Disinfection performance in wastewater stabilization ponds in cold climate conditions: a case study in Nunavut, Canada

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Abstract

Passive wastewater treatment systems are commonly applied in northern Canadian communities. Pathogen removal in these systems, which relies on natural purification, can be greatly affected by Arctic environmental conditions. In 2012, new Wastewater Systems Effluent Regulations (WSER) were implemented in Canada, but not in the far North due to the number of northern communities with limited wastewater treatment infrastructure which could present a challenge in achieving these criteria. In the summer of 2015, two sampling trips were undertaken to Pond Inlet (Nunavut) to study the disinfection performance of a single-celled wastewater stabilization pond (WSP). Sunlight disinfection was only effective close to the water surface, as UV and photosynthetically active radiation (PAR) were completely attenuated within the first 5-10 cm of the water column. The system achieved 0.76-1.28 log removal of *E. coli*, 0.81-1.00 log removal of fecal coliform and 0.79-1.02 log removal of total coliforms during the treatment season. The average *E. coli* concentration in the WSP was $1.3\text{x}10^6$ CFU/100mL prior to annual decant, which exceeded discharge standards set by the Nunavut Water Board. Existing WSP disinfection models were selected to assess their viability to predict the performance of Arctic WSPs. In general, the models over predicted disinfection performance by an order of magnitude or more, and some were unable to replicate trends in the data. A modified model for polar WSPs should be developed, as existing models were designed for temperate or tropical regions.

Keywords

Pathogen removal, wastewater stabilization ponds, *E. coli*, sunlight disinfection, modeling

INTRODUCTION

Nunavut is the largest Canadian territory by land mass with the smallest population of 31, 906 people, dispersed over 2 million square kilometers with many of the communities only accessible by plane. Few of these remote communities exceed populations of more than 2000 people (Centre for Alternative Wastewater Treatment, 2008). The majority of communities in the Canadian Arctic use passive wastewater treatment, such as WSPs and constructed wetlands (CWs), as the extreme climatic conditions and remote environment pose challenges to the implementation of conventional wastewater treatment infrastructure. Moreover, due to the continuous permafrost conditions, it is impractical to build piped systems or buried infrastructure to transport sewage from households to a centralized wastewater treatment facility. Therefore, most northern communities rely on sewage trucks for collection and transport of wastewater (Centre for Alternative Wastewater Treatment, 2008).

WSPs, in comparison to conventional wastewater treatment technology, offer several advantages including ease of operation, lower-cost and lower-maintenance. Therefore, they have been employed in small, rural and remote communities around the world as an economical and sustainable alternative for treating wastewater (Al-Hashimi and Hussain, 2013; Verbyla et al., 2016). WSPs attenuate organic and nutrient loads and have been reported to achieve excellent pathogen removal efficiencies (Davies-Colley 2005; Pearson et al., 2009; Bolton et al., 2010; Kadir et al., 2014) through naturally-occurring biological, chemical and physical treatment mechanisms. However, Arctic environmental conditions such as short summers and lower temperatures can greatly affect their performance, leaving them less effective than WSPs operated in temperate or tropical climates (Mezrioui et al., 1995; Ouali et al., 2014). Pathogen removal is one area of WSP operation where Arctic environmental conditions pose challenges.

Potential pathogens in wastewater effluent include various genera of bacteria, viruses, protozoa and helminth ova, whose presence in effluent wastewater can endanger environmental and human health. Disinfection quality is evaluated through the assessment of indicator organisms, typically *Escherichia coli* (*E. coli*), fecal coliforms or total coliforms. Disinfection in WSPs relies on environmental factors, such as sunlight, pH, dissolved oxygen (DO), temperature and attachment and sedimentation (Maynard et al. 1999; Awuah et al, 2001; Fisher et al. 2012). Previous studies have noted that solar radiation was likely the most potent factor contributing to disinfection in WSPs (Curtis et al. 1992; Davies-Colley et al. 2005, Maïga et al. 2009) with sunlight inactivation more than one order of magnitude higher than dark inactivation rates (Sinton et al., 2002; Ouali 2014). The Northern sun, with an extended photoperiod of 24 hours of daylight in the summer and a small azimuth, could highly influence pathogen removal efficiency in Arctic WSPs. High pH and DO levels were commonly observed in facultative and maturation ponds due to algal activity. pH levels higher than 9 are effective in removing indicator organisms (Davies-Colley et al., 1999; Awuah, 2002; Ansa et al., 2011; Ansa et al., 2012). Oxygen concentrations above 0.5 mg/L have also been shown to contribute to the removal of fecal bacteria (Van Buuren and Hobma, 1991). Many studies have found a positive correlation between disinfection and temperature (Pearson et al., 1987a,b; Mezrioui et al., 1995; Xu et al., 2001; Ouali et al., 2014). However, there have been conflicting reports that would suggest no relationship or even a negative correlation with temperature (Klock 1971; Flint 1987; Mancini, 1978; Auer and Nienhaus, 1993, Craggs et al. 2004).

