Department of Physics, Chemistry and Biology

Final Thesis

Dynamics of phosphorus transport and retention in a wetland receiving drainage water from agricultural clay soils

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LiTH-IFM- A- Ex—11/2400--SE

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Avdelning, Institution
Division, Department

Biology, IFM

Datum
Date
31/3/2011

Språk
Language

☐ Svenska/Swedish
☒ Engelska/English

☐ _____

Rapporttyp
Report category

☐ Licentiatavhandling
☒ Examensarbete
☐ C-uppsats
☒ D-uppsats
☐ Övrig rapport

☐ _____

ISBN

ISRN LITH-IFM-A-Ex—11/2400--SE

Serietitel och serienummer **ISSN**
Title of series, numbering

Handledare
Supervisor Karin Tonderski
Karin Johannesson

Ort
Location Linköping

URL för elektronisk version

Titel
Title

Dynamics of phosphorus transport and retention in a wetland receiving drainage water from agricultural clay soils

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Sammanfattning
Abstract

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Contents

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2. Introduction

2.1 Background

Eutrophication of water bodies is a widespread problem, both in freshwater and estuarine environments, causing negative consequences in e.g. the Baltic Sea with declining oxygen levels at the bottom of the sea (Swedish EPA, 2006). Responsible for this eutrophication is the extensive addition of the nutrients nitrogen (N) and phosphorus (P). P has an important role in this, as it is often the limiting nutrient in both freshwater and estuarine ecosystems (Reddy et al., 1999). Agricultural activities are a large source of P that is transported to streams, lakes and eventually seas. In 1995, as much as 49 % of the P transported to Swedish lakes had its origin in agricultural activities (Swedish EPA, 2010). In the quest of reducing the amount of nutrients in drainage water from agricultural land, constructing wetlands is a popular and commonly used tool in Sweden. Wetlands have the ability to retain both N and P, thus improving water quality and reducing eutrophication in the long run. With the purpose to retain N, wetlands has been constructed for several decades, but constructing wetlands for primarily the retention of P is a quite new area of interest. Though, several studies (e.g. Braskerud et al., 2005; White et al., 2000; Hauge et al., 2008; Sharpley et al., 2009) indicates that if managed in the right manner, constructed wetlands may indeed serve as efficient traps for P as well.

The movement and retention of P in wetlands is influenced by several hydrologic and biotic factors (Kadlec, 2005), and P is transported into wetlands in four different forms; as dissolved inorganic P, orthophosphate; as inorganic P bound to particles; as dissolved organic P; and finally, as particulate organic P (Reddy et al., 1999; Leonardson, 2002). Orthophosphate is the main P form that is readily bioavailable, but other P forms may be more or less available for microbes and plants, at least in certain conditions, and should be

considered bioavailable as well (Reddy et al., 1999). The processes that occur in a wetland and result in retention of P include uptake by vegetation, periphyton and microorganisms, sorption to sediments, chemical precipitation in the water column and sedimentation (Reddy et al., 1999).

Uptake of P by vegetation is generally a short-term storage of P, with a turnover time for above ground parts of one to several months (Reddy et al., 1999). After the wetland vegetation has died and started to decompose, P is released back into the water as bioavailable orthophosphate (Reddy et al., 1999). The same is valid for P uptake by periphyton and microorganisms. How much P that is taken up by plants in a wetland depends to a large extent on which kind of vegetation that is present, e.g. floating and emergent plants have a larger P-storage potential than submerged plants (Reddy et al., 1999). However, not all P will be released back to the water during plant decay. Some organic material accumulates in the sediments, and approximately 10-20 % of the P in the plant is then permanently stored in the sediments and will eventually form new soil and sediment in the wetland (Kadlec, 2005).

Orthophosphate that is transported into the wetland can be adsorbed and bound to the substrate, but due to sensitivity to changed chemical conditions, it can easily be released to the water again (Kadlec, 2005). When pH is acidic (pH<7), P can be adsorbed on hydrous oxides of iron (Fe), manganese (Mn) and aluminium (Al), or precipitate with Fe or Al in insoluble phosphates (Curtis et al. 2009). When pH>7, P precipitate to insoluble phosphates with calcium (Ca) and magnesium (Mg) (Curtis et al. 2009). If, however, pH increases or decreases, the P is released from Fe/Al/Mn and Ca/Mg, respectively, into the water column (Leonardson, 2002). P bound to hydroxides with Fe and Mn is also sensitive to changes towards anaerobic environments. As oxidized forms of Fe and Mn are reduced, they form complexes with sulphides and lose their ability to bind P, which is then released. Also, if P loads to a wetland are low or if it formerly was high and then decreases, the wetland will probably become a source of P instead of a sink (Reddy et al., 1999).

The major source of long-term storage of P in wetlands is sedimentation, i.e. settling of particulate inorganic and organic P (Reddy et al., 1999; White et al., 2000; Braskerud et al., 2002; van der Valk, 2006; Uusi-Kämppä et al. 2000). The extent that settling of particles occur in a wetland is decided by the flow, residence time, hydraulic load, which type and size of particles that is transported from the catchment and the design of the wetland. The concentration of P in inflow water is one factor that influence the retention of P, and previous studies have shown correlations between flow and concentration of total phosphorus (TP) in inflow water, with an increased concentration TP in water during high flow periods (e.g. Ellison et al., 2006; Ulén, 2004). In a study conducted in a stream in Denmark, Kronvang et al. (1997) found that the concentration of suspended solids and P increased during storm events with high flow, due to mobilization of sediments in the catchments. Further, it is known that wetlands often become sources of P rather than sinks during high flow periods (e.g. Rogers et al., 2009).

In contrast to this, Braskerud (2003) found that as flow increased into a couple of Norwegian wetlands, no decline in particle sedimentation occurred. The reason was that the size of particles and aggregates transported from the catchment increased simultaneously with flow. However, according to Ulén (2004), a large part of the particles, and thus P, transported from Swedish agricultural clay soils into wetlands were too small to settle within a reasonable time, having a settling rate of < 1 cm d^{-1}. Further, run-off transported through tile drains at one location in Sweden was found to contain a higher proportion of small particles than surface run-off (Ulén, 2003). These results indicate that as conditions differ between agricultural areas, wetland designs that show effective P retention at one site might not present the same results at another site. Thus, efficient

retention of P through settling of particles in wetlands might be difficult to achieve in Swedish agricultural areas with clay soil, as the particles transported may be too small to settle and do not have the same ability to form aggregates as in Norwegian clay soils.

Koskiaho (2003) found that the single most important factor for P retention in a wetland was the wetland area in relation the catchment area, with a high ratio promoting retention, a result supported by e.g. Uusi-Kämppä et al. (2000) and Braskerud et al. (2005). Similarly, the hydraulic load - and thus the residence time for water in the wetland – has a great influence on a wetlands ability to retain P (Tonderski et al. 2005). A long residence time, but not so long that the flow becomes stagnant, is a key factor if effective retention of P should be achieved. Catchment runoff, wetland size and design decide how long the residence time will be in the wetland. Presence of vegetation often increases residence time and thus increases the hydraulic efficiency of a wetland (Braskerud, 2001), and constructing baffles in the wetland can contribute to an efficient use of the wetland area (Koskiaho, 2003). Inefficient use of the wetland area would decrease residence time and thus decrease the sedimentation in the wetland, as found by Koskiaho (2003). Furthermore, vegetation may prevent the resuspension of particles from the sediments (Braskerud 2001), thus promoting P retention. However, zonation of the vegetation in combination with the bottom topography may instead result in the formation of channels where the water preferentially will flow (Kadlec, 2005). When stem density is high, the water will find ways through the vegetation with the least flow resistance, causing short circuiting and a reduced detention time (Fennessy et al., 1994) Also, Braskerud (2001) found that channelization through vegetation filters increased due to decaying vegetation. Thus, vegetation in a wetland may both increase and decrease the retention of P.

As mentioned previously, the design of the wetland is an important factor that affects the retention of P. According to Koskiaho (2003), a deeper inlet pond followed by a shallow area would be a beneficial wetland design as it decreases the risk of short-circuiting of flow. White et al. (2000) found that sites near the inlet had higher sedimentation rates and P burial rates than sites further down in a wetland. In accordance with this, Sveistrup et al. (2008) found that the particles that settled close to the inlet were larger than particles that settled downstream in the wetland, as large particles settles faster than small ones. Thus, as concluded by Ulén (2004), if a large proportion of the particles entering a wetland are very small, they will not settle at all. Instead, they will be transported out of the wetland with the outflow. A long residence time and high hydraulic efficiency is therefore important to promote retention of P through sedimentation, as the particles need much time in order to settle (Koskiaho, 2003).

Despite all this knowledge, the processes which influence the retention of particles, and thereby to a large extent P, are still not fully understood (Braskerud 2003). Hence, more research is needed in order to fully understand the mechanisms of P retention in constructed wetlands. It is thus of great interest for the future use and design of constructed wetlands for P retention in agricultural drainage areas with clay soils to further investigate the retention of P in constructed wetlands in general and the relationship between flow and concentration of P in particular.

2.2 Aim of the study

The aim of this project was to investigate the dynamics of P retention, especially during high flow periods, in a small constructed wetland in Sweden receiving drainage water from an agricultural catchment with clay soil. The main areas of interest were (1) the relationship between flow and concentration of P in the water, expecting higher P concentrations during high flow, (2) the P retention during high flow periods, expecting a release of P during peak flows, (3) the spatial distribution of gross sedimentation, expecting a higher settling of particles and P close to the inlet. Further, the sampling

methods were critically analysed in order to investigate e.g. if the fortnightly sampling in the monitoring program (2003-2010) was sufficient for a reasonable evaluation of the wetland retention function.

3. Materials and methods

3.1 Study site

The study was conducted at a small wetland at Skilleby farm in Järna, south of Stockholm, Sweden (Fig. 1). The wetland was constructed in 2002 and has a catchment area of 22 ha, which mainly consists of biodynamically cultivated land with clay as the soil type (Granstedt et al. 2004). Since 1967, the farm has been managed according to the biodynamic farming practice, with the purpose to maximize recycling of plant nutrients within the farm by integrating animal and crop production. It is also managed according to ERA, Ecological Recycling Agriculture, which includes not using commercial fertilizers or pesticides, using nitrogen fixing crops and having an animal density in balance with the fodder production of the farm. The catchment of the wetland consists of one third forest and two thirds arable land, the latter including three fields which are system subdrained (Schneider, 2009). One of the fields was a clover ley, and the other two fields' were part of a five year crop sequence consisting of oat, three years of ley and finally winter wheat (Schneider, 2009). Fertilization with composted livestock manure occurred after the third ley, i.e. in 2007 in one field and in 2009 in the other (Koker, 2010).

