Phosphorus retention in a constructed wetland system used to treat dairy wastewater


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Abstract

The aim of this study was to develop an input/output mass balance to predict phosphorus retention in a five pond constructed wetland system (CWS) at Greenmount Farm, County Antrim, Northern Ireland. The mass balance was created using 14-months of flow data collected at inflow and outflow points on a weekly basis. Balance outputs were correlated with meteorological parameters, such as daily air temperature and hydrological flow, recorded daily onsite. The mass balance showed that phosphorus retention within the system exceeded phosphorus release, illustrating the success of this CWS to remove nutrients from agricultural effluent from a dairy farm. The last pond, pond 5, showed the greatest relative retention of 86%. Comparison of retention and mean air temperature highlighted a striking difference in trends between up-gradient and down-gradient ponds, with up-gradient ponds 1 and 2 displaying a positive quadratic relationship and down-gradient ponds 3 through 5 displaying a negative quadratic relationship.

1. Introduction

The ratification of the Water Framework Directive (2000/60/EC) saw a new age of water resources management. The Directive required that all member states put measures into place to achieve ‘good chemical and biological status’ in controlled waters by the year 2015, through the promotion of sustainable management techniques (DEFRA, 2009). Under this piece of legislation all liquid waste producing industries must seek means to treat waste to a specified standard before discharging into a water body. The Water Framework Directive has provided a platform for the development of alternative wastewater techniques that meet legislation criteria whilst also providing a more environmentally viable option. One such technique is constructed wetland systems (CWS). CWS is a soft-engineering technique that is designed to simulate the biofiltration qualities of a natural wetland system with the purpose of attenuating contaminants from wastewater effluent (Vymazal, 2007; Babatunde et al., 2010). In today’s economic climate, cost is a primary issue. CWS provide a more economically viable and labour efficient alternative to current wastewater treatment options (Lee et al., 2004; Healy et al., 2007; Babatunde et al., 2010; Ong et al., 2010a), through low construction, maintenance and energy costs (Vymazal et al., 2006; Babatunde et al., 2010).

CWS are considered to be an efficient wastewater treatment technology (Ong et al., 2010b) and provide an effective means of intercepting agricultural runoff (Braskerud, 2002; Harrington and Mclnnes, 2009). The use of constructed wetlands to treat agricultural wastewater with a high nutrient content is becoming increasingly important (Healy et al., 2007; Carty et al., 2008; Cui et al., 2010; O’Launaigh et al., 2010; Ong et al., 2010a). In the past 10 years, scientific investigation into the effectiveness of CWS in breaking down and treating animal wastewater and removing contaminants has intensified (Healy et al., 2007; Harrington and Mclnnes, 2009; Harrington and Scholz, 2010). There is a greater need to utilise the potential of constructed wetlands as a wastewater treatment method due to an increasing trend of intensive farming and thus more wastewater to be treated (Tilman et al., 2002; Reinhardt et al., 2005). Also, increasing pressures on water resources as a result of current unsustainable treatment practices require the need to develop an inexpensive and proficient water management practice that can be site specific. Use of constructed wetlands in Ireland; however, is limited due to the lack of long-term performance data specific to the island (O’Launaigh et al., 2010). Utilisation of space within an agricultural watershed is an important issue, especially within Northern Ireland, where the average farm size is a relatively small 38 hectares (DARD, 2006). As CWS are designed to provide onsite treatment, space efficiency is important. Knowledge of the optimum pond size that will sequester enough phosphorus (P) in order to meet standards whilst taking up the least amount of space is vital if the implementation of CWS is to be widespread.
Agricultural wastewater includes farmyard runoff, parlour washings, silage, farmyard manure effluents and general farmyard washings (Dunne et al., 2005; Healy et al., 2007). Typical treatment of farmyard wastewater is by diluted land spreading, which has been linked to adverse environmental effects (Lee et al., 2004; Healy et al., 2007). Agricultural runoff has been attributed to up to 50% of water quality degradation in receiving waters (Mitsch et al., 1995; Simeonov et al., 2003). Characteristically, agricultural wastewater contains high levels of nutrients, such as nitrogen and P, has a high biochemical oxygen demand (BOD) and total suspended solids content, and may contain pathogens depending on the source of the waste. The key characteristic causing the greatest problem for Northern Ireland’s waterways are high levels of nutrients, such as P (DARD, 2009).

