater in Cambridge Bay Nunavut, Canada. Kadlec (2008) selected rate constants in the low percentiles of a large group of datasets from FWS wetlands operating in more temperate climates. A limitation to the current design approach is that it is unknown whether the first order rate constants in an arctic environment lie in the low end of the reported literature values, as is typically assumed by designers.

This study was conducted to address uncertainties associated with rate constant adoption in an arctic context. The objectives of the study are to: (1) develop a TIS performance model which accounts for external hydrologic contributions, to assess first order rate constants in an arctic tundra WTA receiving municipal wastewater; and (2) compare the first order rate constants to literature from treatment wetlands situated in non-arctic environments. This study provides the first assessment of the range of first order areal rate constants characteristic of an arctic tundra wetland receiving municipal wastewater, which will reduce uncertainties in performance modeling. Due to the logistical and resource limitations associated with the collection of the comprehensive dataset required to parameterize this model, this study serves primarily as a proof of concept for the model technique, and as an initial derivation of arctic-specific rate constants. The modified TIS model concept may be used as a novel tool to quantify rate constants and to assess the treatment potential of existing and planned treatment wetlands in the arctic and sub-arctic.

2. Material and methods

2.1. Site description

The study site was located in the hamlet of Coral Harbour, Nunavut, Canada which is positioned at 64° 08′13′N; 083°09′51″W (Fig. 1). The hamlet of Coral Harbour has a population of 852 (Government of Nunavut, 2012). The climate is characterized by average monthly air temperatures ranging from −26 °C to −34 °C in January, to 14 °C to 5 °C in July. The average annual precipitation consists of approximately 155 mm of rainfall and 1335 mm as snowfall, which equates to 286 mm of total precipitation (Government of Canada, 2014).

The hamlet of Coral Harbour generates approximately 95 m^3/d (34779 m^3/year) of primarily domestic wastewater (Government of Nunavut, 2013). The wastewater is stored in holding tanks at individual houses and establishments. Pump trucks are used to collect wastewater from the tanks, and for transport to the