Department of Physics, Chemistry and Biology

Master Thesis

Catchment factors affecting particle and phosphorus retention in wetlands receiving agricultural runoff.

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Innehåll

1 Abstract

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Keywords: Agricultural runoff, Catchment characteristics, Clay, Constructed wetlands, GIS, Phosphorus retention

2 List of abbreviations

CA Catchment area
CW Constructed wetland
D.W Dry weight of sediment
IP Inorganic phosphorus
LU Livestock units
L:W Length to width ratio
OP Organic phosphorus
P Phosphorus
PP Particle-bound phosphorus
q Hydraulic load (m day^{-1})
Q Flow (m^3 day^{-1})
RF Specific runoff (mm day^{-1})
TP Total phosphorus
WL Wetland

3 Introduction

Part of the environmental objectives for Sweden is to reduce eutrophication, and the Baltic Sea Countries have adopted the Baltic Sea Action Plan (BSAP) with the aim to achieve a good ecological status in the Baltic Sea by 2021. The part of BSAP that is most urgent and challenging is the reduction of nutrient input. One prime concern is the load from the agricultural sector since it has been stated to be responsible for 45 % of the anthropogenic phosphorus (P) load to the Baltic Proper (SEPA 2009). Preliminary numbers show that Sweden must reduce the annual P load to the Baltic Sea with 290 tonnes until 2021 (SEPA 2009).

Several studies have shown that constructed wetlands (CW) can act as P sinks in agricultural landscapes (Braskerud 2002, Liikanen et al 2004, Braskerud et al 2005, Kadlec 2005). Sedimentation of particle bound P is the dominating retention process in agricultural wetlands (Braskerud 2002, Koshkiaho et al 2003). Retention is the net result of biological processes i.e. uptake by plants or microbes, chemical, sorption and precipitation or physical processes such as sedimentation and resuspension (Kadlec 2005, Kadlec and Scott 2009). There are two main pathways for particle-bound phosphorus (PP) to reach wetlands, either through surface runoff or leaching through the soil profile. In the former, particles containing P are lost through surface erosion and in the latter particles are transported with water that percolates through the soil profile, and into drainage systems. Depending on the size of a catchment and the precipitation, runoff (mm day^{-1}) will differ. This will affect the farm land P losses as its movement is coupled to water flow pathways. Based on normalized standard values from 22 Swedish leaching regions, the mean P loss from Swedish arable land in 2005 was 0.52 kg ha^{-1}, but the regional differences were large (0.1-1.3 kg ha^{-1}) (Johnsson et al 2008).

Generally, as the inflow P concentration (mg L^{-1}) and specific P load (g $m^{-2}yr^{-1}$) increases, the area specific P removal (g m^{-2} yr^{-1}) in wetlands also increases (Braskerud 2002, Koskiaho et al 2003, Braskerud et al 2005, Kadlec 2005). But there are large variations in performance and at times a net release of P has been observed (Koskiaho et al 2003). Kadlec (2005) showed that retention can differ with as much as $*10^3$ gP m^{-2} yr^{-1}at a given inlet concentration. Thus, even if an increased P load generally yields an increase in retention, there is still a lack of knowledge about which factors that contribute to the high variability in wetland performance.

Several factors may explain these large variations. Hydraulic and P load are important, and the latter is affected by catchment characteristics such as, soil type, land use and topography of the landscape. Those factors may determine both the amount of P that is bound to particles and how large and well these particles aggregate and settle within CWs. When estimating P loss from arable land the Swedish EPA use the ICECREAM model, where the input data are: crop combinations, soil texture, landscape slope, soil P classes in different agriculture production areas, and leaching regions (runoff). Studies have also shown that suspended solids and TP in river systems and water bodies are correlated to both steepness of the landscape, crop coverage, land modification, (Ekholm et al 2000, Galbraith and Burns 2007) erosion, soil P content (McDowell et al 2001) soil texture and precipitation (Kyllmar et al 2006). Since these factors are important for the P loss from soils it is expected that they also influence retention in CWs. For example, studies have reported that as specific runoff (mm d^{-1}) increased the particulate-P retention in wetlands also increased (Braskerud et al 2005). In contrast, Greiner and Hershner (1998) found no correlation between TP retention and varying landscape characteristics. However, this was thought to be due to too high similarity in landscape parameters between the studied wetlands. Soil erosion can be affected by soil disturbance such as tillage practices. Ploughing may have a negative effect by tearing possible aggregates apart or a positive effect by destroying macropores and preventing preferential flow (Ulén 2005). Thus, P retention may differ depending on different erosion tendency and aggregate stability of soils. Substantial knowledge needs to be gained concerning the individual importance of specific catchment factors, such as land use and topography, since this could possibly explain the large variations in retention despite similar load.

The highest P losses from soils in Sweden are usually from clay soils (Djodjic 2001, Kyllmar et al 2006). Most clay soils in Sweden are found in relatively flat, arable landscapes that are artificially drained (Ulén and Jakobsson 2005). Ulén (2004) concluded that particles transported in drainage systems from arable land located on clay soils in Sweden had a high proportion of colloidal material and a settling velocity of less than 1 cm day^{-1}, which would make sedimentation in wetlands difficult. On the other hand, Braskerud (2003) investigated small Norwegian CWs, located in catchments with clay soils, and found that an increasing hydraulic load increased the settling of particles. Negative effects of high hydraulic loads were neutralized by an increased load of larger particles and clay particle aggregates with higher sedimentation velocity (Sveistrup et al 2008). Thus clay particles behaved as larger particles and settled to some extent in the Norwegian wetlands. If clay particles settle one could expect an increase in sediment P concentration (mgP kg^{-1}) since smaller particles have larger surface area onto which P could adhere (Pacini and Gächter 1999, McDowell et al 2004).

The purpose of this study was to evaluate if any specific catchment characteristics could explain the difference in particle and P retention in constructed wetlands situated in south Sweden, mainly receiving non-point source runoff. It is important for future estimations of wetland performance based on geographical data and for locating wetlands where they would be most efficient. In addition to this there is a need to put extra effort in studying wetlands situated in catchments with clay soils, since there is a correlation between biologically available P and clay-sized particles (Maynard 2009). The specific objectives were to: 1. Evaluate if there were any specific factors characterizing catchment areas that could be statistically related to the wetlands performance when it comes to particle and P retention. The hypothesis was that retention would increase with load, steepness, and clay content. In addition the factors tilled land, livestock, rural sewage and wetland shape were included. 2. Examine the spatial distribution of settled material and phosphorus within the studied wetlands. The hypothesis was that specific retention would decrease from inlet to outlet, whereas the P concentration in sediment would increase. Additionally it was hypothesized that the P concentration in the sediment would be positively correlated with increased clay content in topsoil of the catchment.

4 Material and methods

4.1 Study sites

The selection of eight constructed wetlands in the southern part of Sweden (figure 1) was based on criteria that should result in a high P load to the wetland i) they should be located in agricultural catchments, ii) on different soils but all with some amount of clay, iii) they should be small in relation to their catchment (< 0.5 %). The wetlands chosen based on those criteria were highly variable with respect to shape, size, islands and vegetation (Fig. 1, Table 1).

In Genarp only the first pond out of two was included in this study. Logården was added to the study in May 2010; hence, the plates were only placed in the wetlands for three months.