Phosphorus is of significant interest due to its status as a limiting nutrient. According to DARD (2009), 30% of P in Northern Ireland’s rivers is attributable to agriculture. P loading to aquatic bodies can cause adverse effects, such as eutrophication; an oxygen limiting process that leads to mass fatalities in the aquatic environment (Braskerud, 2002). Additionally, P loading is dependent upon the retention capacity of the watershed, which is the ability of a wetland to remove P from a water column (Reddy et al., 1999). There are various routes through which P can be retained in this environment; uptake by plant roots or absorbed through plant leaves in submerged species; adsorption to soils and sediments; and uptake by microbiota (Vymazal, 2007). P retention within a CWS is a desirable quality. In terms of quantifying P retention, a study by Braskerud (2002) defines the process as the difference between P mass input and mass output.

Although a universal handbook on constructing a CWS does not exist, it is important to have knowledge on the flow and composition characteristics of the effluent needing treated; the characteristics of the landscape drained and the local climate (Healy et al., 2007; Carty et al., 2008; Harrington and McInnes, 2009). With this information a system can be tailored to treat a particular type of effluent or contaminant, for example Collins et al. (2005) selected particular types of submersed plants based on their ability to accumulate metals. Thus allowing for a more holistic approach to wastewater management.

The objectives of this study were to investigate the degree of P retention within the CWS by (1) establishing a water balance of the system, using hydrological variables of inflow, outflow, precipitation, evapotranspiration, runoff and storage, and model this over the system, and (2) developing a predictive model based on P loading to the ponds, which will determine P retention and P release within the system.

2. Methods
2.1. Site description

The constructed wetland system under study is located within Greenmount Farm, a plot of agricultural land, located approximately 2 km south of Antrim town, Northern Ireland. The farm has a 140 cow dairy herd and a 30 cow cream herd (Forbes et al., 2009). The wetland was constructed in order to treat wastewater with a typical BOD of 2000 mg/L and average P accumulation of 26 kg/year on site. According to O’Launigh et al. (2010), onsite wastewater treatment is preferable in rural Irish dwellings. The effluent originates from various sources on a daily basis: washing from the dairy herd milking parlours and bulk tanks three times a day; livestock yard and roof runoff; and runoff from unroofed silo pits during the winter months (Forbes et al., 2009). The system consists of a series of five ponds, which cover a combined area of 1/25 ha. Each pond differs with respect to shape and area but have an equal depth of 0.5 m. The effluent travels through ponds 1–5 sequentially through a series of connecting pipework. The CWS was built on a gradient to ensure that the effluent would flow through each pond under gravity (Forbes et al., 2009). Following residence in the fifth and final pond, pond 5, the effluent is channelled into Sixmilewater River adjacent to the site. Each pond has been planted with one or more type of vascular macrophyte aquatic vegetation 18-months prior to the commencement of data collection (Forbes et al., 2009). Macrophytes are considered to be most effective in reducing the nutrient, suspended solids and pathogen content of an effluent (Harrington and McInnes, 2009). This particular wetland system was constructed to simulate horizontal surface flow, a common type of wetland water-flow regime.

2.2. Methodology

The CWS at Greenmount Farm was modelled using a variation of the water balance and a mass balance. The first stage required developing a hydrological model to fit the system at the Farm, with the aim of understanding the volume fluxes of each pond and over the whole system. The second stage involved developing an input/output mass balance based on P loading to the ponds, with the purpose of modelling the concentration of P retained within the CWS. In the final stage of the process, relationships between P retained and the variables; hydrological inflow and mean air temperature were tested using multiple regression.

2.3. Hydrological model

Monthly time series data sets for runoff, pond inflows and outflows, precipitation and evapotranspiration were obtained from the Agri-Food and Biosciences Institute (AFBI), Northern Ireland. Water samples at inflow and outflow points of each pond were collected weekly and meteorological data was recorded hourly onsite. The time series outputs for the above variables were available for all ponds, 1–5, from November 2005 to August 2007, inclusive. The hydrological model below (Eq. (1)) (adapted from Kadlec and Knight (1996)) was employed in order to obtain the average monthly change in storage.

\[ V_i + V_c + V_p - (V_o + V_e) = \Delta V \]

where \( V_i \) is the inflow of wastewater volume (\( m^3 \)), \( V_c \) is the catchment runoff volume (\( m^3 \)), \( V_v \) is the precipitation volume (\( m^3 \)), \( V_o \) is the outflow of wastewater volume (\( m^3 \)), \( V_e \) is the evaporated volume (\( m^3 \)) and \( \Delta V \) is the change in wastewater storage in the wetland (\( m^3 \)). Storage values for each pond individually and over the whole system were calculated using the above equation.