Figure 1. *a) Location of Skilleby (arrow), and b) magnification of the square with the location of the wetland marked with an arrow. (Source: www.eniro.se).*

The wetland was constructed with the purpose of reducing the losses of nutrients into the recipient Skillebyån, which is a stream that is heavily loaded with nutrients from agricultural land and from a municipal wastewater treatment plants upstream the wetland. Skilleby wetland has an area of approximately 0.08 ha and thus comprises approximately

0.4 % of its catchment. It is 0.4-1.2 m deep and divided into three different parts (Fig. 2a & 2b). The first part after the inlet, in this report called pond 1, is small (0.013 ha) and form the deepest part of the wetland, 0.6-1.2 m deep. This first part was primarily constructed for sedimentation of particles and retention of P. The second part of the wetland consists of a 0.024 ha large vegetation filter, an approximately 0.4 m shallow area entirely covered by emergent vegetation. After the vegetation filter follows the third part of the wetland, pond 2, which is the largest part with an area of 0.043 ha. Pond 2 has approximately the same depth as pond 1 and is intended to promote denitrification. At the inlet of the wetland, the drainage water passes through a 60° v- notch (Fig. 2c & 3a), installed 2007 instead of the previously used 90° v- notch. At the outlet of the wetland, the water is led through a pipe and a well to Skillebyån (Fig. 3b). The species that dominated the emergent vegetation of the wetland was cattail (*Typha latifolia L.* and *Typha angustifolia L.*), but common reed (*Phragmites australis (Cav.) Steud.*) and herbs as e.g. meadowsweet (*Filipendula ulmaria (L.) Maxim.*) occurred as well. In the ponds, the submerged broad-leaved pondweed (*Potamogeton natans L.*) dominated.

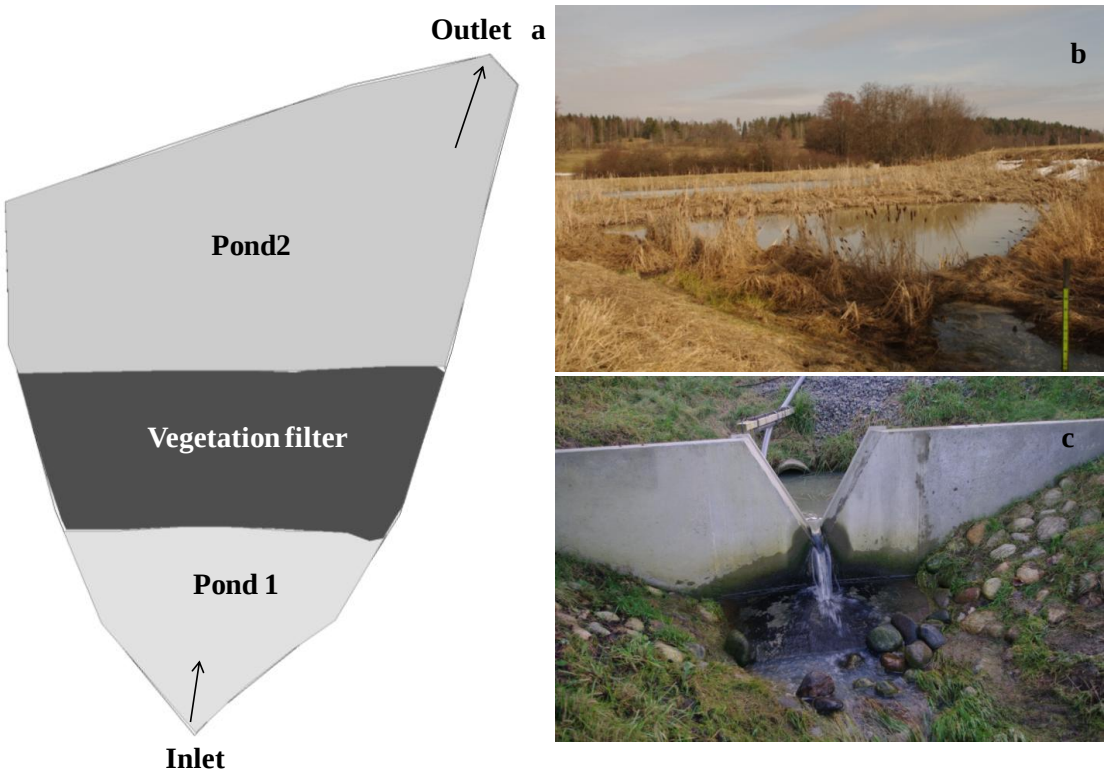

Figure 2. *a) Schematic drawing of Skilleby wetland with the inlet, pond 1, vegetation filter, pond 2 and the outlet marked out. (Drawing by Anna Senior) b) Photo of the wetland, seen from the inlet. c) Photo of the v-notch at the inlet.*

a **b**

Figure 3. *Skilleby wetland before the v- notch at the inlet with the sampling pipe visible (a), and the outlet well with the ISCO- sampler (b).*

3.2 Flow monitoring

During 2003 until July 2005 and from July 2007-2009, the water level was registered continuously with a Druck PDCR 1830 pressure transducer connected to a CR10 Campell data logger at the inlet of the wetland. From January to September 2010, there was no continuous flow data recorded because of problems with the pressure transducer. After a new pressure transducer (model PDCR 1830) was installed in the end of September 2010 and connected to the CR10 Campell data logger, the flow was continuously measured again. During the period 2010 without flow data, daily flow values were interpolated between manually measured flows at the inlet with a two week interval. At these occasions, water height was measured in the v- notch and transformed to flow using the following equation:

$$Q = H^{2.5} \times 47300.6 \qquad (1)$$

where

Q is the flow in L min^{-1}
H is the water height at the v- notch in m
The constant 47300.6 is further explained in Appendix 1.

During the October and November intensive sampling periods, the flow at the inlet was measured manually three times daily, simultaneously with grab sampling. This was done by measuring the flow volume with a bucket and a stopwatch three times and calculating a mean flow from the measurements. The manually measured flow was used to verify the flow calculated according to (1) for the water height measured at the v-notch at the same time.

During the entire period 2003-2010, the flow at the inlet had been assumed to represent the flow at the outlet as well. All flow data were multiplied with the factor 1.1, as earlier investigations had shown that the flow measurement at the inlet underestimates the true flow by approximately 10 % (Schneider et al., 2006).

3.3 Sampling and processing of water and sediment

Water sampling was conducted during three intense periods in 2010, each lasting for 3-5 days; April 7-10, October 19-22 and November 15-19. The April sampling period was in the end of the spring snowmelt period after a winter with unusually large amounts of snow. The October period occurred after a dry summer and heavy precipitation in August and September. The November period occurred during a period with several events of heavy rainfall, and the sampling started just after a flow peak following one of these events.

During each sampling period, water was collected by grab sampling and by continuous sampling with ISCO Wastewater Samplers (Model 2900). Grab samples were taken with a plastic bottle three times per day at 8 am, 2 pm and 8 pm. At the inlet, samples were taken from the flowing water at the v- notch, and at the outlet from the well. Before each sampling, the bottle was rinsed three times with the sample water. At each sampling occasion, two samples were taken from the inlet and the outlet, respectively. One sample was filtered through a 0.45 µm membrane filter using a 50 ml plastic syringe, and the other sample was stored unfiltered. The syringe was also rinsed three times with the sample water before sampling, and a new syringe was used every day. At each sampling occasion, the water temperature was measured at the inlet and outlet. During the November sampling period, pH was measured once every day at the inlet and outlet with a pH-meter (pHep HI98128, HANNA Instruments). pH was not measured during the two previous periods due to technical problems with the equipment.

Parallel to the grab sampling, two ISCO Wastewater samplers were used for continuous sampling of the inflow (before the v- notch) (Fig. 3a) and the outflow (from inside the well) (Fig. 3b). The samplers were programmed in slightly different ways during the different sampling periods. During the April period, the samplers collected approximately 40 ml every 30 minutes with four samples mixed in the same bottle resulting in one sample representing 2 hours. As the samplers handled too small volumes during the April sampling period, the sampling interval was changed during the October and November sampling periods. Instead, one sample of approximately 150 ml was collected every 2 hours. The samples from the continuous sampling were not filtered. All samples from the grab sampling and continuous sampling were stored in plastic bottles that had been acid washed with 2 M HCl for at least 24 h, and were frozen until analysed.

At twelve different locations in the wetland, sediment traps were placed in order to collect the total amount of settled particles at each location during a specific period, i.e. the gross sedimentation. Trap one to five were located in pond 1, trap six to eight in the vegetation filter, and trap nine to twelve in pond 2. The traps were left in the wetland for four different periods; 18th of November 2009- 19th of April 2010, 19th of April- 13th of July 2010, 13th of July- 11th of August 2010 and 11th of August- 17th of November 2010. When collecting the samples, the traps were removed from the wetland, emptied into 500 ml plastic containers and then rinsed with wetland water to transfer all material from the traps into the containers. The traps were then put back into the wetland. In the laboratory, the samples were stored at approximately 6°C degrees for a couple of weeks. When the material had settled, water was decanted off and all large particles, e.g. litter and animals, were removed. Finally, the samples were dried at 50 °C over night and then ground and sieved.

3.4 Chemical analyses

Water. During the three intense sampling periods, unfiltered grab water samples were analysed for total phosphorus (TP) and filtered samples were analysed for total dissolved phosphorus (TDP) and soluble reactive phosphorus (SRP) at Linköping University. Samples from the continuous sampling were only analysed for TP, as only unfiltered samples were collected. Samples to be analysed for TP and TDP were first oxidized with

persulphate, by adding potassium peroxodisulphate and H_2SO_4 to each sample and then digesting them in an autoclave (Tuttnauer 3870 ELV) for 20 min at 121°C (SIS, 1997). All water samples, both unfiltered and filtered, were then analysed according to the method SS-EN 1189 (SIS, 1997). The principle for the analytical method is that orthophosphate ions first react with an acid solution containing antimony ions and molybdate, forming an antimony phosphomolybdate complex. The complex is then reduced with ascorbic acid and the intense blue colored molybdenum complex is formed. To determine the concentration of orthophosphate in the sample, the absorbance of the sample was measured with a spectrophotometer at 880 nm. The samples were analysed manually (April) with a Hitachi U2000 spectrophotometer and automatically (October and November) with an Auto Analyzer 3, using method no. G-175-96. All equipments for P- analyses were washed with 2 M HCl before the analyses.

Sediment. The sediment samples were prepared for the TP-analysis using an ignition method for determination of TP in lake sediments (Andersen, 1976). A known amount of sample (0.2 g) was ignited in a muffle furnace at 550°C for 1 h, weighed again and boiled for 20 minutes with 25 ml 1 M HCl. The sample was diluted to 100 ml and the orthophosphate concentration analysed spectrophotometrically as described above (SIS, 1997), using a blank with only HCl. Additionally, approximately 2 g of the sediment samples were sent to the laboratory at SLU, Uppsala, where it was analysed for total C and N content with a dry combustion method (CN-2000, LECO Corp) using a LECO CNS-2000 Carbon, Nitrogen and Sulfur Analyzer.

