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Research article

Simplified empirical model for phosphorous removal in a facultative wastewater lagoon

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ABSTRACT

Nutrient removal in a facultative lagoon in Manitoba, Canada, was monitored from May 2015 to April 2016. According to the 12-month data, phosphorous concentration in the effluent did not meet the regulatory requirement. Various models have been developed to predict nitrogen removal from lagoon through the years; however, not much effort has been deployed to model phosphorous removal from lagoons. Therefore, this research aims to relate the lagoon phosphate removal to the volatile suspended solids (VSS), metal concentration, and detention time. A simple empirical equation was derived by observing the one-year data, which considers assimilation into biomass as a major mechanism of phosphorous removal. The metals' concentration was found to be very low in the facultative lagoon studied. Hence, phosphorous precipitation by metals was neglected. The model relates assimilation directly to VSS which is simple to evaluate practically unlike other models that require individual algae and bacteria concentration. The correlation coefficient (R^2) between the observed and the predicted effluent VSS was 0.92, which indicates excellent fit. The R^2 between observed and predicted effluent orthophosphate was 0.83, which indicates moderate fit. The trend of modeled effluent phosphate is similar to the observed effluent phosphate concentration, which approves the validity of this model. The model developed in this research can be used to predict the average effluent VSS and phosphorous concentration in similar facultative lagoons.

1. Introduction

Wastewater stabilization ponds (lagoons) are diverse systems that rely on natural processes to aid in wastewater treatment. They depend on a mixture of heterotrophic and autotrophic bacteria, algae, fungi, as well as zooplankton to treat wastewater (Mbwele, 2006). Municipal wastewater treatment using lagoon systems is common practice in small communities in Canada due to the easy availability of land (Federation of Canadian Municipalities and National Research Council, 2004). Comparing with the mechanical wastewater treatment process, lagoons have significant advantages of low energy cost, simple operation, and little maintenance (WHO, 2002).

Traditionally, the main goal of the wastewater lagoon was stabilizing wastewater by removing carbonaceous matter (von Sperling, 2007). Reliable designs have been successfully implemented for the removal of biological oxygen demand (BOD) and suspended solids. Recently, with the increased environmental concerns, nutrient removal (i.e. nitrogen and phosphorus removal) has become mandatory for lagoon operations. In the past decades, much effort has been made for developing models to estimate nitrogen removal from lagoons. Various models have been proposed and developed based on the first-order approach. Among all those models, the most important models are the plug flow model developed by Reed et al. (1995), and mixed flow model developed by Pano and Middlebrooks (1982). These two models have been validated by various studies through the years. However, there is not much information in the literature regarding the development of an empirical model to estimate the concentration of phosphorous in the lagoons' effluents.

In the wastewater lagoons, phosphorus could be detected in several forms. Organic phosphorus, ortho-, and poly-phosphate are the three main phosphorus types of importance (Mbwele, 2006; Metcalf Eddy, 2003; Sawyer et al., 2003). Basically, under the natural conditions, phosphorus can be removed by assimilation into microorganisms such as algae and bacteria as well as precipitation

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by metals (Bitton, 1999; Brown and Shilton, 2014; Crites and Tchobanoglous, 1998; Larsdotter et al., 2010). The latter is greatly influenced by the metals' concentration and pH in the wastewater, and it can be calculated using the solubility equilibrium equations; whereas, phosphorus removed by assimilation of microorganisms is complicated and difficult to predict. In one study, Powell et al. (2006a) studied the phosphorus uptake by microalgae in waste stabilization ponds. Their results showed that phosphorus was being removed by algae and there was a luxurious phosphorus uptake. Algae assimilate phosphorus in the form of inorganic orthophosphates (Becker, 1994). When there is more phosphate available, the algae will assimilate in greater quantities (Aitchison and Butt, 1973; Markou et al., 2012; Powell et al., 2006b). Longer hydraulic residence times (HRTs) have also resulted in greater phosphorus removal rates by algae (Larsdotter, 2006; von Sperling, 2007).

Since phosphorus in the microorganisms can be estimated based on the empirical cell formula, i.e. $C_{106}H_{181}O_{45}N_{16}P$ for algae cell and $C_{60}H_{87}O_{23}N_{12}P$ for bacteria cell, theoretical phosphorus removed by assimilation can be calculated by the microorganisms' concentration and their growth rate (Stumm and Morgan, 1981; Metcalf Eddy, 2003). In one study, a dynamic mathematical model was developed by Beran and Kargi (2005) to estimate the phosphorous removal via assimilation. In this model, the phosphorous removal was associated with algae and bacteria concentration, and their growth rates. However, it is difficult to practically measure the individual concentration of algae and bacteria due to the variety of species as well as their different volumes and sizes. Therefore, this model could not be considered as a convenient option for estimating phosphorous removal via assimilation.