2.4. Input/output mass balance

A phosphorus retention model was designed in order to predict the amount of P retained in sediment within each pond and over the whole system. A simple conceptual model for P retention in the CWS is shown below (Eq. (2)):

\[ I_i + P_s - (O_e + P_t) = R \]

where \( I_i \) is P inflow at start of month (g/month), \( P_t \) is P in pond at start of month (g/month), \( O_e \) is P outflow at end of month (g/month), \( P_t \) is P in pond at end of month (g/month) and \( R \) is the amount of P retained (g/month).

Data of inflow and outflow total P concentrations, as well as hydrological data was used in the model development. Table 1 describes each stage of the model, the formula involved in the calculations and the units used. Following the model completion, values outputted were compared with the basic retention equation (Eq. (3)) (adapted from Braskerud (2002)):
P inputs – P outputs = P retention (3)

The predicted absolute and ratio values of P retention were then correlated with both hydrological inflow and mean daily air temperature from February 2006 to March 2007, inclusive. As the data tended to fluctuate, an order two polynomial trendline was applied to the plots. With respect to mean air temperatures, monthly averages were calculated from daily observations collected and recorded from a weather station onsite at Greenmount Farm. The climate data contained missing observations and so were estimated using averages calculated from raw hourly dry bulb temperature data from a weather station at Hillsborough, approximately 32 km south-east of Greenmount Farm. Regression analysis was then performed on the variables.

3. Results and discussion

3.1. Hydrological model

Storage within the CWS was highly variable throughout the period, November 2005 to August 2007. Generally storage within the system, and the ponds individually, increased with time, with maximum capacity being reached in the final few months of the study period, i.e., May 2007 to August 2007. This upward trend is illustrated in Fig. 1, which shows the average monthly change in storage over each pond and the whole system. The temporal trend of increasing storage volumes may have been a result of a lag time between the commencement of pond filling and peak capacity. Forbes et al. (2009) state that pre-November 2005; the only input into the system was precipitation. Following this, agricultural effluent was channelled in on a continuous basis. Therefore, the increase in storage on a monthly basis may have been due to the lag time between inflow and the ponds reaching maximum depth. Ponds 2 through 5 displayed a similar pattern of fluctuation; the time between inflow and the ponds reaching maximum depth.

The model is based on the assumption that each pond is completely mixed, so the predicted value of P retention is an average over the entire area of the pond (Ahlgren et al., 1988). Therefore, spatial variations within the pond are unknown. The model output suggested that the system is more likely to retain P than release it; positive values indicate P retention and negative values indicate P release. All ponds retained at least two-thirds of P over the 14-month period. Each pond displayed a high degree of variation.
between retention and release. Fig. 2 illustrates the model output for the percentage of P retention in all ponds. The model predicted fairly high values of P retention for pond 3, June 2006, for example, had a retention efficiency of 79.48%. Hydrological conditions during this month showed no net inflow of water and an average air temperature of 14.5°C. However, the following month showed a net release of P under similar hydrological and meteorological conditions as the previous month. Pond 5 showed the highest ratio of retention, occurring in October 2006, where wetland sediments retained approximately 87.46% of P entering the system. The high degree of retention in pond 5 in particular has resulted in 100% of discharge targets being met at this site (Forbes et al., 2009). The degree of P release was greatest in ponds 3 and 4; with 4 months displaying a return of P back into the system. Summer release trends in pond 2 tended to correlate with high values of inflow, relative to the whole period, and high mean daily air temperatures. The pond 3 releases also correlated with high inflow values, for example, in November 2006 the model predicted a 7.91% release of P, which coincided with 1134 m³ of inflow. However, inflow for the month of July 2006 was zero. Release within pond 4 appeared to be slightly more random than in the rest of the system; with the 4 months displaying P release occurring in March, July, October and December 2006. On average pond 4 displayed the greatest magnitude of absolute P release, ranging between 227 and 5546 g/m³.