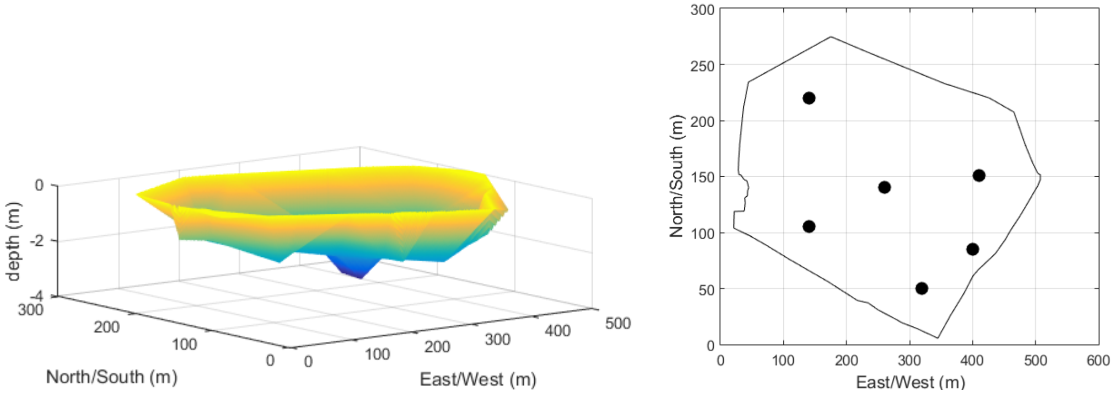
Modelling disinfection can be a useful tool in design considerations and optimizing performance in WSPs. Several models have been developed over the last 40 years to predict and optimize disinfection performance, each considering different combinations of environmental factors (Marais 1974; Curtis et al. 1992; Auer and Nienhaus 1993; Mayo 1995; Xu et al., 2001, Ouali 2014). The Marais (1974) model was the first WSP disinfection model developed and has traditionally been used for maturation pond design. To date, no disinfection models have been developed specifically for cold climate WSP applications. Existing models were generally designed using data from temperate or tropical regions, which may not be representative of cold climate WSPs.

Wastewater treatment facilities in Nunavut are required to meet territorial effluent quality criteria. These criteria are regulated by the Nunavut Water Board (NWB), and are enforced by Indigenous and Northern Affairs Canada (INAC). The discharge regulations vary on a case-by-case basis, with target effluent concentrations ranging from 10^4-10^6 colony forming units per 100mL (CFU/100mL) of *E. Coli*. Previous studies on WSPs in Nunavut have found that effluents inconsistently meet the NWB criteria (Huang et al., 2014). Currently, there is limited data on the disinfection performance of single-celled WSP under extreme climatic conditions. Additionally, the mechanisms affecting the performance of these systems during the summer treatment season with respect to pathogen reduction need to be investigated more fully. The objectives of this study were to monitor an Arctic WSP to assess its disinfection performance and ability to meet regulatory effluent guidelines; and to test existing disinfection models using the data collected to determine whether these models should be employed in the design of cold climate WSPs.

METHODS

Study site

Pond Inlet (72°41’57” N, 77°57’33” W) is a small, predominantly Inuit community, located on northern Baffin Island, Nunavut with a population of approximately 1600 as of 2014. Pond Inlet uses a single celled WSP to treat its sewage. The WSP was designed to be a facultative pond with depths ranging from 1.5 to 3 m. Profile and plain views of the bathymetry of the Pond Inlet WSP are shown in **Figure 1**, along with the sampling locations. The estimated volume of the pond is 100,000 m^3 and daily flow is about 104 m^3/d. The summer treatment season is generally from the middle of June to early September, and the WSP is decanted directly to the Arctic Ocean at the end of the treatment season prior to freezing.