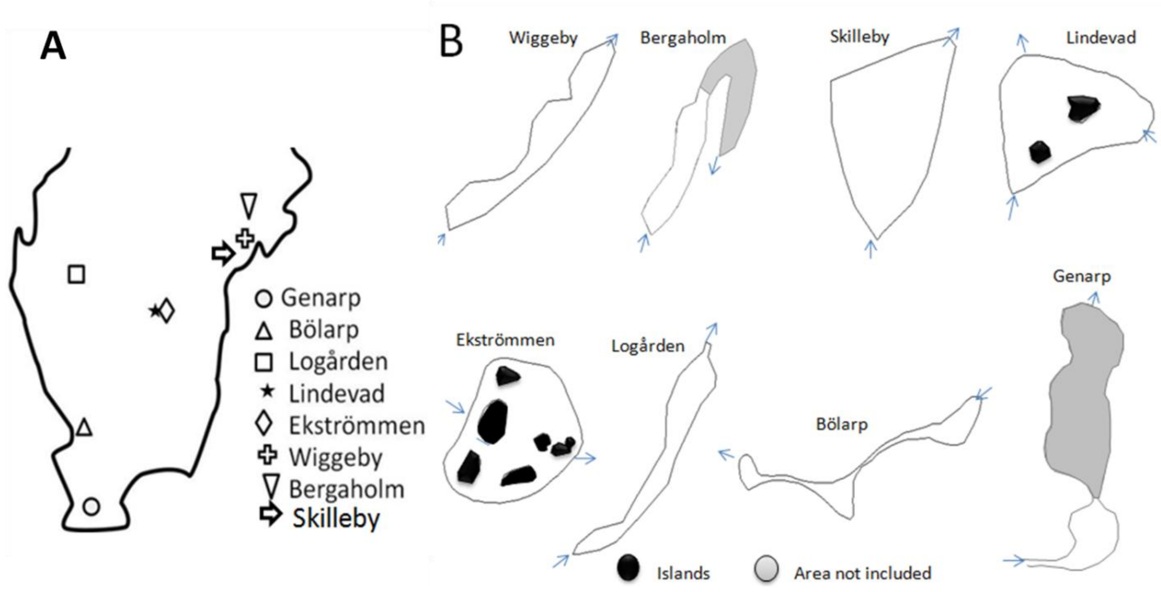

Figure 1A) Location of eight wetlands where net sedimentation and phosphorus retention was studied using sedimentation plates. B) Shape and design of the same eight wetlands. Note that they are not drawn according to scale. ● Represents islands and ○ represents area not included in this study. Arrows indicate inlet and outlet.

Table 1 Site specific characteristics, when visited 2010, of 8 Swedish wetlands where net sedimentation and phosphorus retention was measured using sedimentation plates.

Site	**Const. year**	**Vegetation**	**Mean depth**	**Other characters and observations**
Lindevad	2008	Dense filamentous green algae	0.7 m	2 inlets, 2 islands, rural sewage drainage from 2 households leading into the wetland. Clear water when visited. Drainage pipe
Ekströmmen	2009	Very sparse emergent vegetation	1 m	6 islands, plenty of. wildfowl (dabbling ducks) fed with wheat. Turbid water when visited. Open ditch.
Skilleby	2003	Dense *Typha* sp. & *Potamogeton* sp.	1 m	2 deep basins separated by vegetation filter. Turbid water. Particles in the outlet water. Drainage pipe.
Bergaholm	2009	Planted *Sparganium* sp, *Carex* sp. & *Lythrum* sp.	0.6 m	Deep zone (1m) followed by 0.4 m zone, overflow zone, another 0.4 m zone and deep at the outlet. Drainage pipe.
Wiggeby	2009	Patches of *Typha* sp. & filamentous green algae	1 m	Stones placed perpendicular to water flow at inlet & middle section. Dried out summer 2010, rewetted by heavy rainfall. Open ditch.
Genarp	1997	Sparse emergent vegetation	0.8 m	Long stretched ditch as inlet. wildfowl present. Recieves stormwater from approximately 30 ha urban area.
Bölarp	2002	Dense *Potamogeton* sp., *Typha* sp. & *Callitriche* sp.	0.8 m	Embankment, of settled particles colonized with plants by inlet. Clear at inlet, more turbid towards outlet. Drainage pipe.
Logården	2003	Patches with dense *Typha* sp. & *Phragmites* sp.)	0.6 m	1.25 m deep 07/08 (Marmolin, 2009). Open ditch.

4.2 Geographical data collected

As a first step, data were collected to verify the catchment boundaries for each wetland. Hereafter the following catchment characteristics were determined. i) Average catchment slope ii) coverage for different crops and the extent of agricultural land iii) rural sewage discharge iv) soil type v) annual runoff, as it determines how much water that flows through the wetlands.

4.2.1 Catchments

Catchment areas given by municipalities and County administration boards were verified by topographic maps with contour lines (5m), GSD-elevation data (50*50m) with a maximum standard error of 2.5 m and field surveys. All terrain and elevation maps were collected from The Swedish mapping, cadastral and land registration authority (Lantmäteriet) and used in ArcGIS 9.3.1. The aspect-tool was used on the GSD-elevation data. Since most agricultural fields are drained, looking only at topographic maps and elevation data was not sufficient. In addition, the drainage systems were examined during field surveys by looking in drains and verifying catchment boundaries. In Genarp the catchment was not visited and only determined by maps, additional information on catchment boundaries in Genarp for easier determination was given by Wedding B. at Ekologgruppen and for the urban area of the catchment, VA Syd (authority for water and sewage in Lund, Malmö and Burlöv municipalities). For Logårdens catchment additional information on its boundaries was obtained as a shape file from Andersson J (County administration board, Västra Götaland). In Lindevad, a more detailed topographic map (0.02 m) was obtained from Rangsjö C.-J (consultant, SBA).

4.2.2 Average slope

The same elevation data as used for determining the catchments were used to determine average slope (%) within the different catchments in ArcGIS 9.3.1. Slope was calculated for each cell in a raster, where the highest measure of height change was calculated between each cell and its eight closest neighbors in a 3*3 grid. A maximum change in elevation over the distance between the cell and its eight neighbors identifies the steepest downhill decline from the cell (Burrough and McDonell, 1998). An output raster was constructed where each cell contained the slope of the cell; the higher value, the steeper slope. Mean catchment slope was calculated from all cells within a catchment.

4.2.3 Land use data

Land use data for arable land in 2009 was obtained as shapefiles covering agricultural blocks from the Swedish Board of Agriculture. A block is a connected area with a fairly resistant land use classification from year to year (i.e. classified as field or pasture) they are restricted by roads, ditches, streams, forested areas, regional boarders etc. Within each block there are parcels, each block may contain one or several parcels with different crops. The database was to some extent incomplete when it comes to actual land use in different blocks and parcels. Agricultural parcels where no land use data were available were assigned a land use by the mean known agricultural land use in the catchment, when verifying with land owners was not possible. Based on the crop coverage, the proportion of tilled land was estimated. Ley was grouped with pasture and classified as untilled land. Data on livestock units (LU) per hectare was gathered from field surveys, land owners and municipalities, sometimes, with data from previous years. In Lindevad, Ekströmmen, Skilleby, Bölarp and Wiggeby all data on LU were obtained by field surveys, local land owners and farmers. In Bergaholm data was received from field survey and from SLU (Kynkäänniemi P. pers. com.) In Logården data on LU was obtained from the municipality (Timmersjö A.) as an excel file with geographical coordinates for farms and their livestock in 2009. In Genarp, LU data was obtained from the municipality

(Björnberg E. pers. com.). These LU data cannot be seen as exact measures since there was not always precise records sorted in a way that was extractable to suit this study; however it gives a good estimate of the amount of farm animals in the different areas. The remaining land areas in the catchments are mostly forested areas, private gardens and roads. The exception was Genarp where part of the catchment (approximately 11%) consisted of an urban area with stormwater draining to the wetland (VA Syd, 2011). Rural sewage discharge was included as number of rural households per hectare within the catchments. This was done by counting houses marked on the terrain maps from Lantmäteriet and through field surveys.

4.2.4 Soil type and runoff

The proportion of clay (% clay in mineral soil D.W) in topsoil (0-20 cm depth) was obtained from the Swedish environmental monitoring program on arable soils (SLU, 2010) and included data from 94/95. Lindevad was an exception where the landowner provided the soil mapping results over the entire catchment (Granath A.) Runoff data was obtained from Johnsson et al (2008), where long term monitoring (1985-2004) from the Swedish Meteorological and Hydrological Institute (SMHI) has been used to calculate average runoff mm year^{-1} in 22 leaching regions. In the Bergaholm area more accurate runoff data was received from Ulén B. (SLU). The regional runoff varied from 200mm to 538mm (Table 2). All areas in the western part of Sweden had higher runoff than the ones in the eastern part. Runoff was used to calculate the mean inflow to the wetlands, Q (m^3 day^{-1}) using the following equation:

$$Q = \frac{RF\left(A_1 * 10\right)}{365} \qquad (1)$$

Where RF is runoff (mm year^{-1}), A_1 is the catchment area in hectares and 365 days in one year. In addition the hydraulic load, q (m day^{-1}), was calculated for each wetland using the following equation.

$$q = \frac{Q}{A_2} \qquad (2)$$

Where Q is m^3 day^{-1} and A_2 is the surface area of the wetland in square meters. The hydraulic load affects detention time and the water flow rate through the wetlands.