Phosphorus retention and hydrological inflow for the period of February 2006 to March 2007 are shown in Fig. 3. Ponds 1, 3 and 5 showed similar relationships between retention and inflow. The three ponds displayed an initial positive relationship, with P retention increasing with increasing volumes of inflow; however, once an optimum flow was reached, the concentration of retention decreased, which is a negative quadratic trend. In the case of pond 1, the optimum flow was 450 m³ and the rate of change was gradual (Fig. 3a). A regression analysis performed on the variables indicated that the relationship between the predictant and predictor
was insignificant; this was deduced from the $F$-test result that was less than the critical $F$-value. An $R^2$ of 0.03 indicated that 3% of all changes in P retention could be attributed to inflow fluctuations; this result was not statistically significant. An $R^2$ of 0.03 indicated that 3% of all changes in P retention could be attributed to inflow fluctuations; this result was not statistically significant. A negative linear correlation between retention and inflow, if the negative retention values were ignored. Pond 3 displayed a less exaggerated negative polynomial trend, with the optimum flow being approximately 400 m$^3$. Regression analysis showed that the relationship was statistically significant as the $F$-test was greater than the critical $F$-value. An $R^2$ value of 0.03 indicated that 3% of all changes in P retention could be attributed to inflow fluctuations; this result was not statistically significant. According to analysis, the relationship between total P retention and inflow in pond 5 is statistically significant, with the $F$-test result exceeding the critical $F$-value by 8.23. An $R^2$ value of 0.45 was outputted, indicating that nearly a half of all retention is influenced by inflow fluxes. Also, in the case of pond 5, the optimum flow is much higher than ponds 1 and 3 with a value in the order of 1300 m$^3$ (Fig. 3e). With respect to ponds 2 and 4, the relationships displayed are the inverse of ponds 1, 3 and 5. The relationship is positively quadratic; with an initial negative correlation between the variables until a flow of approximately 400 m$^3$ and 700 m$^3$, for ponds 2 and 4, respectively, followed by a positive correlation. Pond 2 displayed a statistically significant relationship, with an $F$-test result of 1.35 and a critical $F$-test value of 0.27. As the $R^2$ value is 0.12, one can say with 95% confidence that 12% of all changes in P retention within this pond are attributed to hydrological inflow variations. Results for pond 4 were highly variable, resulting in a non-significant relationship. The $R^2$ value of 0.007 indicated that effectively there was no association between concentrations of P retained in sediments and fluctuations of water flowing into pond 4. For all ponds, both absolute retention and retention ratio displayed similar relationships with inflow. There is no obvious characteristic that distinguishes ponds 2, 3 and 5 from the other two. According to Forbes et al. (2009), all of the Greenmount Farm CWS ponds have been planted with types of Typha. These emergent species remove contaminants through assimilation of the pollutant into their tissue and providing a habitat for pollutant transforming microorganisms (Vymazal, 2007; Yang et al., 2007). Studies have shown an average P removal rate of 80% in constructed systems planted with types of Typha (Brix, 1994; Yang et al., 2007). According to analysis, up to 45% of variations in P retention can be attributed to inflow fluxes in pond 5.