(a) (b)

Figure 1. (a) Profile view of the bathymetry of the Pond Inlet WSP. (b) Plan view with sampling locations.

Assessment of water quality

Two field sampling events were conducted at Pond Inlet in the summer of 2015, at the end of July and at the end of August, in the final weeks of the treatment season prior to decant. During each visit, 5 days of sampling were undertaken. Six locations were selected throughout the pond for the collection of grab samples and to make measurements. Five points were chosen to give an even distribution of sampling locations throughout the pond, and a sixth point was included due to the algae blooms noted at the south east side of the pond shown in Figure 1(b). Raw wastewater samples were also collected from sewage trucks to represent the influent to the pond. For both sampling events, downwelling irradiance was measured from 290 nm to 700 nm using a calibrated JAZ-EL200-XR1 spectrometer suite manufactured by Ocean Optics (Florida, USA). Measurements were recorded with smaller depth increments near the surface as ultra violet light is sharply attenuated; every 1 cm for the first 5 cm followed by 5 cm increments until a signal was no longer observed. Temperature, DO and pH were measured using HydroLab DS5 at water surface as well as in raw samples.

Detection of indicator organisms

The effectiveness of pathogen removal in wastewater treatment is typically assessed through routine monitoring of the final effluent for the presence of indicator organisms, such as *E. coli*, or other coliforms. All of these were measured in July and August 2015 to examine the disinfection performance of the WSP system at the beginning and end of the summer treatment season. The culture and enumeration were carried out using the membrane filtration method according to *the Standard Methods for the Examination of Water and Wastewater* (APHA, 2005). Chromocult coliform agar was used to prepare agar plates. Samples were filtered with a filtration kit. The plates were cultured at a temperature of 37ºC for 24 hrs. Subsequently, *E. Coli* and other coliform colonies were enumerated.

Modelling disinfection

Interpolation was used to extend the data sets for comparison with predictions from existing models. This was accomplished using simple linear regression. For pH, DO and temperature data, the line of best fit was calculated using the least squares method. Random noise from a normal distribution was generated using the standard deviation of each data set in order to provide artificial variability. The result is shown in **Figure 2**.

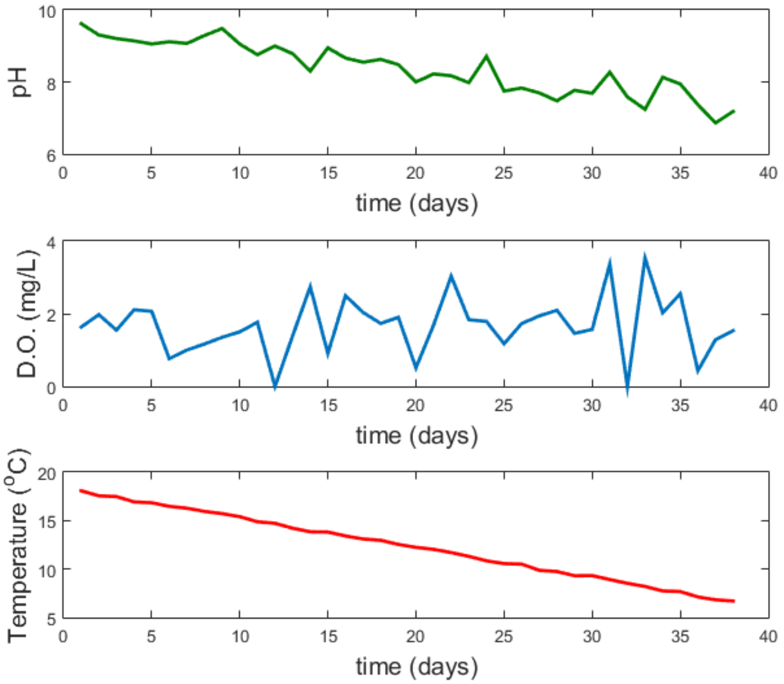


Figure 2. Synthesized data for pH, DO and temperature based on statistics of collected data of sampling events 1 and 2.