Table 2. Construction year, annual regional runoff (leaching regions) number of sedimentation plates and time period for measurement of net sedimentation in 8 wetlands in the south of Sweden. Leaching region and runoff data from Johnsson et al (2008).

Site	No. of plates (sampled)	Leaching region	Annual Runoff (mm)	Plates In/out
Lindevad	7 (6)	4	203	Jul09/Jul10
Ekströmmen	8 (5)	4	203	Jul09/Aug10
Skilleby	13 (10)	6	200	Jul09/Jul10
Bergaholm	18 (17)	6	217*	Sep09/Aug10
Wiggeby	12 (9)	6	200	Dec09/Aug10
Genarp	6	2a	307	Jun09/Jun10
Bölarp	7	1b	538	Jun09/Jun10
Logården	15	5a	318	May10/Aug10

*Local long term monitoring (1988-2009)

4.3 Catchment characteristics

Annual hydraulic loads varied from 0.07 up to 1.54 m d^{-1} in all wetlands except Logården which had a much higher annual hydraulic load of 4.11 m d^{-1}. Three wetlands had less than 0.5 m d^{-1} and the remaining 4 between 1 and 1.6 m d^{-1}. Three of the catchment areas (Lindevad, Genarp and Bölarp) had a low fraction of clay in topsoil (< 15%) whereas the other five all had above 30%. The % of tilled land, varied from 19 to 59 % of the total catchment area where four of the catchments had less than 30%.

Table 3. Wetland area (WL), catchment area (CA), hydraulic load (q) and catchment characteristics (in 2009) for eight wetlands in South Sweden, sorted by hydraulic load (m d^{-1}). (LU stands for Livestock units)

Site	CA (ha)	WL (ha)	q (m d^{-1})	WL: CA %	L:W	Tilled land %	Slope %	Clay soils %	LU/ ha	House /ha
Lindevad	32	0.27	0.07	0.88	1	51	0.2	12	0	0.06
Ekströmmen	160	0.72	0.12	0.46	1	25	1.3	36	0.47	0.01
Skilleby	22	0.08	0.15	0.32	2	34	3.8	52	0	0.18
Bergaholm[1]	26	0.05	0.30	0.18	7	22	4.9	39	0.54	0.15
Wiggeby	121	0.06	1.18	0.05	9	27	2.2	31	0	0.06
Genarp[2]	265	0.17	1.31	0.06	4	19	2.4	8	0.17	0.07
Bölarp	230	0.22	1.54	0.10	20	59	3.2	9	0.93	0.04
Logården	1700	0.36	4.11	0.02	10	38	2.04	36	0.08	0.05

1. Only the part of the wetland where sedimentation plates had been placed was included in the study, the total wetland surface area is 0.09 ha. 2. Only the first pond out of 2 included in this study.

4.4 Sediment sampling and laboratory analyses

In the summer of 2009, sedimentation plates made of 40*40*0.9 cm plastic-coated plywood were placed in transects from inlet to outlet of each wetland. In Bergaholm plates were only placed in the first deep and shallow zone, approximately half the length of the wetland. This is also the only area, from this wetland, included in th calculations. In summer 2010, after approximately 1 year, the plates were removed and the depth of the sediment accumulated upon them measured before it was placed in plastic containers. In the laboratory the samples were weighed and dried at 50° C for dry weight determination (D.W). The sediment D.W. was calculated as g m^{-2} yr^{-1} for each plate. In three of the wetlands, some plates were fixed in the sediment and it was not possible to lift them with the accumulated sediment still intact (four plates in Genarp, one plate in Ekströmmen and one plate in Bölarp). For the points where this happened, a sediment core sampler was used and a sediment sample was collected in close vicinity to the plate. The upper part with the same thickness as the sediment accumulated on the plate as measured with a stick was saved for phosphorus analysis. The calculations for these samples differed since this type of sampling could affect the density of the sampled material. The mean bulk density (kg m^{-3}) of correctly sampled plates within each affected wetland was used to calculate g D.W. m^{-2} yr^{-1} in these cases.

Total phosphorus (TP) was analysed according to Andersen (1975) and glassware were acid washed in 2 M HCl prior to P analysis. First 0.2 g dried and sieved (0.2 mm sieve) sediment from each sample was ignited at 550 °C in a muffle furnace for 1 h. The samples were then boiled in 25 ml 2 M HCl for 20 minutes and diluted to 100 ml with deionised water.
The procedure for inorganically bound phosphorus (IP) followed the same steps as for TP but excluded ignition in a muffle furnace. Organically bound phosphorus was calculated as the difference between TP and IP. Phosphate-P in the extracts was analysed

spectrophotometrically using the Swedish standard method (SIS 1997). The phosphate-P concentration (mg L^{-1}) was calculated according to the following equation:

$$P = \frac{(A - A_0) * V_{max}}{f * V_s} \qquad (3)$$

Where; P is phosphorus in mg L^{-1}, A is the measured absorbans, A_0, is the measured absorbans for a blank sample. V_{max}, is the volume of the diluted sample, f, is the slope of the regression line in a standard curve and V_s is the volume of the undiluted sample. A new standard curve was prepared every day. The result was used to calculate the P concentration (mgP kg^{-1}) in the accumulated material. The amount of P per surface area was then calculated, for each sampling point, by multiplying the amount of soil per surface area (m^2) with the amount of P per kg soil.

The amount of D.W (g m^{-2} yr^{-1}) and P (g m^{-2} yr^{-1}) in each sampling point was used to extrapolate D.W and P over the wetland surface using the IDW method in ArcGIS 9.3.1. Cell by cell in a raster grid (1*1m) was interpolated by adding the means from nearby points. Points closer to the cell will have more influence on the result than points located further away. The inverted distance from each point was used as weight. This method assumes that the variable being mapped decreases in influence with distance from its sampled location, thus the further away a cell is from a sample point the less it will be affected by the sample point.

4.5 Theoretical nutrient load

The theoretical P load to each wetland was estimated based on leakage from arable land in each leaching region using the ICECREAM model (SLU 2007) and runoff data obtained from Johnsson et al (2008). Variables included were: leaching region, soil type and land use (arable). For slope and P content in soil average values for each region were used in thee model. For arable land the following crops were distinguished: spring barley, spring and autumn wheat, autumn rapeseed (representing all autumn oilseeds, flax and peas), spring rapeseed, sugar beets, potatoes (representing any vegetables), oats, rye, fallow and ley (also representing grazed land). The variables were used to obtain a mean P leakage from each catchment. For the remaining areas (i.e. forest and other land) a standard leachate value of 0.050 kgP ha^{-1} was used.

4.6 Statistical analysis

Statistical analyses were mainly used in an exploratory manner to identify potential correlations between wetland/catchment factors and particle or phosphorus retention. Linear regression was used to test for correlations regarding differences in net sedimentation and P retention from inlet to outlet within the wetlands. All values for the dependent variable were log-transformed prior to analysis. In addition, differences in TP and OP concentration in sediment, from inlet to outlet were tested with linear regression. Furthermore, the change in net sedimentation and TP retention from inlet to outlet, from here on referred to as the “settling efficiency”, was analysed for possible correlations with average catchment slope, clay content in topsoil, hydraulic load, length:width ratio and proportion of tilled land in catchment.

To test if the net particle and P retention was highly related to any specific characteristics a principal component analysis (PCA) was performed. These factors were then analysed in regression analyses. Nine factors were initially used to describe catchment and wetland characteristics and they included; 1) clay (%), 2) length:width ratio, 3) hydraulic load, 4) catchment slope (%), 5) number of LU per hectare, 6) proportion of tilled land in catchment (%), 7) specific theoretical TP load (kg ha^{-1} yr^{-1}), 8) number of households with rural sewage discharge per hectare (house ha^{-1}) and 9) wetland:catchment ratio (%). The statistical analyses were performed in Minitab 15 or Statistica 9.1.

One wetland (Wiggeby) was excluded from the overall results since it dried out and was rewetted during a heavy rainfall. This is believed to have caused a flushout of the accumulated material, since the sedimentation plates, except one plate, had very small amounts of material accumulated upon them.

In Lindevad, the two inlets did not receive water from equal fractions of the catchment area. For the inlet receiving less water, the distance from the inlet to outlet was recalculated in proportion to the drainage area in order to be able to compare the net sedimentation on plates placed in front of each inlet. This resulted in a scaled distance from the second inlet to the outlet that was 2.74 times longer than the distance from the main inlet to the outlet. However, this would place the result from the plate in front of the inlet receiving less at 132% from inlet (i.e. outside the wetland). This was balanced by rescaling the result of the plate to 100% from the inlet when studying the net sedimentation differences from inlet to outlet.

5 Results

5.1 Net sedimentation within wetlands.

In five of the wetlands there was a statistically significant decrease in net sedimentation from inlet to outlet. The five wetlands were Logården, Bölarp, Ekströmmen, Bergaholm and Genarp (Table 4, Fig. 2). In Logården one sample was not included in the regression analysis since it was placed immediately in front of the inlet (≈ 13 m) and was thought to represent a very small area affected by the high inlet water velocity. The likelihood of sedimentation here is low due to the high speed of inflowing water. The result for the unfilled diamond in Fig. 2 for Lindevad was the plate placed in front of the second inlet. Its result was moved and was represented by the point at 100% from inlet to scale for the difference in drainage area to the different inlets (see method). The slope of the curves, in the wetlands where there was a significant decrease, was taken as an estimate of settling efficiency.

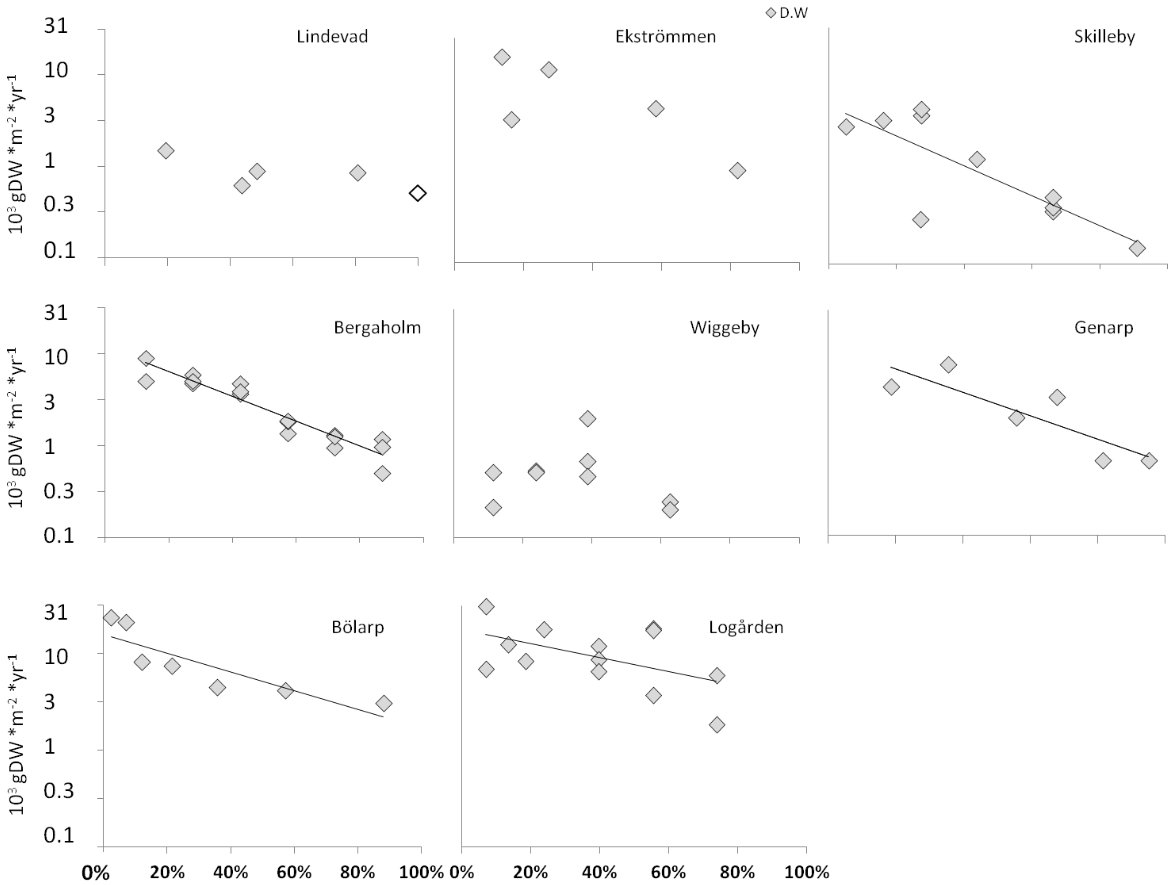

Figure 2. Net sedimentation (g m^{-2} $year^{-1}$) in eight constructed wetlands in the south of Sweden, receiving non-point source runoff as a function of distance from inlet (%). Note the differences in scale on Y-axis. Unfilled ◇ represents moved result due to different inlets (see method).

Table 4. ANOVA-table for linear regression analysis, where log transformed net sedimentation (g m^{-2} yr^{-1}) was tested as a function of distance from inlet to outlet (%). Significant P-values are in bold.

Site	d.f.	F-value	R^2 %	P	Slope coefficient
Logården	13	6.0	33.5	**0.030**	-0.74
Bölarp	6	14.8	74.8	**0.012**	-0.98
Ekströmmen	4	4.8	61.5	0.116	
Bergaholm	16	130.1	90.0	**8.6E-09**	-1.34
Genarp	5	10.8	73.0	**0.030**	-1.30
Skilleby	9	14.7	64.8	**0.005**	-1.59
Wiggeby	8	0.009	0.13	0.925	
Lindevad	4	3.6	54.3	0.155	

An inverse relationship was found between the settling efficiency of sediment and *q* (F = 13.1, R^2=81.0% P = 0.036), meaning that there was a larger difference in net sedimentation between inlet and outlet (i.e. a slower settling) in wetlands with a higher hydraulic load. Neither was there any correlation between settling efficiency and clay (%), catchment slope, L:W nor % tilled land.

5.2 Phosphorus concentration in sediment

Sediment TP concentration varied between 1018 and 1667 mg kg^{-1} with the exception of Genarp which had an extremely high TP concentration (4747 mg kg^{-1}) (Fig. 3A). Genarp, Bölarp and Skilleby had a mean OP concentration above 550 mg kg^{-1} and Ekströmmen had the lowest OP concentration (222 mg kg^{-1}). There was a significant correlation between mgOP kg^{-1} and the organic matter content of the settled particles ($F = 38.2$, $R^2 = 86.4\%$, $P = 0.008$) (Fig. 3B). There was no correlation between mean P concentration of each wetland (mg kg^{-1}) and proportion of clay in the catchment topsoil.

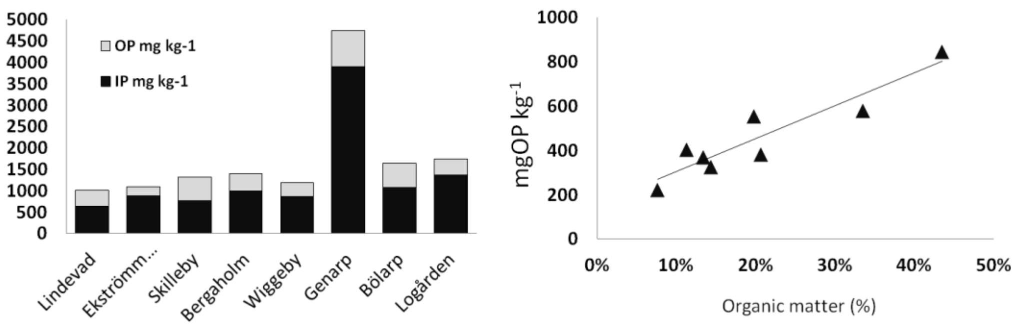

Figure 3. Mean phosphorus concentration, mgP kg^{-1} in settled sediment, sorted with an increasing hydraulic load (A), and concentration of OP mg kg^{-1} as a function of the organic matter content in settled sediment (B)in eight wetlands receiving non-point runoff in south Sweden in 2009/2010.