There is a lack of information in the literature regarding the empirical modeling of the phosphorous removal from the lagoon systems via cell assimilation based on the microorganisms' concentration and growth rates. Therefore, the objective of this study is to model phosphorus removal process to improve phosphorous removal efficiency of an existing facultative lagoon system that is located in the community of Niverville, Canada. According to the Water Protection Act of Manitoba, the lagoon system is exceeding the allowable phosphorus limit of 1 mg/L. The nitrogen concentration is below the regulatory requirements for stabilization pond discharge; however, the phosphorus removal has been identified as the problem. In this study, a whole year's data from May 2015 to April 2016 was analysed and an empirical equation assuming completely mixed condition was derived for phosphorous removal from the aforementioned lagoon. Assimilation into biomass was considered to be the main mechanism of phosphorous removal as precipitation by metals was very low due to the low concentration of metals in the facultative lagoon studied herein.

2. Materials and methods

2.1. Study site and operation

The facultative wastewater stabilization pond is located in the Niverville town in the province of Manitoba, Canada. The latitude and longitude of the study area are 49.638908 and -97.047954, respectively. It serves a community of approximately 5000 residents. It consists of four purely facultative ponds. The primary cell has earthen sides. The three secondary cells have stone riprap around all four sides. The four lagoons have a maximum operating depth of 1.5 m. The primary cell (primary 1) has a maximum capacity of approximately 110,000 m^3; the north secondary cell (secondary 1) is active online for a month and has a maximum capacity of approximately 128,000 m^3; the middle secondary cell (secondary 2) has a maximum capacity of approximately 128,000 m^3; and the south secondary cell (secondary 3) has a maximum capacity of approximately 208,000 m^3. Raw wastewater enters primary 1 through force main piping to the center of the cell. There is generally one secondary cell connected in series at a time. The secondary 1 was filled during the late summer and fall season from August 2015 to November 2015. The secondary 2 was operated from May 2015 to July 2015. The secondary 3 was operational from December 2015 to April 2016.

2.2. Lagoon sampling procedure

The lagoon cells were sampled once a week from the water surface using a 5-m telescopic sample pole from May 2015 to April 2016. The windward and leeward side of the lagoon cells were sampled, and the data were averaged for the cells. The sample containers were stored in a cooler with cold packs after collection and during the transportation to the lab. The containers were then transferred to a refrigerator and stored until the analysis period. Samples were analysed for pH, orthophosphate, and VSS within 24 h of their collection. Metal concentrations in primary and secondary 1 were evaluated once in the whole year in September 2015. The sedimentation layer depth was measured only in April 2016 for all the four lagoon cells.

2.3. Analytical methods

The pH of the samples was measured in the lab and in the field using a Thermo model 230A pH meter. Samples were analysed by a Lachat Instruments flow injection analyser (FIA) to determine the orthophosphate content. Orthophosphate was measured using the ascorbic acid method and the QuikChem® Method 10-115-01-1-A, which are based on the standard methods 4500-P G (Lachat Instruments, Loveland, CO). Volatile suspended solids (VSS) measurement was conducted based on the standard method procedure 2540 E. The metal content was measured using inductively coupled plasma mass spectrometry (ICP) methods. The depth of the lagoons was measured using sludge judging.

2.4. Model assumptions and equations

One-year data from May 2015 to April 2016 was observed and analysed to derive an empirical equation for predicting the effluent phosphorous and VSS concentrations from the lagoon. Data was collected weekly and averaged over a month. Orthophosphate removal from the studied facultative lagoon was observed to be proportional to the influent orthophosphate concentration based on the collected data, which was incorporated into the modeled effluent orthophosphate concentration using the following proportion.

$$PO_4(i) - PO_4(e) \propto PO_4(i)$$

where PO_4(e) is the average effluent concentration of orthophosphate (g/m^3), PO_4(i) is the average influent concentration of orthophosphate (g/m^3), and $\propto$ is the factor of proportionality.

On the other hand, phosphorous assimilation into the biomass was assumed to be dependent on the growth rate of VSS and detention time according to the following proportion:

$$PO_4(i) - PO_4(e) \propto e^A$$

where A is the orthophosphate assimilated into the biomass. This parameter could be calculated using the following equation: