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Phosphorus and particle retention in constructed wetlands—A catchment comparison

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ABSTRACT

Seven constructed wetlands (0.05–0.69 ha), situated in agricultural catchments (22–267 ha) in the south of Sweden, were studied for two years with two aims: to (i) quantify their function as sinks for particles and phosphorus (P) lost from the catchments, and (ii) investigate to what degree catchment and wetland characteristics and modeled loads (using hydrochemical catchment models) could be used to explain differences in retention between the wetlands. The wetland areas ranged from 0.04 to 0.8% of the respective catchment area, and they were situated in areas dominated by fine-textured soils with relatively high P losses and the main proportion of P transported in particulate form. Net P and particle retention were estimated during two years from annual accumulation of particles on sedimentation plates (40 × 40 cm) on the bottom of the wetlands.

There was an annual net retention of particles and P, but with a large variation (for particles 13–108 t ha^{-1} yr^{-1} and for P 11–175 kg ha^{-1} yr^{-1}), both between wetlands and between years. The difference between the two years was larger than the difference in mean P retention between the seven wetlands. There was a positive relationship between P and particle retention and three catchment factors, *i.e.* P status (P-AL) of agricultural soils, average slope in the catchments and the livestock density, and a negative relationship with the agricultural soil clay content. In addition, there was a positive relationship with the wetland length:width ratio. Contrary to expectations, neither the modeled hydraulic load nor P load was significantly correlated with the measured particle and P retention. There was also a positive relationship between P concentration in the sediment and soil P status in the catchment. The results imply that considerable errors are introduced when down-scaling modeled regional nutrient losses to estimate the P loads to small wetlands in agriculturally dominated catchments. A more qualitative approach, using catchment characteristics for identification of hot-spot fields, may be equally good to identify suitable locations for constructed wetlands to reduce diffuse P loads.

1. Introduction

Eutrophication is a problem in Swedish lakes and in the Baltic Sea, causing algal blooms, anoxia and dead bottoms with severe ecological and economic consequences. In freshwater and brackish systems, phosphorus (P) is often the limiting nutrient (Kalff, 2002). Agriculture is an important diffuse source of P, and according to recent estimates, P loads from agriculture in the south of Sweden was 156 t P yr^{-1} to the southern Baltic Sea, which represents 44% of the total load of P from Sweden (Stolte et al., 2009). National estimates (Blombäck et al., 2011) have shown that agricultural areas with clay soils have among the highest P losses. Agricultural catchments with clay soils in Sweden demonstrated long-term loads of 0.3–0.8 kg ha^{-1} yr^{-1} (Ulén et al., 2007, 2012), and from monitored single fields and plots the 4–6 years mean P losses were 1.5 kg ha^{-1} yr^{-1} (Stenberg et al., 2012; Svanbäck et al., 2014). Several other studies have shown that in runoff from agricultural fields in clay and silt dominated areas in Scandinavia, P is transported predominately as particulate P, defined as particles with diameters larger than 0.2 μm (Ulén, 2004; Uusitalo et al., 2000, 2003) or 0.4 μm (Koskiaho et al., 2003).

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The construction of wetlands has been advocated as one of several measures to reduce the transport of P from agricultural land, which is part of the Swedish Environmental Objective "No eutrophication", and of the Baltic Sea Action Plan (EPA, 2014; HELCOM, 2014). High P retention has been documented in wetlands in Norway as well as in England and Wales (Braskerud et al., 2005; Kronvang et al., 2009), but the efficiency of wetlands as traps for P in agricultural runoff in the hydrogeological conditions of South Sweden has not been fully investigated. Studies of in- and out flowing mass loads of P in wetlands receiving agricultural runoff generally show an annual retention, but the variation is large, from a few kilograms of P per hectare wetland area and year (Koskiaho et al., 2003; Kovacic et al., 2006) to over 500 kg ha^{-1} yr^{-1} (Braskerud et al., 2005; Maynard et al., 2009). The amount of P retained in wetlands depends on several factors. Generally, the P load has a positive correlation with area specific P retention (*e.g.* Braskerud et al., 2005), and the load depends on catchment characteristics that determine P losses from land areas, such as soil type (*e.g.* Ulén et al., 2012), land use, topography of the landscape (Ekholm et al., 2000), P status in the topsoil (P-AL) (Svanbäck et al., 2013) and rural sewage discharge (*e.g.* Jarvie et al., 2006). Also, the hydraulic load is important in determining P retention, since it affects the amount of particles and P that enters a wetland, and the water velocity which in turn affects the settling rate of the particles (Carleton et al., 2001). The hydraulic load is closely linked to the ratio between wetland size and the size of the catchment (A_w:A_c), as this determines the volume of runoff that enters the wetland per day (Kadlec and Knight, 1996). There is no 'rule of thumb' regarding the optimum A_w:A_c ratio, since it depends on whether the objective is to achieve clean water in the outlet (*i.e.* high relative retention, expressed as percentage of load) or to achieve a high area-specific retention (expressed as kg P removed per hectare wetland and year). If wetlands are large in relation to the catchment area, the relative retention is usually high, but in agricultural landscapes, the possibility for wetland construction is often limited by land availability. Wetlands that are 2% of the catchments, as recommended in Finland to achieve satisfactory relative particle retention (Puustinen et al., 2001, cited in Koskiaho, 2003) are often not realistic in areas dominated by intensive agriculture. In several studies it has been shown that wetlands that are small in relation to their catchment area (0.05–0.38%) and have a high load, have a higher area specific P retention than wetlands that are larger relatively speaking (Braskerud et al., 2005; Maynard et al., 2009).