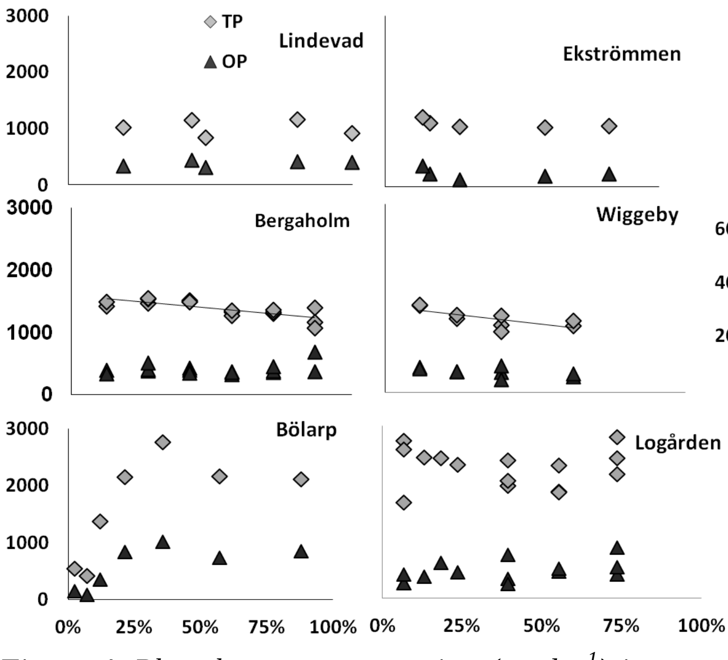

Figure 4. Phosphorus concentration (mg kg^{-1}) in material settled on plates measuring net sedimentation from inlet to outlet in eight constructed wetlands receiving non-point source runoff. (Note the difference in scale for wetland Genarp). Regression lines are shown when significant.

Concentrations from inlet to outlet varied but contrary to expectations no general pattern could be detected (Fig. 4). For Genarp, Bergaholm and Wiggeby there was a significant decrease in TP (mg kg^{-1}) from inlet to outlet (table 5). In Genarp, also the OP decreased significantly. In Skilleby, mg TP kg^{-1} and mg OP kg^{-1} increased from inlet to outlet.

Table 5. ANOVA-table for linear regression analysis, where TP and OP (mg kg^{-1}) was analysed as a function of distance from inlet to outlet (%). Significant P-values for decrease are in bold, for increase bold with.*

	Site	d.f.	F-value	R^2 %	P-value
TP	Lindevad	4	0	0.3	0.927
	Ekströmmen	4	1.9	38.8	0.261
	Skilleby	9	35.3	81.5	**3.4E-04***
	Bergaholm	15	15.8	53.1	**0.001**
	Wiggeby	8	7.8	52.7	**0.027**
	Genarp	5	50.4	92.7	**0.002**
	Bölarp	6	3.5	41.1	0.121
	Logården	13	0.1	0.5	0.807
	Site	d.f.	F-value	R^2 %	P-value
OP	Lindevad	4	0.8	20.9	0.44
	Ekströmmen	4	0.3	10.0	0.604
	Skilleby	9	13.8	63.3	**0.005***
	Bergaholm	16	1.2	7.8	0.293
	Wiggeby	8	3.6	33.8	0.100
	Genarp	5	27.2	87.2	**0.006**
	Bölarp	6	4.4	46.9	0.089
	Logården	13	3.6	23.2	0.082

5.3 Area specific phosphorus retention

Analysis of TP (g m^{-2} yr^{-1}) retention from inlet to outlet showed the same pattern as for net sedimentation on log transformed values (Table 6). There was a statistically significant decrease of TP (g m^{-2} yr^{-1}) in Logården, Bölarp Bergaholm, Genarp and Skilleby. . The slope of the curves, in the wetlands where there was a significant decrease, was taken as an estimate of settling efficiency.

Table 6. ANOVA-table for linear regression analysis, where log transformed TP retention (g m^{-2} yr^{-1}) was analysed as a function of distance from inlet to outlet (%).Significant P-values are in bold.

Site	d.f.	F-value	R^2 %	P-value	Slope coefficient
Lindevad	4	3.1	51.1	0.175	
Ekströmmen	4	5.2	63.5	0.106	
Skilleby	9	9.0	52.8	**0.017**	-1.29
Bergaholm	16	117.7	88.7	**1.7E-08**	-1.48
Wiggeby	7		32.5	0.140	
Genarp	5	20.6	84.7	**0.011**	-1.77
Bölarp	6	29.2	85.4	**0.003**	-0.51
Logården	13	8.7	42.0	**0.012**	-0.82

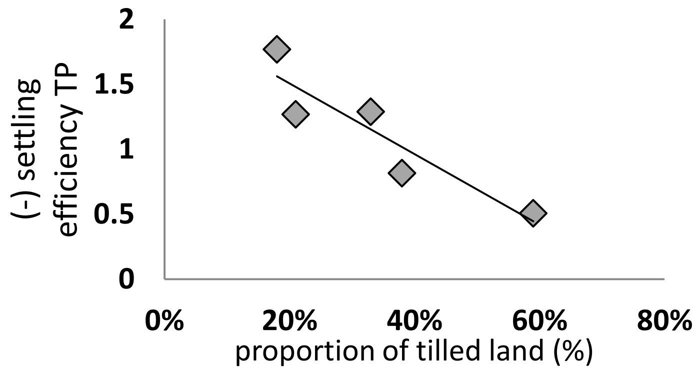

Figure 5). Settling efficiency of net sedimentation and area specific TP retention (i.e. difference in specific retention (g m^2 yr^{-1})) as a function of tilled land within each catchment.

An inverse relationship was found between the settling efficiency of P and the proportion of tilled land in the catchments (F = 15.8, R^2=84.0% P = 0.029), meaning that there was a larger difference in net TP retention between inlet and outlet (i.e. a faster TP settling) in wetlands with a lower proportion of tillage in the catchment (Fig. 5). No such correlation was found with the settling efficiency of particles, but the trend was similar. Neither was there any correlation with settling efficiency of TP and clay (%), catchment slope, L:W nor hydraulic load.

Table 7. Theoretical TP load, mean specific TP retention and net sedimentation in 8 constructed wetlands located in agricultural areas in South Sweden.

Site	TP load (theoretical)	Mean specific TP retention	Mean net sedimentation (*10^3)
	---------------------------g m^{-2} yr^{-1}	--	
Lindevad	0.9	0.8 (±0.2)	0.8(±0.3)
Ekströmmen	6.2	10.4(±6.8)	9.0 (±6.2)
Skilleby	17.6	1.6 (±1.0)	1.4 (±1.3)
Bergaholm	21.5	4.9 (±3.6)	3.4 (±2.5)
Wiggeby	73.6	0.5 (±0.2)	0.4 (±0.3)
Genarp	20.0	13.9 (±13.8)	2.6 (±2.1)
Bölarp	44.8	9.9 (±19.7)	7.7 (±6.1)
Logården	241.1	14.9 (±8.8)	9.0 (±5.1)

5.4 Characteristics affecting phosphorus retention

Eleven factors (including TP retention and net sedimentation) from seven wetlands (Wiggeby excluded) were included in a principal component analysis (Fig. 6, table 8). The three first factors explained 81.5% of the variation. Factor scores are expressions of how much a change in a factor will affect an included variable. The factor scores should be high (> 0.30) and high in only one factor. If a factor has high loading scores for more than one factor it can be seen as multidimensional, thus expressing something more than what is included in one factor. According to Hair et al (2005) the rule of thumb is: Factor scores > ±0.7 well defined; > ±0.5 practically significant; ±0.4 – 0.3 acceptable; < ±0.3 unacceptable.