3.5 Water quality monitoring 2003 - 2010

Monitoring data for the period 2003-2010 were collected from the Biodynamic Research Institute and used to calculate the nutrient transport and retention in the wetland over a longer time period. During this period, unfiltered grab water samples were collected manually at the inlet and outlet using a plastic bottle. The samples were poured into glass bottles in order to prevent contamination of the sample, and sent to Alcontrol Laboratories, Linköping, for analysis of TP content (SIS, 2005). Sampling was conducted fortnightly, except during periods of high flow when samples were taken more often and during periods of low flow or ice cover when samples were taken more seldom.

During December 2009, an ISCO GLS continuous sampler was used at the inlet, which collected a sample every time 10 000 L had passed through the inlet. Concentrations of TP during this month were not interpolated, as the continuous sample was valid for the whole two weeks of sampling.

For the period June 2nd - November 30th 2010, data were used from the water sampling within this study. During this period, continuous sampling of water from the wetland inlet and outlet was conducted with the ISCO Wastewater Samplers (Model 2900) on a weekly basis. During every week, 70 ml samples were collected with a 2 hours interval, and in the end of each week the water was collected in the same type of glass bottle as mentioned above and sent for TP analyses to SLU, Uppsala. Sampling stopped at November 30th 2010 due to freezing of the samplers. During the three intense sampling periods, the weekly sampling was interrupted.

3.6 Calculations and statistical analysis

3.6.1 Calculations of water flow

Measurements of water flow were used to calculate the hydraulic load in the wetland and the run-off from the catchment to the wetland, both for every year 2003-2010 and for the intense sampling periods. The hydraulic load was calculated as:

$$q = \frac{Q}{A} \quad (2)$$

where

q is the hydraulic load in m d^{-1}
Q is the inflow in m^3 d^{-1}
A is the wetland area in m^2

Further, the annual catchment run-off was calculated as the annual inflow divided by the area of the catchment:

$$R = \frac{Q_{yr}}{A_{cm}} \times 1000 \quad (3)$$

where

R is the run-off from the catchment in mm yr^{-1}
Q_{yr} is the inflow to the wetland in m^3 yr^{-1}
A_{cm} is the area of the catchment in m^2

3.6.2 Calculations for phosphorus transport and retention

For the period 2003-2010, daily concentrations of TP were estimated using linear interpolation between the fortnightly sampling occasions. During December 2009 and June- November 2010, when continuous time proportional sampling was done, each concentration was instead assumed to represent that particular two- week's period. Daily transport of TP into the wetland during this period was calculated with the following formula:

$$P_{in} = \frac{Q_{in} \times C_{in}}{1000} \quad (4)$$

where

P_{in} is the transport of TP into the wetland in g d^{-1}
Q_{in} is the water flow measured at the inlet in L d^{-1}
C_{in} is the concentration of TP into the wetland in mg L^{-1}

The formula (4) is valid for calculation of P- transport in the outflow, but Q_{in} is used for the outflow calculations as well.

The daily transport of P in and out of the wetland calculated according to (4) was then summarized for each year (July 1st- June 30th) and for each month during the monitoring period. The result was divided with the wetland area, expressing annual and monthly transport of P in g m^{-2} yr^{-1} and g m^{-2} mon^{-1}, respectively. Further, flow adjusted mean concentration of TP for each year was calculated by summarizing the daily transport of each sampling day and dividing this by the summarized flow during the same day.

The area specific retention of P for each year or sampling period was calculated as:

$$P_{ret} = P_{in} - P_{out} \quad (5)$$

And the relative retention in % of load as:

$$P_{ret\,(\%)} = \frac{P_{ret}}{P_{in}} \times 100 \qquad (6)$$

Similar calculations were performed for the data from the intense sampling periods as well. However, concentrations of TP/TDP/SRP were interpolated for each hour between the sampling occasions three times daily and transport calculated according to (4), but for hours instead of days. The transported mean amount of P per hour during every period was then converted to annual transport, expressed in g m^{-1} yr^{-1}. The retention for each period was calculated according to (5) and (6). The mean concentrations of TP, TDP and SRP were calculated on the actual measurements, not the interpolated concentrations in between, and concentration of PP was calculated by subtracting the TDP concentration from the TP concentration at each sampling occasion.

3.6.3 Calculations of phosphorus content in the sediment

To enable a comparison between the three different parts of the wetland, the results from the analyses of the twelve traps were combined into a mean value for each of the three parts. Trap number one to five represented pond 1, trap six to eight the vegetation filter, and trap nine to twelve pond 2. Data from the samples in the sediment traps were used to calculate the mean gross sedimentation rate:

$$SED_{TSi} = \frac{dw_{ij} \times A_i}{n_j} \qquad (7)$$

where

SED_{TSi} is the gross sedimentation rate for the wetland part i in g m^{-2} d^{-1}
dw_{ij} is the mean amount of dry weight sediment in the traps in wetland part i for the time period j, expressed in g m^{-2}
A_i is the area of the wetland part i (m^2)
n_j is the length of the period j (days)

The P content in the sediment of each wetland part in g TP kg^{-1} sediment was calculated as the mean of the TP concentrations in the traps in each part. Further, the total amount of TP that had settled in the traps during each sediment sampling period was calculated, and compared with the total amount of P transported into the wetland during the same period. The total amount of P settled was calculated as:

$$SED_{Pij} = \frac{SED_{ij} \times C_{Pi} \times A_i}{n_j} \qquad (8)$$

where

SED_{Pij} is the total amount of TP that settled in wetland part i during period j (g d^{-1})
SED_{ij} is the amount of particles that settled in wetland part i during period j (kg m^{-2})
C_{Pi} is the mean concentration of TP in the sediment of wetland part i (g kg^{-1})
A_i is the area of the wetland part i (m^2)
n_j is the length of the period j (days)

3.6.4 Statistical analyses

The correlation between flow and P concentration was evaluated with correlation and the deviation from the linear regression analysis at the significance level 95 %. Before the

analysis, the residuals and normal distribution was investigated. Water flow was as common praxis log-transformed when necessary.

In order to evaluate the continuous automatic water sampling versus grab sampling, the concentrations of TP in water collected with the two different methods at the same time were compared with a paired t- test at a significance level of 95 %. Two different comparisons were made; first, between all concentrations from the three sampling periods together, and secondly, between the concentrations for each of the three sampling periods. Both inflow and outflow concentrations were tested. The H_0, null hypothesis, was that the mean difference between concentrations did not differ from zero, and the H_1 was that there was a difference between them. A result that rejects H_0 would, thus, mean that the sampling techniques do not take equal samples of the water. The opposite result, if H_0 not can be rejected, means that there is a high probability that they do.

All statistical analyses were conducted in Minitab 15, Statistical Software, and all other calculations in Microsoft Office Excel 2007.

4 Results

4.1 Phosphorus transport and retention during 2003-2010

The transport of TP has varied during the years that have passed since the wetland was constructed, with the largest transport during the season 07/08 (Tab. 1). Annual retention of TP was negative (i.e. a release of P from the wetland) during four of the five years with available data; the first monitoring year after construction it was as low as -40 %. In subsequent years, the retention was quite similar and negative during the three last years. The catchment runoff and hydraulic load varied quite much between the years, with low values in 03/04 and 08/09, modest values in 04/05 and 09/10 and high values in 07/08. The flow adjusted mean concentrations of TP were highest during 07/08 and 08/09 and somewhat lower during the two initial years and the last year of monitoring. The apparent lack of agreement between inflow/outflow concentrations and estimated retention for some years (04/05, 07/08 and 09/10) is explained by the few occasions used to estimate flow adjusted mean concentration, while for the transport estimates interpolated daily concentrations values were used.

Table 1. *Number of measurements (n) at the inlet/outlet, catchment runoff, hydraulic load, transport and retention of TP and flow adjusted mean concentration of TP calculated from continuous water flow measurements and grab samples every two weeks for each year (July-June) after the construction of Skilleby wetland. Observe that data are missing for the years 05/06 and 06/07.*

Year	n	Run-off ($mm\ yr^{-1}$)	Hydr. load ($m\ d^{-1}$)	TP- transport ($g\ m^{-2}\ yr^{-1}$)		Ret. (%)	TP- conc. ($mg\ L^{-1}$)	
				In	Out		In	Out
03/04	16	124	0.1	5.0	7.1	-39.9	0.15	0.19
04/05	16	202	0.16	7.0	6.9	1.4	0.16	0.20
07/08	13/12	283	0.22	31.1	32.1	-3.3	0.44	0.44
08/09	15	129	0.1	10.9	11.3	-4.5	0.32	0.33
09/10[1]	19	212	0.16	11.4	11.9	-3.6	0.28	0.25

1 Continuous sampling with ISCO-sampler at the inlet in December 2009 and June 2010.

The retention of TP has varied greatly over the years, but during the majority of the months the retention was 0 ± 1 g m^{-2} mon^{-1} (Fig. 4). However, the number of months with negative retention was approximately equal to the number of months with positive retention or with no flow in to the wetland. During four out of the five years evaluated, one or several of the summer months (May-September) were dry, without flow in to the wetland. The months with the largest retention of TP were January 2005, January 2008 and December 2008. The months with the largest release of TP were December 2003, February 2005, April 2008, November 2008 and October 2010. The month with the largest release of TP during the entire period was October 2010, with a release of 3.7 g m^{-2} mon^{-1}.

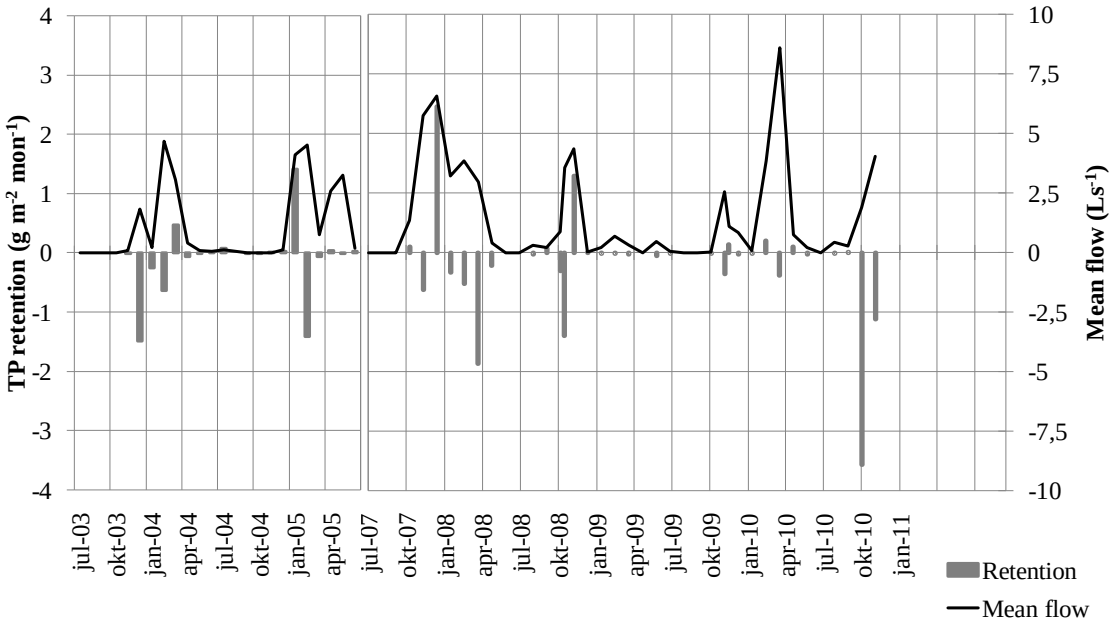

Figure 4. *Retention of TP and mean flow in Skilleby wetland for each month since the monitoring started in 2003. Observe that the years 05/06 and 06/07 are missing in the figure. Grab samples at the inlet and outlet during 2003-2009; Continuous sampling at the inlet and grab sampling at the outlet during December 2009; and continuous sampling at the inlet and outlet during June-November 2010.*

4.2 Intensive sampling periods during 2010

During the three intensive sampling periods, the temperature varied slightly, with the lowest temperature in the wetland water in April and the highest in October (Tab. 2). In November, the pH of the water was approximately neutral and no significant change occurred as the water passed through the wetland.