Since a significant part of the P transported from agricultural fine-textured soils presumably is attached to particles, sedimentation is likely the predominant P retention process in wetlands receiving drainage and runoff water from such soils. Sedimentation rates depend on the size and shape of the particles, but also on the water velocity and wetland depth. Hence, the design of the wetland (shape and depth) is important. According to Stoke's law, it will take the coarsest clay particles (diameter 2 μm) approximately 88 h to sink 1 m in fresh water (15 °C) (Sheldrick and Wang, 1993). Therefore, to promote sedimentation of clay particles, the residence time in a wetland needs to be quite long, *i.e.* a low hydraulic load. In addition, the water velocity will be higher in a long and narrow wetland (high length:width ratio, L:W) than in a short and wide one with the same area, but on the other hand the distribution of water over the entire area (hydraulic efficiency) will be better in the former (Persson and Wittgren, 2003). In a study of several constructed wetlands in Norway, Braskerud (2003) showed that fine clay particles in runoff from arable land had sedimentation velocities similar to coarse clay or silt, and a high degree of soil particle aggregation was confirmed by a more recent study (Sveistrup et al., 2008). A Swedish study, on the other hand, showed that a majority of particles in the drain flow from a clay soil were colloids with a theoretical settling velocity of 0.08 cm day^{-1} (Ulén, 2004). In a catchment with such soil, the efficiency of wetlands as sinks for particles and associated P might be substantially lower than in wetlands located in catchments with well aggregated fine-textured soil, as those studied by Braskerud (2003). There is a need to evaluate the function of constructed wetlands receiving high loads, and to investigate their efficiency as traps for P and particles. Further, it is important to evaluate catchment factors potentially affecting area specific retention in constructed wetlands, in order to choose appropriate sites for their locations.

1.1. Aims and hypotheses

The first aim of this study was to quantify the annual soil particle and particulate P retention in small, fairly high-loaded constructed wetlands situated in South Sweden in agricultural catchments with various content of clay. Retention was quantified based on particle settling on sediment plates. A second aim was to investigate if available data on catchment and wetland characteristics could be used to explain some of the observed retention differences between wetlands. We had the following three hypotheses:

- All wetlands would function as traps for both soil particles and P, and the amount would be higher in wetlands with a higher load, possibly with an upper limit.
- Factors known to be positively correlated with catchment P losses would be positively correlated with the amount of particles and P retained in the wetlands on annual basis.
- Long and narrow wetlands would have higher particle and P retention than wetlands with a more round shape.

2. Material and methods

2.1. Wetland descriptions

The wetlands included in this study were selected based on the following criteria, indicative of a high P load from the catchment to the wetland, (i) located in a catchment dominated by arable land, (ii) varying proportion of clay content in the agricultural soils in the catchment, (iii) a wetland area preferably <0.5% of the catchment area. Based on those criteria, seven wetlands were selected (Fig. 1). They varied in size, shape and vegetation cover. The wetlands were additionally with or without design elements in the form of small islands and berms. Two of the wetlands, Ber and Ski, were both designed with a shallow section covered with emergent plants following an open water inlet section. Ber consisted of a 1 m deep sedimentation pond followed by a 0.3 m deep section with emergent plants (Kynkäänniemi et al., 2013). In Ski, the shallow (0.2–0.3 m) section was placed between two deeper (approximately 1.2 m) sections (Fig. 1). All the other wetlands were constructed without distinct sections (depth varied from 0.5 to 1.3 m), and both emergent and submersed plant species were established in the wetland areas (Table 1). In Eks and Lin, islands had been created to provide shelter and refuge for waterfowl. Such islands may additionally alter the hydraulic pattern of a wetland.

The wetland area to catchment area ratio (A_w:A_c) was calculated and the wetland shape was described by the wetland mean length to width ratio (L:W), estimated by calculating the L:W for every 10 m transect from the inlet to the outlet of the wetland, using aerial photographs (Table 1).