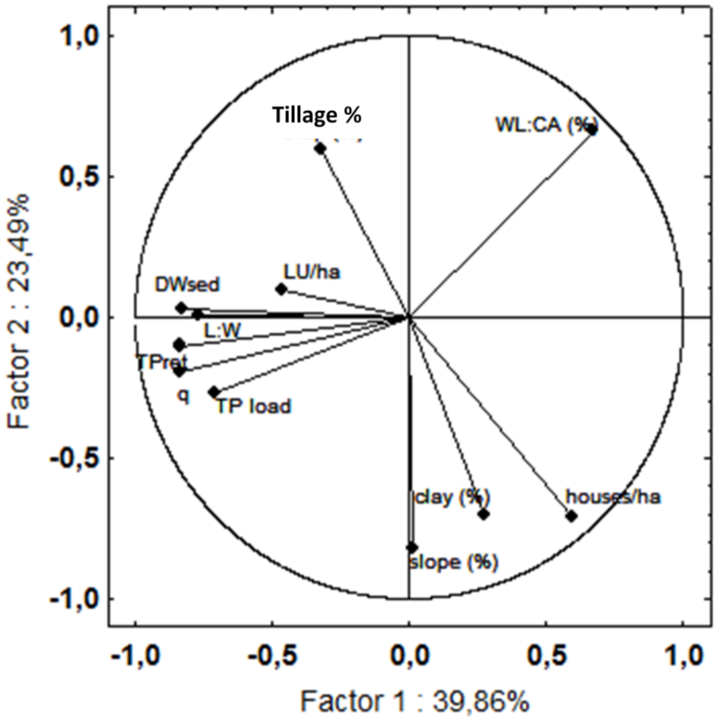

Figure 6. Principal component loading plot with variables from seven wetlands in South Sweden where: TPret, specific retention (g m^{-2} yr^{-1}) ; DWsed, net sedimentation in wetlands (g m^{-2} yr^{-1}); P load, theoretical specific TP load on each wetland kg ha^{-1}, L:W, length:width ratio, WL:CA, wetland:catchment area ratio; q, annual hydraulic load; tillage %, proportion of tilled land in the catchment; slope (%), average catchment slope; clay (%), proportion of clay in mineral topsoil; LU ha^{-1}, Number of livestock units per hectare in catchment; house/ha, number of houses per hectare (with rural sewage discharge).

Factor1. Specific TP retention (TPret) had the largest negative load for PC1, accompanied by net sedimentation (DWsed), hydraulic load (*q*), length:width ratio and specific TP load (< -0.75). LU per hectare and proportion of tilled land had smaller negative loadings for PC1. WL:CA ratio had the largest positive load for PC1, whereas houses per hectare, proportion of clay in topsoil (%) and average catchment slope (%) had smaller positive loadings for PC1. As both TP load and *q* had larger negative scores for factor 1 it is seen as the “load factor”. In factor 2 proportion of clay in topsoil, average catchment slope (%) and proportion of tilled land within each catchment, which may be coupled to erosion, had high or fairly high loading scores together with houses per hectare. Thus, factor 2 is seen as the “erosion factor”.

Table 8. Loading scores in principle component analysis showing factors included when evaluating characteristics affecting specific P retention in seven constructed wetlands (Wiggeby excluded) in south Sweden. Scores at 0.7 and above are in bold since they are most important. Factor scores below 0.3 are not included.

Variable	Factor 1	Factor 2	Factor 3
TPret	**-0.842**		
clay (%)		**-0.700**	
slope (%)		**-0.819**	0.567
LU/ha	-0.461		**0.790**
DWsed	**-0.829**		
L:W	**-0.767**		0.569
q	**-0.833**		-0.383
WL:CA (%)	0.673	0.658	
houses/ha	0.594	**-0.709**	0.193
Tillage (%)	-0.322	0.593	0.386
TP load	**-0.709**		-0.484

Proportion of variability explained by each principal component: PC1, 39.9%; PC2, 23.5%; PC3, 18.1%. Cumulative:81.5%.

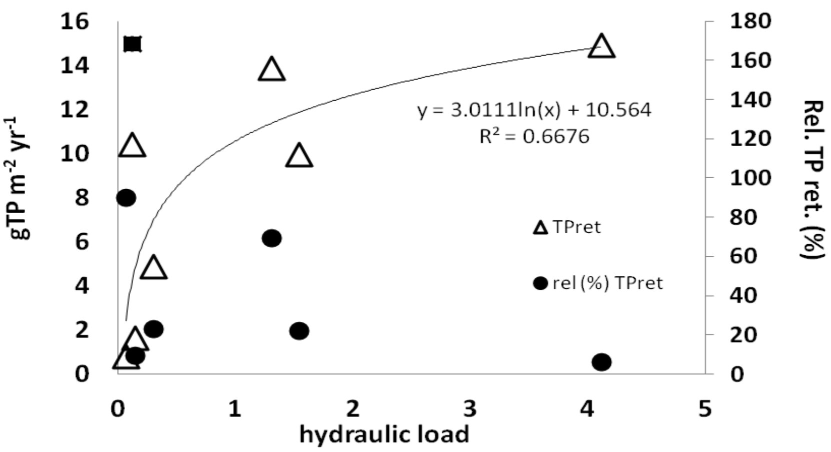

*Figure 7. Mean amount of TP (g m^{-2} yr^{-1})(left axis), and relative TP retention (%), using an estimated value of TP load, in seven constructed wetlands in south and central Sweden mainly receiving non-point source runoff, as a function of hydraulic load. Note that * is a relative retention well exceeding 100%.*

There was a significant correlation between TP retention (g m^{-2} yr^{-1}) and hydraulic load (log transformed) (d.f = 6, F = 10.0 R^2 = 66.8, P = 0.02) (Fig.7). TP retention increased with an increased hydraulic load, up to approximately 1.5-2 m d^{-1} when the curve flattened out at 15 g m^{-2} yr^{-1}. In agreement with the PCA there was a significant inverse correlation between specific TP retention and log transformed WL:CA ratio (d.f = 6, F = 9.0, R^2 = 64.4, P = 0.03) (*Y = -3.431ln(x)-14.042*). However, there was no significant correlation between specific TP retention and L:W ratio nor with specific TP load (kg ha^{-1} yr^{-1}). No significant correlation was found between net sedimentation and hydraulic load, WL:CA nor L:W ratio.

The relative retention (% of load) was calculated from the area specific retention and the theoretical TP load to each wetland. There were large differences between the wetlands and when using these data to estimate the relative retention Ekströmmen had a retention well exceeding 100% (Fig. 7).

6 Discussion

6.1 Factors affecting phosphorus retention

The overall aim was to study whether the differences in net sedimentation and TP retention in eight Swedish wetlands, primarily receiving agricultural runoff, was correlated to different catchment characteristics. Despite the characterization of catchment factors believed to affect particle and P transport the results show that the most important factors were coupled to the load on, and the length to width ratio, of the included wetlands (Fig. 6). The correlation between hydraulic load (*q*) and specific TP/particle retention could be the result of more and coarser particles being transported into the CWs at higher runoff. This is supported by a previous study in wetlands in Norway, where the negative effect of increased *q* was neutralized as more, and larger, particulate-P entered the CWs at high runoff (Braskerud, 2002). WL:CA was negatively correlated to specific TP retention. The size of the catchment, together with runoff determines the hydraulic load. Thus, different wetlands with the same WL:CA can have variable *q*, due to natural differences in precipitation (i.e. runoff). Small wetlands may however, be too small to be efficient, due to short detention time and a risk for resuspension (Koskiaho et al 2003, Koskiaho 2003). Hence, there could be an upper limit to how the hydraulic load may be before the water velocity gets too high and retention declines. The current results imply that the upper limit for hydraulic load would be at 1.5-2 m d^{-1} where the curve flattened at retention of about 15 gP m^{-2} yr^{-1} (Fig. 7). However, this is the result from only seven wetlands during one year; thus, more studies are needed, both over a longer time period and in additional wetlands.

The TP load did not explain TP retention better than hydraulic load (*q*). The TP load on each wetland in this study was calculated from a theoretical (ICECREAM) model and based on the mean for each leaching region, which could explain the lesser correlation with P retention compared to *q*. This point to the difficulties in using this type of *regional* model results to estimate loads in a *local* scale. Depending on the variations within catchments there could be large divergences compared to the regional standard values used to estimate P, and hydraulic load in this study. An implication for the future would be to include more specified catchment data into the model to see whether the estimated load correlates better with retention. It would also answer the question whether using this model, with specific catchment characteristics could be an efficient tool in planning wetland locations.

Increased particle and TP retention was also coupled with a larger length to width ratio (Fig. 6), meaning that a long-stretched design is to prefer rather than a wider wetland. Too low (close to 1:1) L:W ratio may result in channelization and thus, high water velocity and resuspension (Persson and Wittgren 2003). On the other hand, *too* high L:W ratios may also prevent the initial water velocity from slowing down as much as necessary for efficient retention. The decreasing settling efficiency at high *q* in this study implies that particles may not have time to settle if the CW is too short. However, it was suggested by Weisner and Thiere, (2010) that hydraulic load, particulate-P load and distance between inlet and outlet were important variables for the P retention. In their theoretical model higher load lead to low, and eventually zero retention when distance from inlet was 2-300 m, whereas retention increased with load at 100 m between inlet and outlet. The importance of length and width combined with hydraulic load needs to be further investigated as it could yield specific knowledge on the preferable wetland design at different *q*.