Fig. 2. Model output for the percentage of phosphorus retention and release in each pond (a–e) and averaged over the whole CWS (f).
There is an obvious distinction between up-gradient (ponds 1–2) and down-gradient (ponds 3–5) ponds when looking at retention vs. daily temperature between February 2006 and March 2007 (Fig. 4). It is assumed in this project, that the P retention predicted is a result of sedimentation. Other processes of P retention, such as biological, can also contribute to the reduction of P in wastewater (Mitsch et al., 1995). Such processes are influenced by seasonal variations in water column temperature and so the mean daily air temperature of the watershed is expected to have a direct impact on these processes. Mean air temperature is also important with respect vegetation productivity, with sub-zero temperatures potentially causing structural damage to the species (Kimball et al., 2007; Lenihan et al., 2008). Up-gradient ponds, 1 and 2, display a positive quadratic relationship, with the greatest retention occurring at low and high temperatures (Fig. 4a). Down-gradient ponds, 3, 4 and 5, however display a negative relationship with poor levels of retention occurring at low and high temperatures (Fig. 4b). Trend analysis for pond 5 showed different trends for absolute and retention ratio. With regards to ponds 1 and 2, retention initially decreased with increasing daily temperatures until approximately 10 °C and 13 °C, respectively; succeeding this, the concentration of retention appeared to increase with increasing daily temperatures. Statistical analysis showed that the relationship between total P retention and mean daily temperature was not significant and the $R^2$ value of 0.004 indicated that there was no correlation between the two variables. Within pond 2 however, inflow did appear to have an influence on the degree of retention, accounting for approximately 24% of variations. The $F$-test value of 3.15 was greater than the critical $F$-value of 0.11, therefore the relationship was considered significant at the 95% confidence level. Comparison between ponds 1 and 2 showed that the trendline of pond 2 was less exaggerated, resembling more of a linear trend. Ponds 3 and 4 both showed an initial positive correlation between retention and temperature, until an optimum temperature of 12 °C and 11 °C, respectively. Analysis for pond 3 indicated that the relationship was significant to a 95% confidence level, with the order to 6% of fluctuations in P retention being caused by changes in daily mean air temperature. As in the case of retention and inflow, model results for pond 4 were highly variable and non-significant. Ponds 1–4 all showed similar trends in both absolute retention...
and retention ratio. Trend analysis for pond 5 however showed a positive quadratic relationship between absolute retention and daily air temperature, and a negative quadratic equation between the percentage of P retained and daily air temperature. The former of which was statistically significant with an F-test value of 7.39 and a critical F-value of 0.21. Also, the $R^2$ value of 0.42 indicated that 42% of changes in P retention were considered to be a result of fluctuations in daily air temperature. For absolute retention, the temperature at which retention starts to increase was around 15°C. The relationship between the percentage of P retained and daily air temperatures displayed the same characteristics as ponds 3 and 4, with an optimum temperature of about 10°C. The relationship differences between up- and down-gradient ponds, with respect to retention and daily temperatures is likely to be due to differences in hydraulic and effluent loadings to each pond. Low retention experienced at extreme high and low temperatures in down-gradient ponds occur at times when there is low to no flow of effluent through the system, such as hot summers with high evapotranspiration levels or freezing winters. This would result in a high concentration of P in the water column. Up-gradient ponds however have sufficient loading of effluent throughout the year creating opportunity for continuous retention. Knowledge of temperature influence on P retention in wetland systems is vital for adaption to future climate changes. The CWS at Greenmount Farm is a pilot for Northern Ireland and so a model or series of models are required as a basis of extrapolation.

The results show that the system in Greenmount Farm, Co. Antrim, is more likely to retain P than release it. This finding coincides with studies that found a net deposit of P in aquatic sediments, such as lakes and wetland systems (Bostrom et al., 1988; Tiessen et al., 2011). The short period of observation, 14-months, tends to favour retentive processes. The model outputs therefore may under-represent the degree of release within the wetland system over time. It is thought that the structure of the model developed can be employed to design a study that will further develop the methods of predicting P retention within constructed wetland systems. For example, the predictive value of the model can be used to control the inflow volume of effluent on a seasonal basis, based on prior knowledge of the time-scale of P release. The model has highlighted the effectiveness of sedimentation as a process of retaining P; this knowledge may therefore be used prior to the design stages of CWS. Through increasing the perimeter of the ponds the potential for sedimentation may also be increased. Both the water balance and mass balance can be applied to determine various wetland parameters, such as hydraulic retention time and mass balances for other contaminants of concern (Davies and Cottingham, 1995). Knowledge of the former is important in order to ensure optimum exposure of contaminants to wetland processes. The mass balance produced is a practical method of predicting the amount of phosphorus within a CWS at any given month, this knowledge is particularly useful for watershed managers who do not need to know about the dynamics of the system, simply quantities. Incorporation of retention time with the input/output mass balance can be used to predict an optimum pond size which will retain enough P to meet standards whilst taking up the least amount of space, a vital attribute for implementation of the systems in Northern Ireland.

4. Conclusion

An input/output mass balance was effective in predicting P retention and release in a CWS used to treat dairy wastewater. The water balance showed a liner trend of increasing volume with time over the whole of the five-pond system. The last pond in the system (pond 5) was the most effective in removing P. The model showed that the CWS displayed a greater tendency to retain rather than release P. Differences in relationships between up-gradient and down-gradient ponds, with respect to retention and daily air temperature, were considered to be a result of differences in hydraulic and effluent loadings.

References


