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Temporal phosphorus dynamics affecting retention estimates in agricultural constructed wetlands

Karin M. Johannesson[a,*], Karin S. Tonderski[a], Per Magnus Ehde[b], Stefan E.B. Weisner[b]

[a] IFM Biology, Linköping University, 581 83 Linköping, Sweden
[b] Wetland Research Centre, Halmstad University, 301 18 Halmstad, Sweden

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ABSTRACT

Data from seven constructed wetlands (CWs) in the south of Sweden were analyzed to investigate the effects of water flow and season on inflow phosphorus (P) concentrations and temporal P retention variations in CWs receiving runoff from arable land. The form of P (dissolved or particulate) during different water flows (high and low) and seasons (warm and cold) was investigated using the results of total P (TP) and phosphate analyzed in grab samples that had been collected regularly or occasionally during two to nine years, along with continuous water flow measurements.

The form of inflow and outflow P (particulate or dissolved P) differed between CWs, and also varied with season and flow. For instance, in three of the CWs, particulate P (PP) dominated the inflow during the cold period with high flow, while during the other periods the proportion of PP was approximately 50%. In one CW situated in a catchment with high clay content, PP dominated both inflow and outflow at all times. The average clay content in catchment top soils was positively correlated to the flow-weighted inflow TP concentrations.

In three CWs receiving runoff through drainage pipes, the relationship between TP concentrations (TP_{in}) and water flow was positive, both during high and low flow, and during warm and cold period. However, in four CWs that received surface water runoff, the relationship between TP_{in} and water flow was positive during high flow periods (*i.e.* the 25% sampling occasions with the highest flow), and during low flow and warm period, the relationship was negative in these four wetlands, indicating either anoxic stagnant water upstream or influence from rural wastewater.

The temporal dynamics of P concentrations mean that in some of the CWs, the main part of the annual P retention may occur during a few days with high water flows. The correlation between concentration and water flow suggests that the water sampling strategy may have a considerable impact on retention estimates, as exemplified by some calculation examples.

1. Introduction

Water draining from catchments dominated by agricultural land is an important source of phosphorus (P) that contributes to eutrophication problems in aquatic systems (*e.g.* Liikanen et al., 2004). As P is often the limiting nutrient in both freshwater ecosystems and coastal waters, there is a particular need to reduce the P transport from agriculture. In the Baltic Sea drainage basin, construction of free water surface (FWS) wetlands has been proposed as a means to mitigate P losses from arable land, supplementing best management practices (EPA, 2014; HELCOM, 2014). If constructed wetlands (CWs) are to be implemented as a cost-effective mitigation measure, an improved understanding of how seasonal and water flow variations affect the P retention efficiency is required.

Studies of FWS wetlands constructed to remove nutrients from agricultural streams and drainage pipes have shown that they generally function as sinks for P, but the results are quite variable. For instance, in an investigation of 17 FWS wetlands, P retention varied from 2 to 578 $kg\,ha^{-1}\,yr^{-1}$ (Braskerud et al., 2005). In that study, P retention variation was statistically related to differences in P load, runoff and wetland age. One challenge when evaluating CWs for P retention is the incomplete understanding of how factors such as water flow variations and seasonal dynamics affect P retention. Some of the difficulties lie in the gaps in knowledge regarding P behavior in catchments and wetlands, *i.e.* when and in which

* Corresponding author.
E-mail addresses: karin.johannesson@liu.se (K.M. Johannesson), karsu@ifm.liu.se (K.S. Tonderski), per_magnus.ehde@hh.se (P.M. Ehde), stefan.weisner@hh.se (S.E.B. Weisner).

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form P is transported. Weather driven variations in both water flow and P concentrations add complexity to the issue of understanding the variations in P retention in CWs in agricultural catchments. In cold temperate regions, such as Scandinavia, the effect of different seasons probably has a strong influence on P transport from agricultural land, and thus on P retention in CWs. Usually, the periods with highest runoff are during snow melt in spring and during heavy rainfall periods in the autumn. For instance, Kronvang et al. (2003) investigated the P transport in two Danish streams and demonstrated the dynamic nature of P concentrations during rainfall. In their study, the highest P concentrations were found during rainfall in autumn, when much of the P retained in the stream channel during low flow periods was washed away. Pionke et al. (2000) showed that 90% of the P export from an agricultural watershed in U.S. occurred during storm flow. Such sudden events will have a significant impact on the P retention processes in wetlands constructed to mitigate the P transports from arable lands, as has been shown in several studies (Raisin and Mitchell, 1995; Braskerud, 2002a; Jordan et al., 2003; Koskiaho et al., 2003). In contrast, summer runoff is commonly very low and sometimes drops to zero, which can also be true for the winter period. Estimates of P retention in wetlands receiving such variable inflows are thus highly depending on a sampling program that can accurately capture those variations in both the inlet and outlet of the wetland.