As P and particle losses are generally higher in clay soils than from other soil types in Sweden (Djodjic 2001, Kyllmar et al 2006), it was expected that proportion of clay in topsoil would be related to the retention. Contrary to expectations there was no clear relation between retention of neither particles nor TP, and the “erosion factor” in the PCA (factor 2) which included clay. In Norway, Braskerud (2003) found that clay particles settled with a rate that was similar to larger particles, and a later study stated that they were well aggregated (Sveistrup, et al 2008). The possible explanation for the current results could be that the clay fraction was, in most cases, based on data from a larger region, and there could be large deviations from this within these specific catchments. A second explanation is that even if more particles did enter the CWs in catchments with more clay in their soils the smallest fractions did not settle within the wetlands. The clay particles, transported in the drainage pipes and streams, may have been too small and unaggregated (possibly colloidal) to settle within these WLs (Ulén 2004).

It has been observed that the clay fraction of soils contain higher fractions of P than larger sized particles (Pacini and Gächter, 1999, McDowell et al, 2004). Hence, a higher P concentration could be expected in the settled sediment in wetlands with more clay in their catchments soil. However, the results did not provide any support for this. For example, in Skilleby, which had the highest clay % in topsoil (table 3), the mean TP concentration in settled sediment (1320 mg kg^{-1}), was lower than in four of the other wetlands with lower clay content in the catchment soil (Fig. 3). In addition, the water entering the adjacent stream in Skilleby was visibly turbid, supporting that fine particles are transported out of the wetland. The catchment with the lowest proportion of clay in the topsoil (Genarp) had extremely high TP concentration in accumulated sediment compared to the other wetlands. An interesting observation was that the TP concentration in accumulated sediment was higher than the mean for the respective leaching region in all the studied wetlands (SLU, 2010). This could indicate a size selective erosion tendency, where small particles erode and similarly sized particles settled in these wetlands, but that the finest clay fraction did not. This tendency was found in Ballantine et al (2009) where the surface area of particles was larger in surface runoff and recently accumulated sediment than in its cultivated source soil. Additionally, the surface area of particles was higher in surface runoff than in the newly accumulated sediment, indicating that the smallest fraction did not settle.

The extremely high P concentration in the sediment of Genarp is difficult to explain. The leaching region where Genarp is located has, based on the Swedish arable soil monitoring program (SLU 2010), the highest mean P-HCl (875 mgP kg^{-1}) in arable soil, compared to the lowest value (692 mgP kg^{-1}) in the region where Logården is located. Still, the difference is not high enough to explain the extremely high P concentration in the accumulated sediment of Genarp. This is regional data and there can be large local variation (Eriksson et al 2010). Part of the catchment of the Genarp wetland consisted of an urban area. Unfortunately it has not been possible to obtain information on the P content in the stormwater from this area; but stormwater is generally not an important source of P load compared to agriculture (Brandt 2002).

Other variables included in the “erosion factor” (factor 2) in the PCA which could reflect erosion, and thus particle distribution and transport, were slope and tillage. The slope calculation was the average slope for the entire catchments, which for some catchments included more than 50% non-arable land, which is less prone to particle and P losses. Thus, there might be high P losses statistically detectable if one would only consider the steepest arable fields within the catchments. However, due to the resolution of the digital elevation model it would be inappropriate to use this data for such small scale. The result implied that the proportion of tilled land was a weak predictor for TP retention. Effects of crop and soil management may be difficult to measure since it can be affected by differences in soil disturbance, fertilization, salinity and organic matter (Ulén 2005, SBA 2008, Ulén 2010). Still, the negative correlation between TP settling efficiency and increased proportion of tilled land (Fig. 5) supports that tillage breaks up aggregates and causes an increased transport of smaller particles from fields. This was also consistent with Sveistrup et al (2008) who found that soil disturbance affected aggregate stability negatively and Ballantine et al (2009) who found larger difference in P concentration, compared to source soils, in runoff and sediment from cultivated land than from pasture land.

The relative TP retention in Ekströmmen was close to 170 % suggesting an underestimation of the P load and/or internal variables affecting. As previously discussed, there are difficulties in scaling down results based on regional data to a local scale. The high net sedimentation (Fig 2, table 7) could also be due to the six islands impact on the waters pathway as displacement may lead to serious short-circuiting and dead-zones (Persson 2005), and/or natural erosion/bioturbation around the boarders of the islands. Apparent soil erosion around the islands was noticed, when visited Nov. 2011. Also, there were approximately 100 dabbling ducks present for 6 months of the year, which contribute to the P load. Manny et al (1994) suggested that dabbling ducks contribute 0.22 g P per duck per day. This would add approximately 4000 gP yr^{-1} in Ekströmmen and increase the load on the wetland with ≈ 9%. Hence, it could not specifically explain the high P retention found in the wetland. However their movement habits may cause even more soil particles to erode into the water and onto the sedimentation plates.

There is a need for simple tools when determining where CWs should be located to be most efficient. The results here imply that high hydraulic load increases retention and that the shape of the wetland has an impact. However, even if specific retention increases with q there is still a need to know more how the other catchment characteristics may contribute to particle and P distribution. Is it reasonable to use regional standard values or is there a need for specific catchment data when planning the location for CWs? And what is the size distribution of settled particles, does the clay fraction settle and if so how (i.e. are there aggregates). Are wetlands able to retain these small particles or are there other measures that need to be taken, besides trying to prevent erosion from agricultural fields? Further studies aiming for these answers are needed.

6.2 Internal sediment and phosphorus distribution

Net sedimentation and TP retention generally decreased from inlet to outlet, showing that most particles and P settled in the beginning of the wetlands. This is also supported by the embankment of settled particles observed in front of the inlet in Bölarp. However, the difference was not significant in all eight wetlands. The wetlands where there were no decreasing trends from inlet to outlet were Wiggeby, where a flush-out of the material accumulated on the plates occurred after a heavy rainfall in July 2010, Ekströmmen, where it is suspected that the net sedimentation was affected by erosion of particles from its islands (previous section), and, Lindevad where the recalculation done to compensate for two inlets (Section 3.5) may have had some impact on the result. In addition, the rural sewage discharge, leading into the Lindevad wetland might explain the coverage of filamentous green algae in this wetland, which in turn may affect the distribution of P over the wetland surface. Lindevad was also the wetland with the highest WL:CA ratio, the detailed determination of catchment boundaries revealed that its WL:CA ratio was somewhat larger than the initial criteria for this study (>0.5%). The location of the islands in Lindevad and Ekströmmen (Fig 1) may also have an impact on the settling distance results. As for Logården, where the sedimentation plates were placed for a shorter time period, one can draw the conclusion that there is an overall positive net retention since the mean depth in summer 2010 was approximately 0.6 m compared to the depth of 1.25 m given in Marmolin (2009). However, it still differs from the other wetlands when it comes to method, which must be taken into consideration when evaluating the results.

Contrary to expectations there was no general change in P concentration (mg kg^{-1}) from inlet to outlet in the accumulated material (Fig.5). A possible explanation could be that the majority of incoming matter settled in the beginning of most CWs. And/or possibly similar sized particles settled as there was no clear difference in TP concentration between most of the included wetlands. Smaller particles have a larger surface area onto which P could adhere, thus, a higher P concentration could have been expected in wetlands with high clay content in their catchment topsoil if clay particles had settled to a large extent. The further into the wetlands, the likelier that other internal factors such as vegetation cover, decomposition or bioturbation affects the results. The relatively high mean OP concentration in Lindevad, Bölarp and Skilleby are likely due to dense vegetation, (Table 1) whereas for Genarp any specific reason remains unexplained. It was also observed that the OP:TP ratio increased from inlet to outlet in Skilleby and Bölarp supporting that internal processes, such as degrading vegetation and bioturbation, are the source of some of the accumulated material on the plates.

The results emphasize that internal processes, such as vegetation and bioturbation are of importance. There is a need for further studies on P cycling processes and retention within wetlands. Measuring P accumulation and net sedimentation on sedimentation plates is a less costly and less time consuming method than continuous water sampling. It also visualizes the internal processes that may be involved in a better way. Studying these CWs over subsequent years and adding additional CWs would reveal inter annual variations and more accurate results which could be used for future estimation of wetland performance and where they should be located.