Hourly sunlight data was interpolated by first using simple linear regression with the measured downwelling irradiance between the two sampling events. These measurements were taken roughly at noon. The line of best fit was calculated using the least squares method, and random noise was used for variation. During Arctic summers, the hours of daylight extend to nearly 24 hours a day. However, there is still hourly variation in sunlight intensity, and this variation intensifies toward the end of the treatment season as the number of sunlight hours decreases. Hourly variation in sunlight at the pond surface was approximated by **Equation (1)**.

$$I_o = S_i \sin\left(\frac{\pi t_{ij}}{24}\right) \tag{1}$$

Where I_o in W/m^2 is the downwelling irradiance measured at the pond surface, S_i is the daily peak irradiance in W/m^2, t is the time where i is the day, j is the hour. If there is sunlight at the *jth* hour of the *ith* day, then $t_{ij}=t_{ij}$. If there is no sunlight at the *jth* hour of the *ith* day, then $t_{ij}=0$.

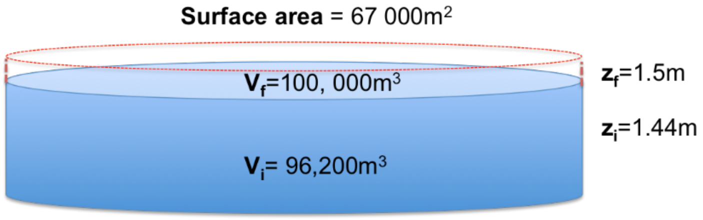


Figure 3. Approximated geometry of the Pond Inlet WSP for ease of calculations.

The simulations were performed from July 26th to September 1st for a total of 38 days. The measured bathymetry of the pond is shown by **Figure 1(a)**, however the geometry was approximated as shown in **Figure 3**, to simplify calculations. The controlled discharge WSP had no outflow, such that the water level increased over the course of the treatment season, making this a non-steady state hydraulic model. The volume of wastewater in the WSP at a given point in time (V_i, m^3) is given by **Equation (2)**.

$$V_i = V_{i-1} + (Q_{in} - Q_{out})\Delta t \tag{2}$$

Where i is the day, Q_{in} is the flow rate into the pond in m^3/d, Q_{out} is the wastewater outflow in m^3/d and Δt is the time step of 1 day. Q_{out} is zero because there is zero outflow. It was assumed that the daily inflow was pumped into the pond in a single event, daily at noon. The equation becomes:

$$V_i = V_{i-1} + (Q_{in})\Delta t \tag{3}$$

Changes in volume due to infiltration, evaporation and precipitation were considered negligible and outside the scope of this study due to the lack of available data, but should be considered in future work.

The spatial variation of indicator concentrations, pH, DO and temperature in the pond were found to be minimal, and therefore a continuously stirred tank reactor (CSTR) model was employed. Additionally, the low length to width ratio of the WSP supported the use of a CSTR model (Von Sperling, 2005). CSTRs have been shown to yield more conservative estimates for disinfection performance, which is safer for design (Buchaeur, 2007).

First order models to represent disinfection in WSPs have been developed using first order kinetics as defined by Chick's Law:

$$\frac{dC}{dt} = -k(t)C \tag{4}$$

Where C is the bacteria indicator concentration in CFU/100mL, t is the time in h or d and k is the mortality constant in h^{-1} or d^{-1}. Models have been developed to predict the mortality constant. Generally, the equation for the mortality constant is of the form:

$$k = k_d + k_s I \tag{5}$$

Where k is the mortality constant in h^{-1} or d^{-1}, kd and k_s are the dark and the irradiance disinfection rates; I is the total solar irradiance incident upon the pond surface in W/m^2. Models and parameters considered to predict the mortality rates in this study are shown in **Table 1**.

RESULTS AND DISCUSSION

WSP performance

Sunlight inactivation of pathogens has been reported to occur as a result of three mechanisms: direct DNA damage by UV-B wavelength (280–320 nm), indirect endogenous damage caused by UV-B, and indirect exogenous damage involving UV-A (320–400 nm), UV-B and PAR wavelengths (Davies-Colley et al. 2000). The latter two mechanisms are known as photo-oxidation, which is a process where endogenous or exogenous sensitizers absorb light and transfer this energy to other molecules, catalyzing the formation of reactive oxygen species (ROS), which are toxic to microorganisms.

Table 1. Disinfection models predicting total coliform concentrations and the parameters they incorporate.