Table 2. *Mean value and standard deviation for water temperature and pH in wetland (inlet and outlet) during the intensive sampling periods. N.d.: no data available.*

Sampling period	Water temperature (°C)		Water pH	
	In	Out	In	Out
April	3.0 ± 1.0	2.8 ± 0.4	n.d.	n.d.
October	6.4 ± 1.4	5.6 ± 0.2	n.d.	n.d.
November	4.4 ± 0.2	4.2 ± 0.3	6.8 ± 0.4	6.9 ± 0.3

The first sampling period, April 7- 10, lasted for 65 hours and occurred during a decreasing flow in the end of a snow melt period. Initially, the flow was 4.5 L s^{-1} and decreased to 2 L s^{-1} (Fig. 5 a-c). There was no significant relationship between flow and concentration of TP, TDP or SRP (Tab. 3). The TP and TDP concentrations were quite variable in both inflow and outflow, whereas the SRP concentration was at a low and even level during the entire period and with equal concentrations in inflow and outflow water. Overall, the mean concentrations of TP, TDP, SRP and the calculated PP during April were the lowest of all three sampling periods in both inflow and outflow water (Tab. 4).

The second sampling period, October 19- 22, lasted for 72 hours. After a moderate flow peak (3.6 L s^{-1}) during the first hours the flow decreased to a low level where it remained the rest of the sampling period (Fig. 5 d-f). There were significant correlations between flow and concentrations of TP, TDP and SRP in the inflow water, but not between flow and concentrations of P in the outflow water (Tab. 3). The inflow concentrations were always higher than the outflow concentrations at the same sampling occasion. The mean concentrations of P were higher than the April concentrations at all occasions, and lower than or equal to the November concentrations at all occasions but one, the inflow SRP concentration (Tab. 4).

The final sampling period, November 15- 19, lasted for 90 hours and was preceded by a couple of weeks with short periods of intense precipitation. Thus, several flow peaks occurred before the start of sampling and period 3 was initiated just after one of these high flow peaks (Fig. 5 g- i). The flow in the beginning of period 3 was far higher than during the other two periods, but it quickly decreased to a lower level, approximately equal to, and below, that of period 1. When the first samples were collected, the flow was 18 L s^{-1}, but just a few hours earlier the flow had peaked at 48 L s^{-1}. There were significant positive relationships between the TP concentrations and flow in both the inflow and outflow of the wetland (Tab. 3). This was also the case for SRP in and out of the wetland and flow. TDP, on the other hand, was not correlated with the flow, neither in inflow nor outflow (data not shown). However, for outflow concentrations, the best regression model was obtained when using log- transformed flow data, indicating a smaller increase in concentration towards the end of the period. The TP concentration in the outflow water exceeded the concentration in the inflow water at all grab sampling occasions except one, and the same pattern occurred for SRP (Tab. 4). For TDP, however, the concentrations varied quite much, but the mean concentration in inflow water was nevertheless higher than the mean concentration in the outflow for the entire sampling period.

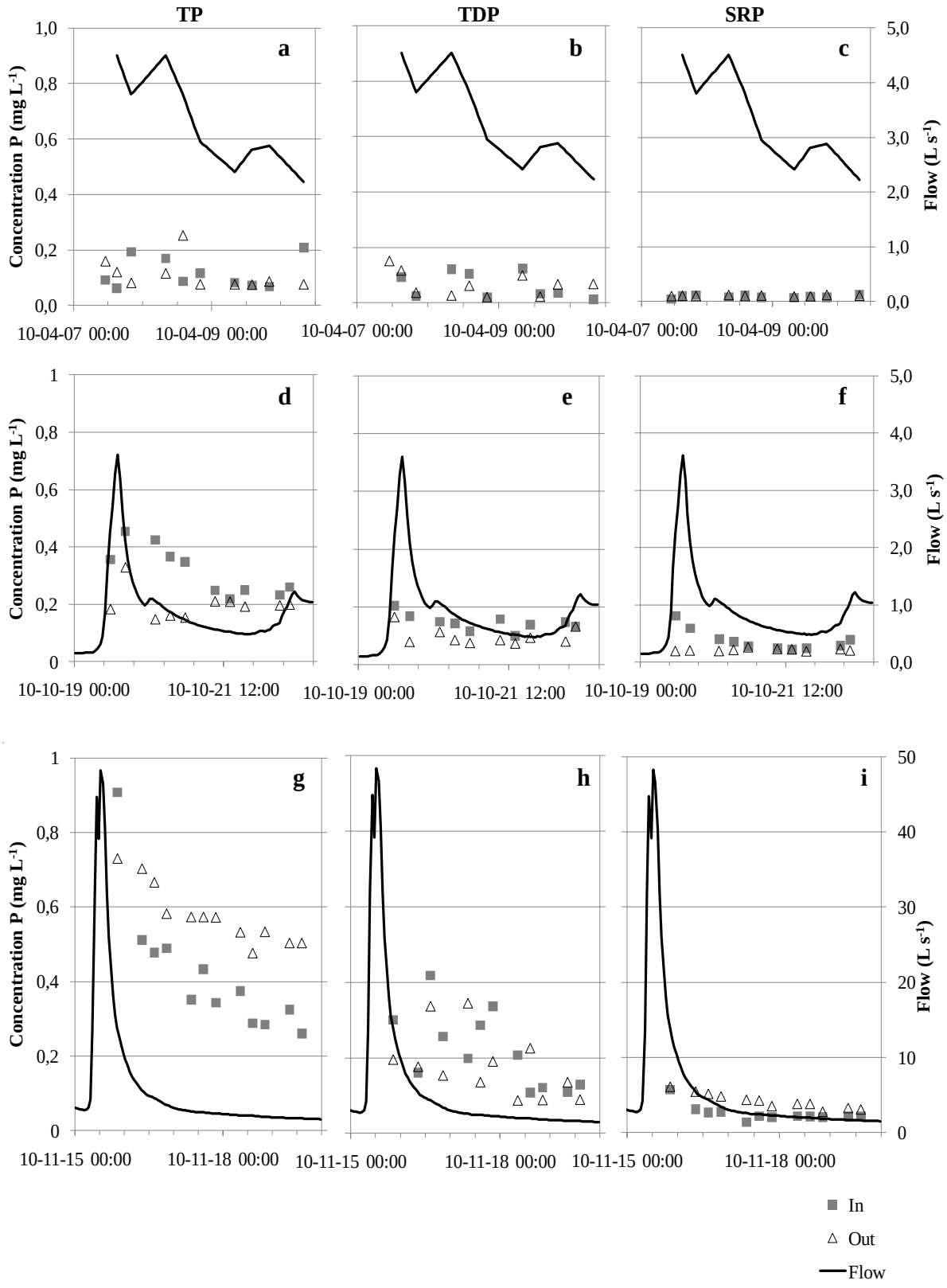

Figure 5. *Water flow (L s^{-1}) and concentrations (mg L^{-1}) of TP, TDP and SRP during intense sampling periods in April (a-c), October (d-f) and November (g-i) 2010 in Skilleby wetland. Observe that the flow scale for November is ten times larger than the scale for April and October.*

Table 3. *Regression analysis for concentrations (mg L^{-1}) of TP and SRP in inflow and outflow water versus flow (Q; L s^{-1}) during different sampling periods in Skilleby wetland in 2010. N.S.: no significant correlation (p> 0.05); *S.: Significant correlation (p≤ 0.05); ***S.: Highly significant correlation (p≤ 0.001).*

Sample		Sampling period	n	p- value	r^2	Regression equation
TP	IN	April	9	N.S.	0.0	0.1 – 0.001 Q
		October	10	*S.	0.54	0.3 + 0.3 log Q
		November	12	***S.	0.94	0.2 + 0.05 Q
	OUT	April	9	N.S.	0.21	0.01 + 0.03 Q
		October	10	N.S.	0.2	0.2 + 0.04 Q
		November	12	***S.	0.87	0.5 + 0.3 log Q
SRP	IN	April	9	N.S.	0.02	0.02 + 0.001 Q
		October	10	***S.	0.95	0.02 + 0.06 Q
		November	12	***S.	0.93	0.03 + 0.01 Q
	OUT	April	9	N.S.	0.13	0.02 + 0.001 Q
		October	10	N.S.	0.19	0.05 – 0.003 Q
		November	12	***S.	0.87	0.05 + 0.07 log Q

Table 4. *Mean P- concentration in water samples during the three separate sampling periods. TP, TDP and SRP are results from analyzes, PP was calculated by subtracting the TDP concentration from the TP concentration at every grab sampling occasion, and then calculating a mean concentration.*

		April	October	November
TP (mg L^{-1})	IN	0.1±0.05	0.3±0.08	0.4±0.2
	OUT	0.1±0.06	0.2±0.05	0.6±0.08
TDP (mg L^{-1})	IN	0.09±0.1	0.2±0.03	0.2±0.1
	OUT	0.07±0.04	0.1±0.03	0.2±0.09
SRP (mg L^{-1})	IN	0.02±0.005	0.08±0.04	0.05±0.02
	OUT	0.02±0.002	0.04±0.004	0.08±0.02
PP (mg L^{-1})	IN	0.1±0.07	0.2±0.08	0.2±0.2
	OUT	0.05±0.06	0.1±0.06	0.4±0.09

When summarized, the October period stands out as it had a mean total flow and hydraulic load that was approximately 3.5 and 2.7 times lower than the flow during the sampling periods in April and November (Tab. 5). The latter periods had a quite similar flow and hydraulic load, even though the flow in the beginning of the November period was much higher than the flow during the April period. The transport of P (TP, TDP and SRP) was despite this much larger during November than during the periods in April and October (Tab. 5). There was a positive retention of TP in the wetland during the sampling periods in April and October, but not in November. For TDP, there was a positive retention in the wetland during all three sampling periods. For SRP, on the other hand, there was a positive retention in the wetland only during the sampling period in October.