6.3 Conclusions

Despite the characterization of catchment characteristics, the hydraulic load, TP load and the wetland length to width ratio were the factors that best explained differences in particle and TP retention in the studied wetlands.

Contrary to expectations clay content in soil and slope of the catchments, factors that could be associated to erosion, did not correlate with retention of neither particles nor TP.

Higher P concentrations would have been expected in wetlands with higher proportion of clay in their catchments topsoil if the smallest clay particles had settled. Similarity in sediment P concentration implies that the size fractions that settled were similar in the investigated wetlands.

Generally, the highest amounts of settled particles and P were found close to the wetland inlets. The results indicate that tillage affect the aggregation of particles negatively and increase the loss of small particles, unlikely to settle in these wetlands.

In wetlands with abundant submersed and floating leafed plants the P concentration in sediment increased from inlet to outlet, implying that internal site-specific factors can have a large impact on P distribution. Future studies are needed on sedimentation and internal processes in wetlands constructed to trap P and particles from agricultural fields.

Using models and data from a regional scale on local scale should be done with consideration. Depending on the local variations within smaller catchments there could be large differences compared to regional standard values and this could give misleading results. Further studies are needed to find simple tools to estimate wetland performance based on geographical data since it would help in planning the preferred wetland locations.

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8 References

Andersen J.M. (1975) An ignition method for determination of total phosphorus in lake sediments. Water Research 10:329-331

Ballantine D., Walling D. E. and Leeks G. J. L. (2009) Mobilisation and transport of sediment-associated phosphorus by surface runoff. Water Air and Soil Pollution 196:311-320

Brandt M. and Ejhed H. (2002) Transport – Retention – Source apportionment. Load on the Sea. Report 5247, Swedish Environmental Protection Agency, Stockholm. In Swedish.

Braskerud B. C. (2002) Factors affecting phosphorus retention in small constructed wetlands treating non-point source runoff. Ecological Engineering 19:41-61

Braskerud B. C. (2003) Clay particle retention in small constructed wetlands. Water Research. 37:3793-3802

Braskerud B. C., Tonderski K. S., Wedding B., Bakke R., Blankenberg A-G B., Ulén B. and Koskiaho J. (2005) Can constructed wetlands reduce the diffuse phosphorus loads to eutrophic water in cold temperate regions? Journal of Environmental Quality 34:2145-2155

Burrough P. A. and McDonell R. A. (1998) Principles of Geographical Information Systems Oxford University Press, New York

Djodjic F. (2001) Displacement of phosphorus in structured soils. Doctorial Thesis, Swedish University of Agricultural Sciences. Agraria 283 Uppsala

Ekholm P., Kallio K., Salo S., Pietiläinen O. P., Rekolainen Y. L. and Joukola M. (2000) Relationship between catchment characteristics and nutrient concentrations in an agricultural river system. Water Research 15:3709-3716

Eriksson, J., Mattson L., and Söderström M. (2010) Current status of Swedish arable soils and cereal crops. Report 6349, Swedish Environmental Protection Agency, Stockholm. In Swedish.

Galbraith L.M. and Burns C. W. (2007) Linking land-use, water body type and water quality in Southern New Zeeland. Landscape Ecology 22:231-241

Johnsson H., Larsson M., Lindsjö A., Mårtensson K., Persson K. and Torstensson G. (2008) Nutrient leaching losses from arable land in Sweden. Report 5823, Swedish Environmental Protection Agency, Stockholm. In Swedish.

Kadlec R. H. and Scott W. D. Treatment wetlands, 2.ed, CRC Press, Boca Raton, 2009

Kadlec R. H. (2005) Phosphorus removal in emergent free surface wetlands. Journal of Environmental Science and Health. 40:1293-1306

Koskiaho J. (2003) Flow velocity retardation and sediment retention in two constructed wetland-pond. Ecological Engineering 19:325-337

Koskiaho J., Ekholm P., Räty M., Riihimäki J. and Puustinen M. (2003) Retaining agricultural nutrients in constructed wetlands – experiences under boreal conditions. Ecological Engineering 20:89-103

Kyllmar K., Carlsson C., Gustafson A., Ulén B. and Johnsson H. (2006) Nutrient discharge from small agricultural catchments in Sweden Characterization and trends. Agriculture and Ecosystems Environment 115:15-26

Lantmäteriet, Consent I 2011/0096, The Swedish mapping, cadastral and land registration authority, Gävle

Liikanen A., Puustinen J., Väisänen T., Martikainen P. and Hartikainen H., (2004) Phosphorus removal in a wetland constructed on formal arable land. Journal of Environmental Quality 33:1124-1132

Manny B. A., Johnsson W. C., and Wetzel R. G. (1994) Nutrient additions by waterfowl to lakes and reservoirs: Predicting their effects on productivity and water quality. Hydrobiologia 279/280:121-132

Marmolin C. Wetland sediment – resource or a risk to society. (2009) Report 2/09, Agricultural Society, Skaraborg county. Skara. In Swedish.

Maynard J., O´Green A. T., and Dahlgren R. A. (2009) Bioavaliability and fate of phosphorus in constructed wetlands receiving agricultural runoff in the San Joaquin Valley, California. Journal of Environmental Quality 38:360-372

McDowell R. W., Sharpley A. and Folmar G. (2001) Phosphorus export from an agricultural watershed: Linking source and transport mechanisms. Journal of Environmental Quality 30:1587-1595

McDowell R. W., Biggs B. J. F., Sharpley A. N. and Nguyen L. (2004) Connecting phosphorus loss from agricultural landscapes to surface water quality. Chemistry and Ecology 20(1):1-40

Pacini N. and Gächter R. (1999) Speciation of riverine particulate phosphorus during rain events. Biogeochemistry 47:87-109

Persson J. and Wittgren H. B. (2003) How hydrological and hydraulic conditions affect performance of ponds. Ecological Engineering 21:259-269

Persson J. (2005) The use of design elements in wetlands. Nordic Hydrology 36(2):113-120

SBA (2004) Quality criteria for wetlands in agricultural landscapes: Critera for purification of plant nutrients with regard to biodiversity and cultural heritage. Report 2004:2,. Swedish Board of Agriculture, Jönköping In Swedish

SBA (2008) Phosphorus losses from arable land – what can we do to mitigate the problem? Arable information 27:2008 Swedish Board of Agriculture, Jönköping. In Swedish

SEPA, (2009) Sweden's commitment in the BSAP. Draft National Action Plan. Report 5985, Swedish Environmental Protection Agency, Stockholm. In Swedish

SIS (1997) Swedish Standard SS-EN 1189. Standardiseringen i Sverige.

Sveistrup T. E, Marcelino V and Braskerud B. C. (2008) Aggregates explain the high clay retention of small constructed wetlands: a micromorphological study. Boreal Environment Research 13:275-284

SLU, (2007) Leaching coefficients and results from calculations of the normal leakage of phosphorus. Swedish University of Agricultural Sciences. Division of Water Quality Management. Uppsala, 2007-12-19

SLU (2010) National monitoring programme. http://www-jordbruksmark.slu.se/AkerWebb/MgiPub/Index.jsp?PageType=0&PageID=0 Accessed: April 11 2011.

Ulén B. (2004) Size and settling velocities of phosphorus-containing particles in water from agricultural drains. Water, Air and Soil Pollution 157:331-343

Ulén B. and Jakobsson C. (2005) Critical evaluation of measures to mitigate phosphorus losses from agricultural land to surface waters in Sweden. Science of the Total Environment 344:37-50

Ulén B. (red) (2005) Phosphorus losses from soils to water. Identifying critical sources and possible countermeasures. Report 5507, Swedish Environmental Protection Agency, Stockholm. In Swedish.

Ulén B., Aronsson H., Bechmann M., Krogstad T., Øygarden L. and Stenberg M. (2010) Soil tillage methods to control phosphorus loss and potential side effects: a Scandinavian review. Soil Use and management 26:94-107

Weisner S. and Thiere G. (2010) Less phosphorus and nitrogen from arable land – Evaluation of constructed wetlands within the Environment- and Rural development program and the new Rural development program. 21:2010, Swedish Board of Agriculture, Jönköping. In Swedish

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