Authors	**Parameters**
Curtis et al., 1992	pH, DO, sunlight
Auer & Niehaus, 1993	Sedimentation, depth-averaged sunlight
Mayo, 1995	pH, sunlight
Xu et al., 2002	Temperature, depth-averaged sunlight

Figure 4 (a and b) shows the attenuation of PAR and UV irradiance, respectively, in the Pond Inlet WSP. Approximately 80% of PAR was attenuated within the first 5 cm in water column, and over 90% was attenuated within the first 10 cm. There was no PAR detection below 15 cm from the water surface. On the other hand, UV irradiance was attenuated more readily than PAR, with greater than 99% attenuated within the first 5 cm of the water column, and no UV detection below 5 cm. The attenuation coefficient (K_d) is an indication of how easily light penetrates the water column at depth. In this study, the average K_d for PAR was 29 m^{-1} and the average K_d for UV was 80 m^{-1}. The results aligned with other findings, where UV light was reported to be attenuated within the first few centimeters of the water column, and thus may not contribute significantly to overall pathogen removal (Curtis, 1994; Kohn & Nelson, 2007; Kadir, 2014). Rather, it is likely that the longer wavelength, PAR, which penetrates deeper into the column, could contribute more effectively to disinfection via exogenous photo-oxidation (Kadir, 2014).

Hence, the results suggested minimal sunlight disinfection, which would only be effective at the surface of the pond. This was likely due to the high turbidity in the pond as suspended solids and algal biomass are known to be two major constituents that influence the attenuation coefficient of WSPs (Heaven et al., 2005). Heaven et al. (2005) examined the overall attenuation coefficient (K_{dPAR}) for a range of suspended solid and algal concentrations, and found that the typical range varies between 5-25 $m^{-1,}$ which corresponds well with the results from the Pond Inlet WSP.

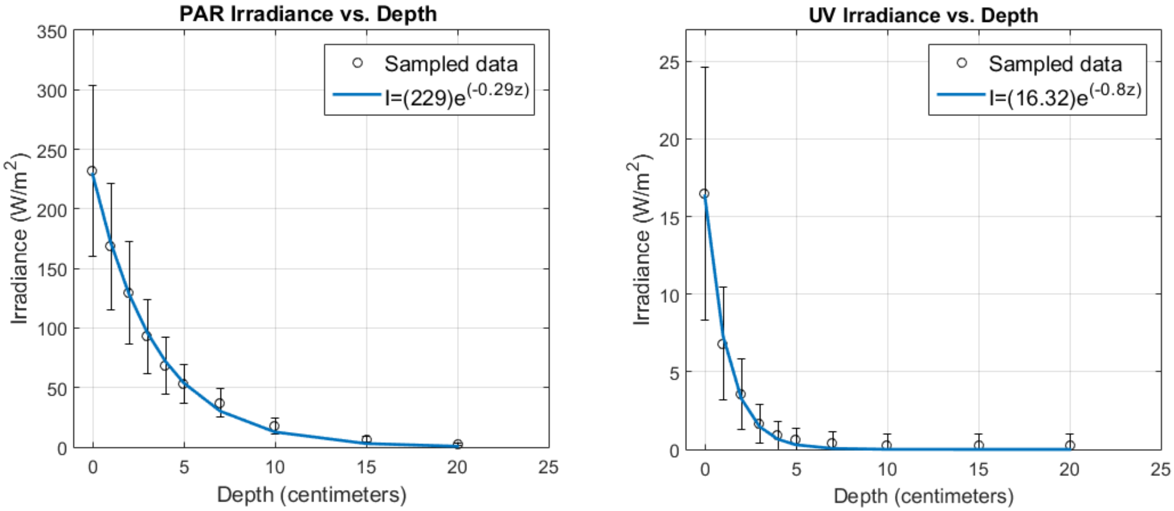


Figure 4. (a) The spatial and temporal average of attenuation of PAR irradiance in Pond Inlet WSP. (b) The spatial and temporal average of UV irradiance in the Pond Inlet WSP.

The influent parameters were very similar for each of the sampling events. The influent pH was 7.3, while pH in the pond during the July sampling event was 9.4, which could be attributed to algal activity. Algal blooms were observed during the July sampling event, but not during the August sampling event. The pH in the pond for the August sampling event was 7.4, which was very similar to the pH of the influent. Algal activity was most likely influenced by temperature and sunlight as the water temperature decreased from 17.5ºC (July) to 7ºC (August). It is likely that the lower temperature and reduced sunlight inhibited algal activity during the August sampling event.