***Table 5**. Run-off (mm yr^{-1}), hydraulic load (m d^{-1}), transport (g m^{-2} yr^{-1}) in and out of Skilleby wetland for TP, TDP and SRP, and retention (%) for each of them, for three short grab sampling periods in April, October and November 2010.*

			April	October	November
Run-off		(mm yr^{-1})	465	136	479
Hydraulic load		(g d^{-1})	0.36	0.1	0.37
TP	IN	(g m^{-2} yr^{-1})	16.4	13.5	69.2
	OUT	(g m^{-2} yr^{-1})	14.0	8.2	83.9
	Retention	(%)	14.9	39.0	-21.4
TDP	IN	(g m^{-2} yr^{-1})	8.6	5.9	31.7
	OUT	(g m^{-2} yr^{-1})	6.8	3.7	25.7
	Retention	(%)	20.8	36.5	18.9
SRP	IN	(g m^{-2} yr^{-1})	2.4	3.4	8.3
	OUT	(g m^{-2} yr^{-1})	2.9	1.6	12.7
	Retention	(%)	-18.4	53.3	-53.5

4.3 Gross sedimentation

When the traps were emptied the first time, in April, they had been in the wetland during five months. Analysis of dry weight sediment (Fig. 6a) showed that the largest part of the material settled in pond 1; there were almost 18 times more sediment per square meter in pond 1 than in the vegetation filter, and five times more than in pond 2. The sediment in pond 2 had the highest TP concentration of the three wetland parts, and pond 1 the lowest (Fig. 6b).

When the traps were emptied next time, three months later (July), the gross sedimentation was once again highest in pond 1, four times higher than in the vegetation filter and pond 2 (Fig. 6a). The concentration of TP was quite similar in the sediment from the vegetation filter and from pond 2, and the concentration in pond 1 at approximately the same concentration as in November-April (Fig. 6b).

The traps were emptied only one month later, in August, and it was revealed that all traps in the vegetation filter had tipped over and thus sediment was not collected. There are therefore no results from the vegetation filter in July-August. The amount of sediment accumulated in pond 1 was seven times larger than in pond 2 (Fig. 6a), but the concentration TP in the sediment were quite similar in the two parts (Fig 6b).

The last time the traps were emptied, in November, the traps had collected sediment for three months. The amount of sediment was also this time highest in pond 1, six and four times higher than in the vegetation filter and pond 2 respectively (Fig. 6a). The concentration TP was though similar in pond 1 and 2, but much lower in the vegetation filter, especially if comparing to the concentration in November-April and April-July. In pond 1, the concentration of TP was approximately the same at all sampling occasions, while in the vegetation filter and in pond 2, the concentration varied a lot between the different periods (Fig. 6b).

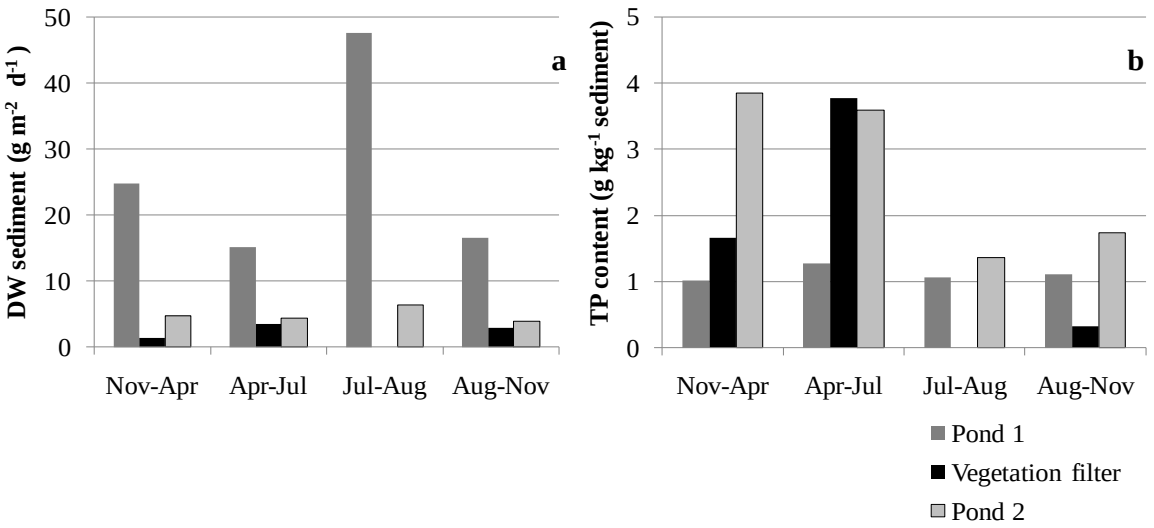

Figure 6. *Gross sedimentation (a) in Skilleby wetland and mean concentration of TP (b) in the sediment captured in 12 traps and collected at four different occasions from pond 1 (trap one to five), the vegetation filter (trap six to eight), and pond 2 (trap nine to twelve). Values are missing for the vegetation filter in August because of a sampling error.*

The material that settled in pond 2 had the highest content (%) of both carbon and nitrogen in all periods except in April- July, when the sediment from the vegetation filter had a slightly higher C and N content (Fig. 7). It was also in April- July that the sediment had the highest content of both C and N in all three parts of the wetland. The sediment from traps in pond 1 had the lowest content of C and N at all four occasions.

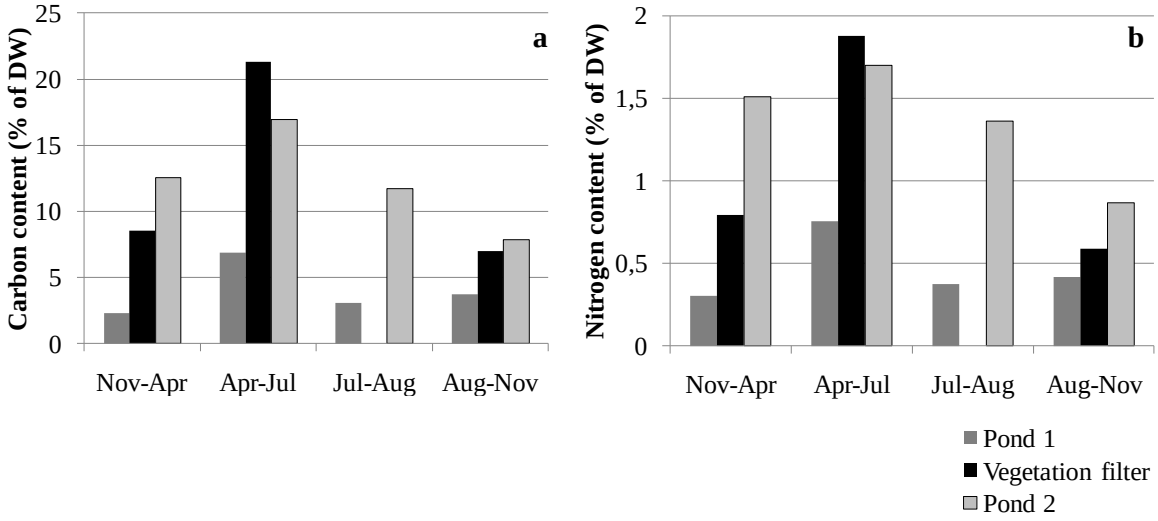

Figure 7. *a) Mean total carbon content and b) mean total nitrogen content (% of dry weight) in sediment captured in sediment traps located in different places in the Skilleby wetland, collected at four different occasions. The twelve traps were grouped to represent three parts: Pond 1 (trap one to five), vegetation filter (trap six to eight) and Pond 2 (trap nine to twelve). Values are missing for the vegetation filter in August because of a sampling error.*

In total, the largest amount of phosphorous had settled in pond 2 during all periods except July- August, when most phosphorous was found in the traps in pond 1 (Fig. 8). The amount of phosphorous found in traps in the vegetation filter was generally low, with the exception of April- July, when more TP was found in the vegetation filter than in pond 1. Transport calculations showed a similar pattern during the April- July and the July- August periods, with more TP recovered in the sediment traps than was transported with the inflow. During the April- July period, 12.4 g TP d^{-1} settled in the traps but only 5.6 g TP d^{-1} was transported into the wetland. During the July- August period, only 0.1 g d^{-1} of TP was transported into the wetland, but still a total amount of 10.3 g TP d^{-1} had settled in the two ponds (data from vegetation filter missing). During the November- April and August- November periods the opposite pattern occurred. During the November- April period, 53.4 g TP d^{-1} was transported into the wetland while only 11.4 g d^{-1} settled in the traps. Similarly, during the August-November period, 41.9 g TP d^{-1} was transported into the wetland, but only 5.6 g d^{-1} TP was recovered in the wetland sediment. Noticeable is that despite the different amounts of TP transported into the wetland during the four periods, approximately the same amount of TP were recovered in the traps.

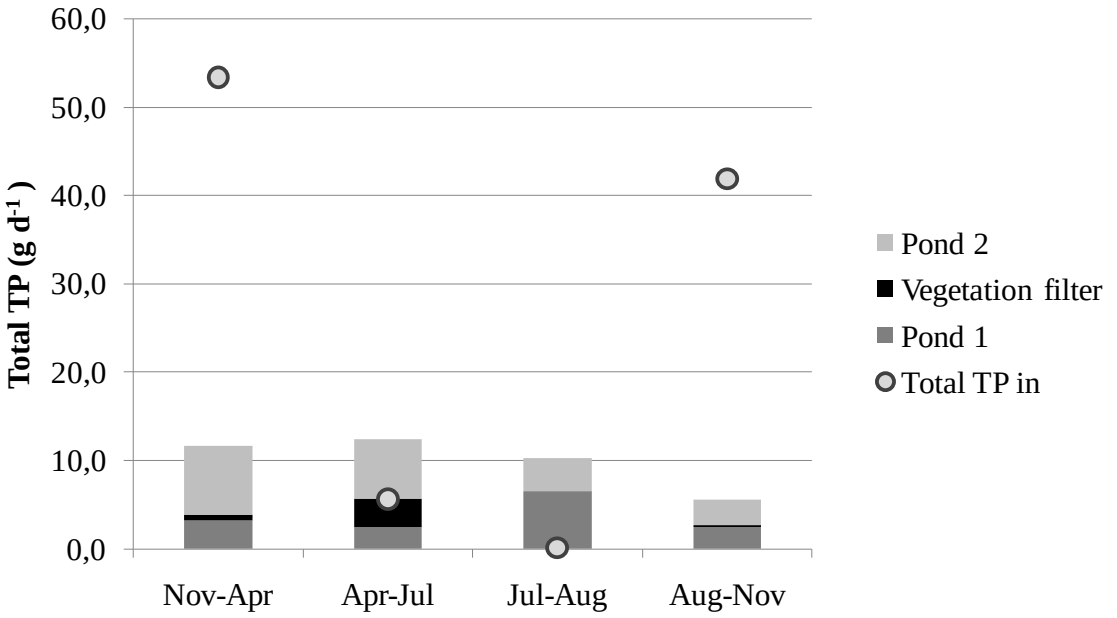

Figure 8. *Total amount of TP in g d^{-1} that had settled per day in each wetland part during every individual trapping period (bars) and total amount of TP transported into the wetland during the same periods (points). Values for the vegetation filter in August are missing.*

4.4 Critical analysis of sampling strategy

A comparison was made between concentration of TP in grab samples and automatic samples, to investigate if the automatic water samplers collected representative samples of the inflow (Fig. 9a-c) and outflow (Fig. 9d-f) water. The statistical t- test showed that for the three periods together, H_0 could not be rejected, neither for inflow samples ($n=27$, $t=-1.52$, $p>0.05$) nor for outflow samples ($n=26$, $t=-1.46$, $p>0.05$). Concentrations in the grab samples in outflow during the November period were significantly higher than concentrations in automatic samples ($n=11$, $t=-3.62$, $p\leq0.05$). The t- test of the other individual periods showed non- significant differences, meaning that H_0 could not be rejected.