It is probable that some of the P retention variations analyzed in the study by Braskerud et al. (2005) can be explained by differences in sampling technique and unreliability of estimates of water and P budgets. There are several different sampling strategies for estimating P retention in CWs, *e.g.* grab sampling, time proportional automatic sampling or flow proportional automatic sampling. The simplest is grab sampling, *i.e.* manual sampling at specific occasions, when water samples are collected from the inlet and the outlet of the wetland. Water flow can be measured either manually at every occasion, or with a continuous flow meter, installed at either inlet or outlet, or both (*e.g.* Koskiaho et al., 2003). Time proportional sampling includes an automatic sampler that collects water samples at specific time intervals at both inlet and outlet, in combination with continuous flow measurements (*e.g.* Reinhardt et al., 2005). In comparison, flow proportional sampling includes an automatic sampler that collects samples in relation to the water flow, and not at specific times. The automatic sampler can be controlled by either only the outflow (as in Braskerud, 2002b) or by both inflow and outflow (as in *e.g.* Jordan et al., 2003 and Kynkäänniemi et al., 2013). There are several challenges when trying to obtain accurate data on phosphorus mass inflow and outflow. For instance, even if flow proportional sampling is employed, the time lag in flow variations between inlet and outlet is not accounted for if the flow is only measured at one point. If concentrations are correlated with flow variations, this can introduce systematic errors in the estimates of mass in-and outflows. Such errors are aggravated if a time-proportional sampling methodology is used with no adjustment for water flow variations. This is of particular importance when the transport is highly event-driven with large and sudden variations in concentrations, such as for movement of particles in streams (Jarvie et al., 2002). For instance, (Kronvang and Bruhn, 1996) showed that in two Danish streams, TP transport was nearly always underestimated, especially for PP.

With these considerations in mind, the aim of this study was to analyze the temporal dynamics of P concentrations in CWs in agricultural catchment areas, and assess the importance of such variations for P retention estimates. The results are used in a discussion of P retention efficiency in wetlands constructed to capture P in runoff from arable land.

2. Materials and methods

2.1. Site descriptions

The wetlands included in this study are situated in the south of Sweden (Fig. 1), and are all constructed in agricultural catchments, although the percentage of land used for agriculture differs between the sites (Table 1). They were all excavated on mineral soils, and vary in size but are relatively small compared to their catchment area, from 0.06% (L.B.) to 2.2% (Ste) of the catchment area. L.B. is the oldest wetland, constructed 1991, and Ste the most recently constructed (in 2003). The wetlands L.B., Böl. Ede, Gen and Slo have a similar design, with a long and narrow shape, with length to width ratios ranging from 6 to 15 (Fig. 1, Table 1), while Råb and Ste have more rectangular shape. Mean water depth varies from 0.5 m in Ste to approximately 1 m in L.B., Slo, Råb and Ede.

2.2. Sampling strategy for water flow and quality

Monitoring data on water flow and nutrient concentrations were obtained from Ekologgruppen (for Råb, Gen and Slo), the Wetland Research Centre at Halmstad University (for L.B., Böl and Ede) and WRS Uppsala AB (for Ste). In all wetlands, continuous automatic water flow measurements were carried out for the sampling periods (Table 2). In six of the wetlands, water flow was measured only at the outlet, while in one wetland, Ste, water flow was measured both at the inlet and the outlet.

Monitoring of the seven wetlands included automatic water sampling (either time or flow proportional) at the inlet and outlet. Additional grab samples were taken as supplements to the automatic sampling regularly (*i.e.* once a week) in L.B., Böl and Ede. In Ste, Gen, Råb and Slo grab samples were taken with less regularity. Frequent grab samples were collected for shorter periods in three of the wetlands (L.B., Gen and Ste), in order to investigate the movement of P with a higher resolution. During those periods (mostly with high flow), grab samples were collected daily or twice a day. For this study, only data from grab samples were used, since the aim was to investigate the short term temporal variation in P concentrations and how that may affect retention estimates. Data from the automatic sampling were only used for P load estimations.

2.3. Chemical analyses

All grab samples from all seven wetlands were analyzed for TP after autoclave-mediated digestion (120 °C, 100 kPa, with $K_2S_2O_8$ and H_2SO_4) according to Swedish standard procedures. Grab samples taken in L.B., Ede and Böl were analyzed for TP on unfiltered samples and phosphate (PO_4-P) on filtered samples (0.45 μm membrane filter), while samples from the intensive grab sampling periods in Gen and Ste were analyzed for TP on both filtered and unfiltered samples. In Råb and Slo grab samples were analyzed for TP and PO_4-P on unfiltered samples only, but the PO_4-P results were not used in the data analyses due to the difficulty to interpret PO_4-P data based on unfiltered samples. Phosphate concentrations in the samples were measured as molybdate reactive P (MRP) using the Swedish standard for P determination (SIS, 1997). The difference between TP and PO_4-P concentrations was used as a proxy for PP concentration for L.B., Ede and Böl, and for Ste and Gen, the difference between $TP_{unfiltered}$ and $TP_{filtered}$ was used. Hence, the difference between TP and PO_4-P and $TP_{unfiltered}$ and $TP_{filtered}$, respectively, is hereafter referred to as particulate phosphorus (PP).

2.4. Data analyses

In all wetlands except Ste, water flow was only measured in the outlet (Table 2). For all calculations involving the