The concentrations of *E. coli*, other coliforms and total coliforms in the influent and effluent are shown in **Table 2**. Overall, the single-celled system achieved 0.76-1.28 log removal of *E. coli*, 0.81-1.00 log removal of fecal coliforms and 0.79-1.02 log removal of total coliforms during the monitoring period in 2015 summer. This is in comparison to WSPs operated in temperate and tropical regions, where 2-6 log removal of bacterial indicator organisms have been commonly achieved (Tyagi et al. 2011; Reinonso et al. 2011). The second August sampling event took place one week prior to decant, and the average *E. coli* concentration in the pond was 1.3×10^6 CFU/100mL which exceeded the NWB discharge standards.

Table 2. The concentrations of indicator organisms in the influent and effluent of Pond Inlet WSP

	Trip 1 (July)			**Trip 2 (August)**		
Indicator organisms	**Influent**	**Effluent**	**Log removal**	**Influent**	**Effluent**	**Log removal**
E. coli (CFU/100ml)	5.1×10^6	8.9×10^5	0.76	2.5×10^7	1.3×10^6	1.28
Other coliforms (CFU/100ml)	1.8×10^7	2.8×10^6	0.81	1.1×10^8	1.1×10^7	1.00
Total coliforms (CFU/100ml)	2.3×10^7	3.7×10^6	0.79	1.3×10^8	1.23×10^7	1.02

Comparative analysis of disinfection models

Models were evaluated on two bases: their ability to accurately predict concentrations of fecal coliform in the pond, and their sensitivity to replicate important trends in the observed data, particularly the increasing concentration of fecal coliform over the course of the treatment season. In general, the models over-predicted the disinfection performance in the WSP by at least one order of magnitude, as shown in **Figure 5**. This included the Marais (1974) model, which is commonly used for designing WSPs for disinfection. This was significant because one order of magnitude could be the difference between complying or failing to meet regulatory discharge requirements. The over-prediction likely resulted from: 1. extrapolation of the mortality rate outside of the range for which the model was designed; 2. the use of surface irradiance for quantifying the effect of sunlight rather than depth-averaged irradiance.

It should be noted, however, that these models were designed and calibrated with data that was collected in both tropical and temperate regions, rather than Arctic data. In some cases, the parameter values in Pond Inlet, particularly temperature and sunlight irradiance, were much lower than those used to build the models. For example, the irradiance values used to calibrate the Curtis et al. (1992) model were between 429-1096 W/m^2, while the average daily peak surface irradiance in Pond Inlet was 250 W/m^2. Extrapolation of models can be challenging, particularly when the data employed is outside the range for which the model was originally developed. The Xu et al. (2001) model most closely predicted the performance of the Pond Inlet WSP. This model was developed using year-round data from a pond in Noirmoutier, France. The winter climate in Noirmoutier is comparable to the summer treatment season in Pond Inlet, especially in terms of temperature and irradiance.

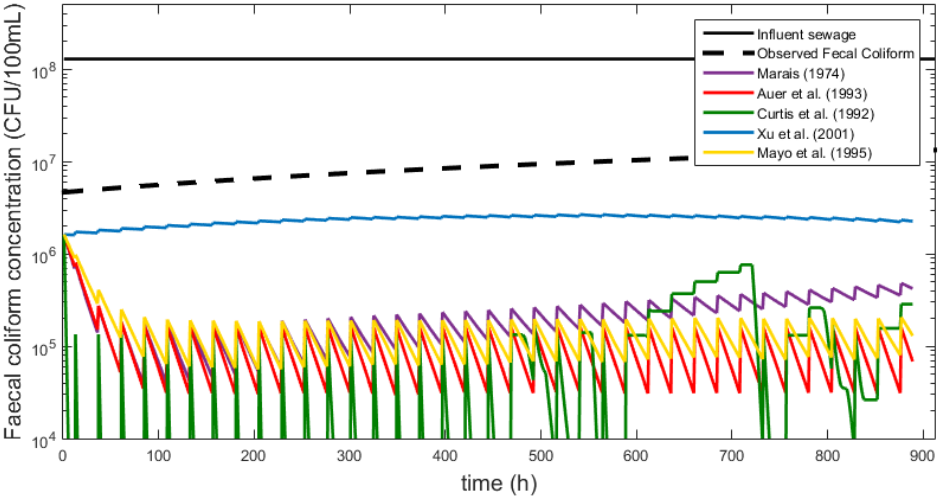


Figure 5. Observed fecal coliform concentrations (CFU/100mL) compared with predicted concentrations by various disinfection models over the treatment season.