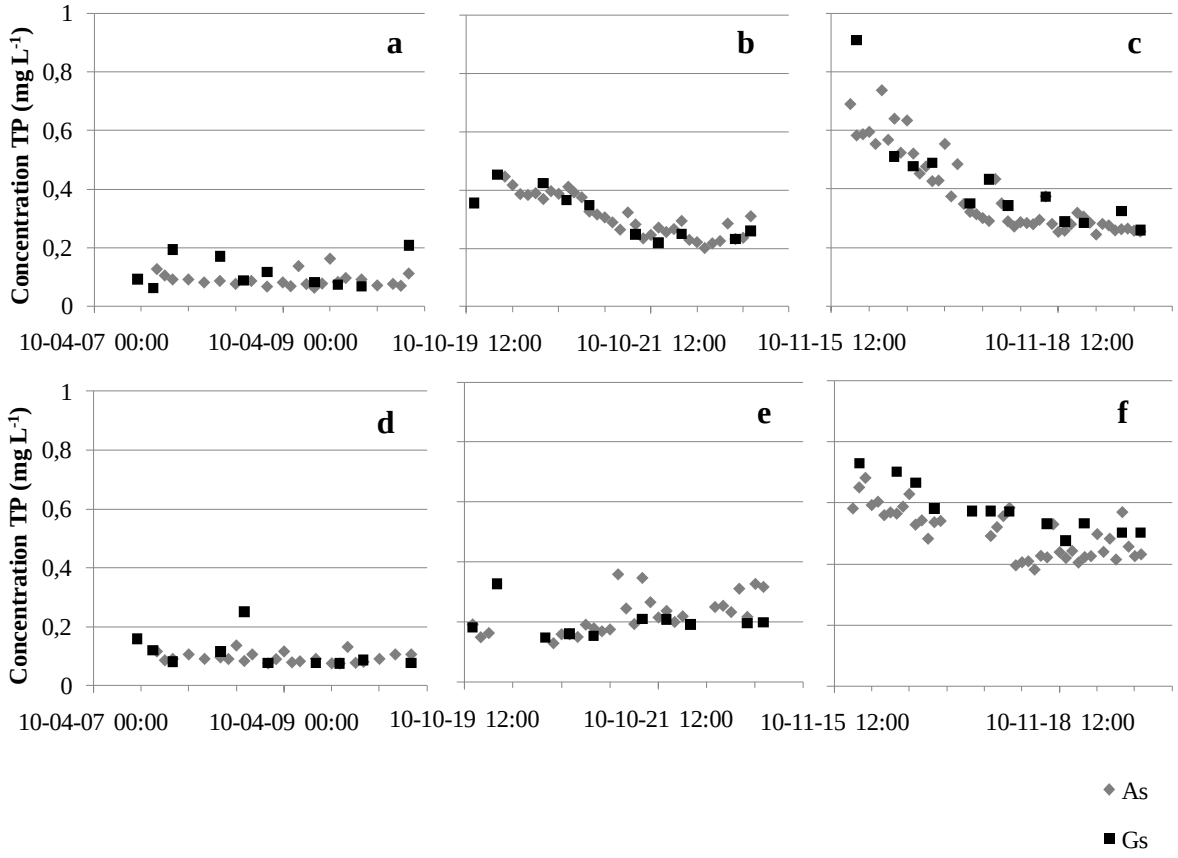

Figure 9. *Concentration TP in inflow water (a, b, c) and outflow water (d, e, f) for each intense sampling period. Comparison of automatic samples (As) and grab samples (Gs).*

Furthermore, the automatic flow measurements were compared with manual flow measurements during the sampling periods in October and November (Fig. 10). During the October period, the ratio manual/automatic had a mean value of 0.94 for the corrected automatically measured flow, and 1.03 for non-corrected values. The corresponding ratios for the November sampling period were 0.93 for the corrected and 0.90 for the non-corrected flow values. When the ratio was the lowest, in November, the flow was the highest and thus very difficult to measure manually.

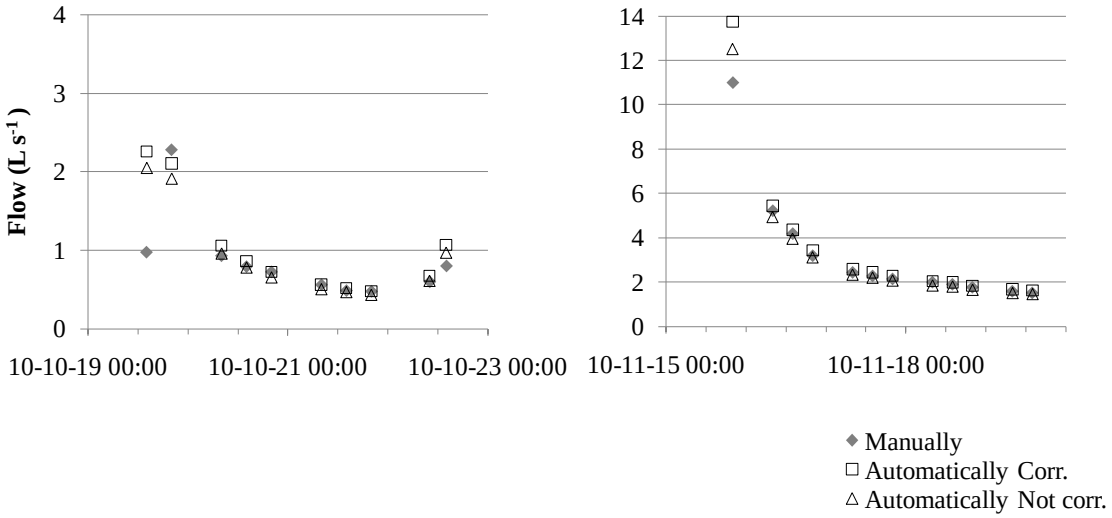

Figure 10. *Automatically registered and manually measured flow values during the October (a) and November (b) sampling periods in Skilleby wetland in 2010. Manual flow measurements were done at the inlet v- notch, using stop watch and bucket. Automatically registered values are also shown, both uncorrected and corrected with a factor of 1.1.*

Visual observations during the three sampling periods revealed that the flow measured at the inlet did not fully represent the flow at the outlet of the wetland. During the April and October sampling periods, no large variations were noticed in the flow at the outlet, but during the November period it was obvious that there was a delay in the flow decrease at the outlet. When the sampling was initiated, the flow at the inlet decreased rapidly whereas the flow at the outlet remained more or less constant. Not until approximately 24 - 36 h hours after the sampling started there was a noticeable decrease in flow at the outlet as well. This means that calculations of transport of e.g. P at the outlet will be somewhat misleading during periods of extreme flow changes such as when the November sampling period started. To evaluate the impact of this problem on transport calculations, TP transport at the outlet was recalculated for the November period with approximated flows. The flow value for the outlet was shifted 10 hours, so that the peak in inflow that occurred at 10 am 10-11-15 was set to represent the flow at the outlet at 8 pm the same day. The result showed that the transport increased greatly with the new flow (Tab. 6).

Table 6. *Outflow, transport of TP in outflow and retention of TP with original flow and with time- adjusted flow at the outlet for the November period, 20101115-20101119, in Skilleby wetland. The outlet flow was set equal to the inlet flow 10 hours earlier to compensate for delay in flow changes at the outlet versus the inlet.*

Period	**Outflow (m^3 d^{-1})**		**TP (g m^{-2} yr^{-1})**		**Retention (%)**	
	Org.	**Adj.**	**Org.**	**Adj.**	**Org.**	**Adj.**
November	294	597	84	181	-21	-161

5 Discussion

5.1 Phosphorus transport and retention in Skilleby wetland

The transport calculations for the years 2003-2010 points towards an overall release of TP from the wetland instead of a retention. Especially the first year after construction, 03/04, the release of TP from Skilleby wetland was noticeable. According to the monitoring data, as much as 40 % more TP was released from the wetland than was transported into the wetland with the inflow (Tab. 1). This indicates that the wetland does not work as it is supposed to and not has stabilized during the seven years that has passed since construction, which otherwise could be expected (e.g. Braskerud et al., 2005; Pant et al. 2003). Overall low estimated retention of P in Skilleby wetland could be explained by (1) rapid flow increases, causing resuspension of sediments and thus release of P, due to quick inflow response on precipitation and the drainage pipe that leads directly into the wetland, (2), uncertainties in monitoring data from fortnightly water sampling as well as lack of outflow measurements and continuous water flow measurements and (3) increased resuspension of sediments due to construction work, bioturbation and the initial absence of vegetation as well as low gross sedimentation due to channelization of the flow, low sedimentation rate and unstable sediments caused by the clay soil.

5.1.1 Rapid flow increases causing release of phosphorus

Inconsistent to other studies (e.g. Braskerud et al. 2005; White et al. 2000; Hauge et al. 2008; Sharpley et al. 2009), the results from this study unanimously points towards an unsatisfying retention of P in Skilleby wetland. However, the estimations are extremely sensitive to variations in flow and concentrations of P. The results from the intense sampling periods showed that there were very fast changes in both factors over time in Skilleby wetland. Release of P occurred more often during high flow periods with a high flow peak. For TP, the retention during the high flow period in November was -21.4 %, but positive during the two earlier sampling periods with lower flow peaks, the sampling period in April (14.9 %) and the period in October (39.0 %) (Tab. 5). During the November period, there was also a large negative retention of SRP (-53.5 %).

The negative retention of TP and SRP in November is likely explained by the high flow that promoted resuspension of sediment; the concentration of PP was twice as high in the outflow as in the inflow during this period (Tab. 4). None of the other P forms had such a large increase in the outflow concentration as PP, which indicated that the high flow must have promoted resuspension during this period. Similarly, release of particles and TP during high flows was observed by e.g. Kronvang et al. (1997). Further, the particles transported from the catchment during the high flow period were probably too small to settle in the wetland (Ulén, 2004). Thus, only a small fraction of the particles in the inflow settled and instead they were directly transported out of the wetland with the outflow. The delay in outflow versus inflow might explain the much larger concentration of TP in the outflow during the November sampling period (Tab. 4). Since no sampling occurred during the inflow peak, it is not known which concentration of TP the inflow water had at that point. The first inflow sample collected during the November period, while flow still was high, had a higher concentration than the outflow sample (Fig.5), indicating that the TP concentration was very high in the inflow as well during the flow peak. There were correlations between concentrations of TP and SRP and flow in both inflow and outflow during the November sampling period (Tab. 3), which agree with previously performed studies (e.g. Ellison et al., 2006). The correlation between flow and concentration at the outlet further indicated that very little settling of particles occurred when the water passed through the wetland during high flow. However, the slope of the regression lines, as well as the log- transformations, points towards a small decrease in flow when the water passed

through the wetland and the peak in outflow was thus not as high as the peak in inflow. Also, the wetland delayed the increase of flow at the outlet, which also affected the slope of the line. However, there was no correlation between concentration of TDP and flow, and this does not have any logical explanation other than a possible sampling error.

In October, there was a positive retention of TP, TDP and SRP (Tab. 5), which most likely was due to the low flow during this period. There were correlations between flow and concentrations of TP, TDP and SRP in the inflow, but not in the outflow (Tab. 3). This indicated that the wetland actually worked as a P sink during low flow periods and when peaks in flow were low, as settling of particles occurred and resuspension of sediments were avoided.

Remarkable is, however, that despite the high flow during the April sampling period, equal to the mean flow during November, the transport of TP, TDP and SRP was more equal to the transport in October when flow was low. This was due to much lower concentrations of P in the run- off during the April period than during both the October and the November periods (Tab. 4), and no correlations between flow and concentrations of P was observed (Tab. 3). A possible explanation to this could be that the sampling period in April occurred in the end of the snow melt period. The winter 2009/2010 was unusually rich in snow, and flow observations at a constructed wetland located northeast of Södertälje, 25 km from Skilleby wetland, showed that the snow melt started in the middle of March and the flow started to decrease in April. Because of the short distance between the two wetlands, it is very likely that the snow melt started at approximately the same time at both locations. Hence, it is likely that the transport of P, both dissolved and bound to particles, had decreased from the fields after a longer period of high flow and transport of both particles and dissolved P.

The conclusion of the results from the intensive sampling periods were that release of P occurred during high flow periods with high flow peaks, due to resuspension of the sediments and very little settling of the inflow clay particles. However, when flow was high during a longer period, the inflow concentrations of P decreased and the wetland acted as a P sink for TP instead of a source. During low flow, the wetland acted as a P sink. The November sampling period showed, though, that even a couple of hours of high flow which is common in Skilleby wetland plays an important role on overall retention of P.

5.1.2 Uncertainties in monitoring data

The results from the intensive sampling periods showed that fortnightly water sampling and flow measurements were too infrequently to enable reliable estimations of P transport and retention. Kronvang et al. (1997) made the same observations and showed that fortnightly sampling underestimated annual transport of PP in streams by -8.6 % and -151 % for the two study years, respectively. Further, Kronvang et al. (1996) concluded that an intensive monitoring approach was needed as the majority of the P transport occurred during short high flow periods in the studied stream. Unfortunately, during the majority of the monitoring period 2003-2010, data was based on fortnightly grab water sampling. Additionally, during January-September 2010, the pressure transducer at the inlet was out of order, thus continuous flow measurement was interrupted. Instead, fortnightly notations of water height in the v- notch were made. This leads to the conclusion that calculations of annual and monthly P transport and retention in Skilleby wetland during these years are highly uncertain.

However, during October and November 2010, monitoring was made through continuous flow measurements as well as continuous, weekly water sampling at the inlet and outlet. Thus, the data from these months must be considered reliable. During October 2010, the wetland acted as a P source, releasing 3.6 g m^{-2} mon^{-1} of TP, which were the by far largest release observed during the entire monitoring period (Fig. 4). Similarly, during

November 2010, there was also a release of TP of 1.1 g m^{-2} mon^{-1}. During both months, short periods of high flow whit rapid flow increases and high flow peaks occurred, which exclusively were responsible for the estimated large negative retentions. As the wetland actually acted as a P source during these circumstances, it is likely that the function of Skilleby wetland as a P sink can be doubted. Thus, the pattern showed in the results from the monitoring years 2003-2010 (Tab. 1 & Fig. 4) is probably true, though the actual numbers are uncertain.

Due to this uncertainty, it cannot be ensured that the estimated retention for all monitoring years except 03/04 actually was negative or positive, respectively, as the retention these years was close to zero (Tab. 1). However, estimation of monthly P retention showed that the months October-February had the largest influence on annual retention of TP (Fig. 4). Release of P during these months coincided with high flow, while the remaining months with smaller influence on annual retention often had low or no flow at all. This relationship was confirmed by monitoring data from e.g. February 2004, when a high flow period occurred with a flow peak at 53 L s^{-1}. During the eight days the high flow period lasted, approximately 40 % of the annual TP transport out of the wetland occurred. This result also corresponds with previously performed studies (e.g. Kronvang et al. 1997). Rogers et al. (2009) showed for instance that 98 % of the sediment mobilized during a study period was mobilized during three individual high flow periods, indicating that the wetland was a P source during these periods. Also, Jordan et al. (2003) found that half of the inflow to a studied wetland during a two year period occurred in 24 days, confirming that short high flow periods influences the annual flow to a large extent.

From this it can be concluded that the estimation of annual and monthly retention and transport of P in Skilleby wetland is highly uncertain when based on fortnightly sampling. Though, since the results from October and November 2010 with reliable data indicate a release of P during high flow periods, it is likely that Skilleby wetland often act as a P source instead of a P sink.

5.1.3 Possible factors causing phosphorus release

Since Skilleby wetland occasionally acted as a source of P, there were obviously factors causing the release of P from the wetland. During the first monitoring year 03/04, when the wetland was quite newly constructed, the release of P was substantial (40 %). This large estimated annual release could be due to that the wetland was disturbed by construction activities and influenced by the lack of vegetation. Vegetation promotes sedimentation of particles, and thus retention of P, by decreasing the speed of the inflow water. Braskerud (2001) showed that the resuspension of sediments had decreased by 40 % four years after construction of a Norwegian wetland due to the establishment of vegetation. Hence, the lack of vegetation could have influenced the retention of P in Skilleby wetland. Also, during the construction work, top soil was excavated which makes the soil more susceptible to resuspension when the area was flooded. An additional factor that could influence the release of TP during 03/04 is that the year 2002 was the last year of ley at one of the fields. It is known that the leaching of P increases the year after the third ley due to soil cultivation (Schneider, 2009). Additionally, manure is spread on the fields after the third ley, which further promotes the leaching of P. The following monitoring year, 04/05, there was a small estimated positive retention of P, indicating that the impacts of construction and the initial leaching of P after flooding had decreased.

Observation of the vegetation filter indicated that channelization might be a factor influencing the retention of phosphorus in the wetland. At a couple of locations in the filter, channels could be seen, which indicated short-circuiting of water. Vegetation filters, areas planted with macrophytes, is considered a tool for increasing hydraulic efficiency in wetlands (Braskerud, 2001), thus promoting P retention. However, it is known that

zonation of the vegetation might create channels through the filter (Kadlec, 2005; Braskerud, 2001) with short- circuiting and a reduced detention time as result (Fennessy et al., 1994), thus reducing the ability to retain P. In addition to possible channelization, the water depth in the vegetation filter in Skilleby wetland is quite low (~0.4 m), whereas there is a risk that the water flows through the filter at a too high speed, not leaving time for sedimentation. Thus, as channelization probably occurred in Skilleby wetland, it is likely one of the reasons to the release of P from the wetland.

Furthermore, a factor that could be influencing, and partially causing, the negative phosphorus retention is erosion in the wetland by trampling animals. In a study conducted by Kronvang et al. (1997), bed erosion was concluded as a source of 66-89 % of the suspended solids and PP in the stream water, and the banks being trampled by cattle one of the factors contributing to the large erosion. At Skilleby, there are no cattle grazing at the site of the wetland, but due to its location it cannot be excluded that animals occasionally visit the vegetation filter of the wetland, at least during summer when flow usually is low. Trampling in the vegetation filter would indeed increase the erosion of bed material and resuspension of settled materials, thus having a negative effect on retention of PP.

However, it is known that there were plenty of invertebrates in the wetland. At all occasions when traps were emptied, several of the traps contained a great deal of invertebrates of different kinds as e.g. *Asellus*, *Hirudinea*, *Hydrachnidia* and larvae of *Chironomidae*, *Trichoptera* and *Zygoptera*, Most of the invertebrates were found in traps in pond 2 and in the vegetation filter, but also in pond 1 at some occasions. When invertebrates exist in large amounts, bioturbation is likely to occur (e.g. Mermillod-Blondin et al., 2008; Lagauzère et al., 2011). That is, the animals probably promote resuspension of sediments and could be one reason to the release of P from Skilleby wetland. As there are large amounts of animals and plants in Skilleby wetland, and orthophosphate is released from both when they decay, it also could be expected a release of orthophosphate from the wetland. However, the results from the intensive sampling periods indicate that it mostly is PP that causes the negative retention, not SRP. Also, the results indicate that conditions not becomes anaerobic due to the vegetation, which otherwise also would have promoted release of P.

The most likely explanation to the low retention of P in Skilleby wetland is that the particles transported into the wetland are too small and do not have time to settle before the water leaves the wetland. Results of a study by Ulén (2004) showed that a large part of the particles transported from clay soils, similar to the soil at Skilleby, had a settling rate of <1 cm d^{-1}, which means that particles of this size do not have time to settle in Skilleby wetland. Further, the drainage is transported to the wetland through tiles, which not either promotes the settling of particles or the formation of aggregates (Ulén, 2004). Due to this, and as the residence time in Skilleby wetland were quite short during the high flow periods when most of the PP were transported, most of the incoming particles were probably transported through the wetland with the outflow as well. Also, the particles that did settle in the wetland were probably sensitive to resuspension during high flow periods, as showed by Koskiaho (2003). Thus, the transport of PP out of Skilleby wetland was likely to increase further during these high flow periods due to resuspension.

As concluded by e.g. Koskiaho et al. (2003), Uusi- Kämppä et al. (2000) and Braskerud et al. (2005), the wetland area in relation to the catchment area is one of the most important factors when constructing a wetland. The ratio between wetland and catchment area at Skilleby are quite low, with the wetland comprising approximately 0.4 % of the catchment. Though, the ratio is larger than the smallest ratio (0.1 %) recommended by Braskerud et al. (2005) in order to enable retention of PP. However, inconsistent to that recommendation, Koskiaho (2003) concluded that a ratio of 0.5 % likely is too small for an

efficient wetland, and if a substantial P retention should be achieved, the ratio should be larger than 2 % (Puustinen et al., 2005). Hence, these results indicate that Skilleby wetland probably would have had a greater chance to act as a P sink if it would have had a larger area.

Other studies have found negative retention of TP in constructed wetlands as well (Koskiaho et al., 2003; Ulén, 1988), but more research is needed in order to investigate the reasons to why some wetlands act as P sources rather than P sinks.

5.2 Patterns of sedimentation

The results from this study showed that most of the gross particle sedimentation in the wetland occurred in pond 1 (Fig. 6a). This result agree with e.g. the results of White et al. (2000), which found that sites near the inlet had higher sedimentation rates and P burial rates than sites further down in the wetland. In Skilleby wetland, particles in pond 1 originated from the catchment whereas the particles that settled in the vegetation filter and in pond 2 seemed to originate from processes within the wetland, as they had higher TP, C and N concentrations (Fig. 7). The TP content in pond1 sediment was overall low (Fig. 6b) and equal throughout the year, indicating that the same type of material settled in the traps throughout the year. According to Swedish EPA (2010) a normal C content of clay soils is approximately 2-3 %. The C content in pond 1 was during most of the year close to this percentage, with the exception of July when the C content was somewhat higher. This confirms the conclusion that sediment found in pond 1 originates from the catchment and mainly consists of clay soil.

Unlike the P and sediment recovered in the traps in pond 1, the sediment that settled in the vegetation filter and pond 2 probably originated from internal processes in the wetland rather than from the catchment. In the vegetation filter and pond 2, C content varied between 7-21 % and 8-17 % (Fig. 7), respectively, substantially higher than if the sediment originated from the catchment. This high C content, in combination with the high N content, points towards a high content of organic substances in the two latter parts of the wetland. Also, the TP content in the sediments varied greatly over the year, which further indicates influence of biological processes. Hence, most of the sediment in the vegetation filter and pond 2 must have originated from internal processes and material, as plants and animals and from resuspension of sediment. Also, the C and N content in the vegetation filter and pond 2 seems to be seasonally dependent, with higher content during summer than during winter, which further points towards that biological activity has great influence on the sediment content in these two wetland parts.

The gross sedimentation of phosphorus in Skilleby wetland during April- July and July- August, respectively, exceeded the measured P inflow (Fig. 8). This can be concluded despite the absence of continuous flow measurements, as it is known that the flow during these two periods was low and with few variations. Thus, the fortnightly notations of water height were sufficient to make a reliable estimation of P transport. As opposed to the spring and summer months, only a small fraction (20 % and 10 % respectively) of the TP transported into the wetland settled and was recovered in the traps during winter (November- April) and autumn (August- November) (Fig. 8). It can thus be concluded that the wetland did not work satisfying as trap for settling P. Additionally, during the summer when flow was low, the most of the P recovered in the traps originated from the wetland P cycling. The gross sedimentation rate seemed rather stable throughout the year with little influence from the variations in TP load. Why this pattern appeared is difficult to say, but perhaps it is the amount of small particles that increase the most in the run-off during high flow. As they likely not settles during any circumstances in Skilleby wetland (Ulén, 2004), and the amount of larger particles were stable, the gross sedimentation did not increase during periods of higher flow.

The conclusion to be drawn from this part of the study is that a relatively low proportion of TP could settle in the wetland. Most of the TP in the inflow water that did settle in the wetland settled in pond 1, but in the vegetation filter and pond 2 the TP originated within the wetland. It is possible that some of the TP transported out of the wetland was biologically produced in the wetland, and it is likely that the particles that did not settle in pond 1 could not settle in pond 2 neither as the particles were too small and the settling speed too slow (Sveistrup et al., 2008).

5.3 Evaluation of sampling strategies

The investigation of how well the automatic time proportional samples represented the concentrations in grab samples showed that the results from the automatic sampling agreed with results from grab sampling in most cases. Only one of the t- tests performed resulted in a significant difference between the two sampling techniques, data from outflow water during the November sampling period (Fig. 9f). The November period had the highest flow of all sampling periods, and the flow at the outlet was substantial during almost the entire sampling period. As the grab samples had a significantly higher TP content than in automatically collected samples, it is likely that the ISCO- sampler did not collect representative samples of the water. Since turbidity was high during November due to the high flow, the underestimation was probably related to the placement of the sampling tube in the well; there was perhaps less turbidity at this location than where the grab samples were collected, even though the intention was to sample at the same location in the well. It seems that automatic sampling might be less reliable at times of high flow and high TP concentrations. This is confirmed by Fig. 9c, where it can be seen that the high TP concentration in the first grab sample at the inlet was not found in the corresponding sample from the ISCO- sampler. Also, Ulén (2003) found that manually sampled water had 4-20 % higher PP concentrations than automatically sampled water, which further confirm the results. Though the data available from this study is not enough to draw any firm conclusions, it is advocated that care be taken when using automatic samplers in very turbid waters.

The comparison of flow during the intensive sampling periods in October and November 2010 showed no obvious pattern (Fig. 10). Actually, the results were quite ambivalent with some measurements when the corrected flow corresponded best to the manually measured flow and some measurements when the not corrected flow corresponded best. During the October sampling period, the not corrected flow corresponded best over the entire period with a ratio of 1.03 (corrected flow ratio 0.94), but during the November sampling period the corrected flow corresponded best with a ratio of 0.93 (not corrected flow 0.9). There were far too little data in this study in order to draw any conclusions from this, but an investigation to determine which way a true estimation of flow is achieved is surely of interest in order to perform transport and retention calculations.

To further point out the difficulties to calculate transport and retention in such small streams and wetlands without continuous and true data, a recalculation was made of the run- off, transport and retention of TP during the intensive sampling period in November. This confirmed that changing the flow at the outlet greatly influenced the outcome of the calculations. Only through shifting the flow measured at the inlet to represent the outflow ten hours later, to better correspond to the visual flow changes, the estimated outflow doubled. Further, the transport of TP out of Skilleby wetland increased by 100 g m^{-2} yr^{-1} and the retention of TP became as low as -161 %, in comparison to the retention of -21 % with the original flow data. Thus, calculations of this kind are extremely sensitive to fault in data, not only to skewed flow data but also to water sampling conducted too seldom, as TP concentrations are often correlated with flow. If water sampling by chance occurs on a

high flow peak that last for a couple of hours, this water sample will influence the interpolated TP concentrations for two whole weeks and thus, if flow remains low the rest of the period, TP transport will be overestimated. Of course, the opposite scenario will appear if water sampling is conducted during the low flow period and sampling during the high flow period is missed out entirely. It is for instance very likely that the results of the intensive sampling period in November should have looked very different if the sampling had been initiated a couple of hours earlier and hence also covered the flow peak. As it was performed, sampling started when the flow peak almost had reached base flow again.

The accuracy in calculating annual retention of TP based on fortnightly water sampling and flow data with large internal uncertainties can thus be discussed. Many different factors influence the result and this study has pointed out several that might, if changed marginally, alter the result and the conclusions completely. If monitoring should be conducted properly at a wetland such as Skilleby wetland, it should definitely include a more close watch of changes in flow and a more frequent water sampling, especially during and after flow peaks. The correctness in continuous flow measurements should be evaluated and compared to manual measurements of flow, both during low flow and high flow periods. Further, the results from this study concludes that an investigation of the relationship between inflow and outflow during high flow periods would be highly valuable in order to enable better conditions for estimations of P transport and retention in Skilleby wetland.

5.4 Conclusions

From this study it could be concluded that:

- There was an overall negative retention of P in Skilleby wetland during the majority of the monitoring period, thus the wetland often acted as a P source rather than a P sink. Most of the released P was transported from the wetland during infrequent short periods with high flow and high flow peaks, and the released P was mainly in particulate form. It is thus likely that this P release to a large extent was caused by a combination of clay particles in the inflow that did not have time to settle in the wetland, and that the high flow promoted resuspension of previously settled sediments. Other contributing factors could be the influence of the construction work, bioturbation, channelization of the flow and the small wetland area in relation to catchment area.
- There were correlations between flow and concentration of TP and SRP during the intensive sampling period in November, with high flow, but not during the high flow period in April. This indicated that the concentration of P in inflow decreased with time when there was high flow during a longer period, as in April. There were correlations in both inflow and outflow during November, further indicating that no settling of particles occurred during the high flow period. During the low flow period in October, there were correlations for TP, TDP and SRP at the inlet but not at the outlet, indicating that settling of particles did occur. Thus, retention of P occurred during the low flow period. However, as such large part of the annual flow occur through short high flow periods in Skilleby wetland, these periods influence the annual transport of P in a much larger extent than the low flow periods when retention do occur.
- The sediment analyses showed that settling of inflow clay particles mostly occurred in pond 1, as the C and N content of the sediment was similar to that of the soil in the catchment. The sediment found in the vegetation filter and in pond 2 likely originated from internal processes, as their C, N and TP contents were substantially higher than if it would have originated from the catchment. Also, the contents varied between seasons, indicating biological processes influencing as well. Additionally, the gross

sedimentation of phosphorus during April- July and July- August, respectively, exceeded the measured P inflow, thus indicating that much of the sediments originated from internal processes. Similar amounts settled during all four periods, indicating that the same amount of particles could settle despite of the different flows.

- The results showed that, as flow and concentration of P changed rapidly in Skilleby wetland, high frequency sampling must be done at least during these high flow periods. Similarly, when automatic water sampling is used caution must be taken during high flow in turbid waters, as the results indicated that representative samples might not be collected. Fortnightly sampling was not enough to perform reliable estimations of annual P transport and retention. Also, investigation of the relationship between inflow and outflow during high flow periods should be performed for the same reasons, as the ouflow obviously differed from the measured inflow at Skilleby wetland during these periods. However, as periods with sufficient data indicated that Skilleby wetland acts as a P source during high flow periods, the results from this study based on fortnightly sampling should be considered reliable, even though the actual numbers are uncertain.

6 Acknowledgements

First of all I would like to thank my supervisors at Linköping University, Karin Tonderski and Karin Johannesson, for guidance and inspiration during all stages of this thesis, with the setup of the study, analyses of the results, feedback on the report and by providing answers to all my questions. I also would like to thank Barbro Ulén and Pia Kynkäänniemi at SLU Uppsala for valuable help, for providing me with monitoring data and for answering my questions whenever needed during this thesis. Further, I would like to thank Anna Senior and Karin Johannesson for good collaboration and company during the many hours in the laboratory. Also, I would like to thank Sepehr Shakeri Yekta at Linköping University for helping me with the Auto Analyser when analysing water samples. Finally, I would like to thank Wijnand Koker at the Biodynamic Research Institute, Skilleby farm, without whom this study would have been very difficult to perform. He has helped me during the field work, provided me with monitoring data and with valuable information about Skilleby wetland during the entire study.

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Appendix 1

The constant 47300.6, which is used to calculate the water flow (Q) in L min^{-1} from the water height at the v-notch, is calculated as:

$$Constant = \frac{8}{15} \times Cd \times \sqrt{2g} \times \tan\frac{\alpha R}{2} \times 1000 \times 60$$

where

Cd = 0.578; coefficient (approximately constant)
g = 9.81 m^2 s^{-1}; the acceleration on earth due to gravity
αR = 1.0472; the radian of the angle 60° (α)

(Swedish EPA, 2002)