Depth-averaged irradiance was calculated by the following:

$$I = \frac{I_o}{KZ}\left(1 - e^{-KZ}\right) \tag{6}$$

Where I is the depth-averaged irradiance in W/m^2, I_o is the surface irradiance, and Z is the depth of the WSP. This relationship takes into consideration both the turbidity and depth of the pond as being factors to consider for sunlight-mediated disinfection. The Curtis et al. (1992) model only considers surface irradiance and was designed using relatively clear tertiary wastewater. As such, it tends to over predict sunlight-mediated disinfection rates in the Pond Inlet primary WSP. Hence, this model may be impractical for a number of Arctic communities that only have single or two staged WSP systems with turbid wastewater.

The total coliform concentration in the Pond Inlet WSP increased by nearly one order of magnitude between the July and August sampling events. The decrease in pH, sunlight and temperature could be responsible for this trend. This increase in concentration corresponded to decreasing mortality rates, k, in the models as shown in **Figure 6**. The Xu et al. (2001) and Auer and Nienhaus (1993) models showed an *increase*, rather than decrease,in mortality rate over the course of the treatment season. The models that incorporated both sunlight and pH values predicted a decreasing mortality rate. This would suggest that exogenous photo-oxidation, which requires sunlight irradiance, as well as a high pH, could be an important disinfection mechanism in Northern WSPs.

CONCLUSION

This study investigated disinfection performance and modeling of an Arctic WSP. In order to maximize the disinfection power of the sun, a wastewater system could be designed with two or multiple cells in series. This ecological engineering strategy would allow solids and organic material to settle in the primary cell; allowing sunlight to more extensively penetrate in the clearer secondary cell. The comparative analysis of disinfection models showed that current models present challenges in predicting disinfection performance for WSPs. Hence, a new model should be developed for Arctic application that considers relevant parameters and is calibrated with appropriate ranges of those parameters. Sunlight should be quantified using depth averaged irradiation in order to make the model more widely applicable.

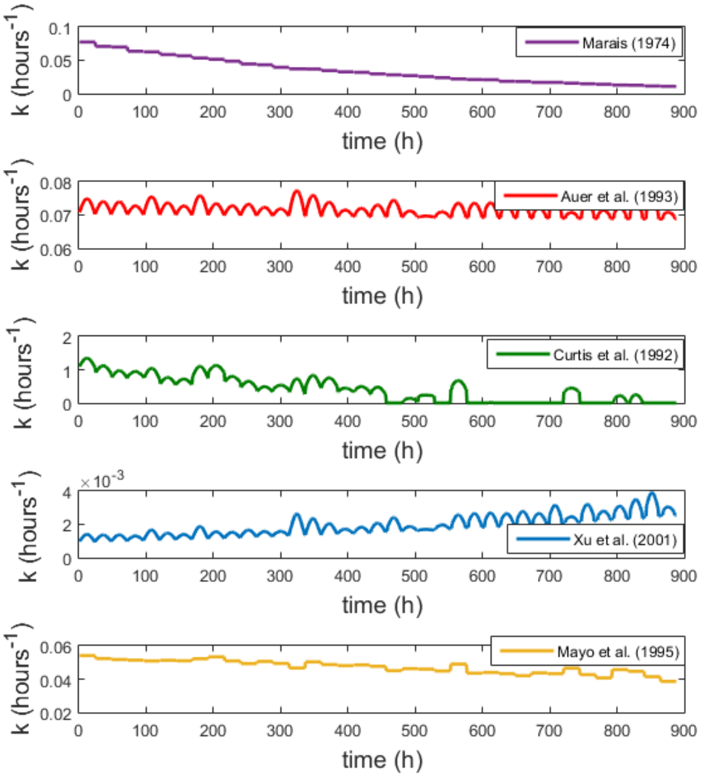


Figure 6. Predicted mortality rate constants (k) of the 5 different models.

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