Small Wetlands Designed for Phosphorus Retention in Swedish Agricultural Areas

Efficiency Variations during the First Years after Construction

Pia Kynkäänniemi
Faculty of Natural Resources and Agricultural Sciences
Department of Soil and Environment
Uppsala

Doctoral Thesis
Swedish University of Agricultural Sciences
Uppsala 2014

Acta Universitatis agriculturae Sueciae
2014:70

Cover: Bergaholm wetland constructed to trap phosphorus (P-wetland).
(photo: Pia Kynkäänniemi)

ISSN 1652-6880
ISBN (print version) 978-91-576-8088-4
ISBN (electronic version) 978-91-576-8089-1

Print: SLU Service/Repro, Uppsala 2014

Small Wetlands Designed for Phosphorus Retention in Swedish Agricultural Areas.
Efficiency Variations during the First Years after Construction

Abstract

This thesis examined retention of particles and phosphorus (P) losses from agricultural clay soils in small wetlands with an initial deep area followed by a shallow area with emergent plants. Two long, narrow wetlands (Bergaholm and Nybble) specially designed for P retention (P-wetlands) were constructed, and their efficiency in sediment accumulation were compared with those of six existing wetlands with a different design.

Monthly area-specific P retention was positively correlated with P load in the Ber P-wetland, though outflow P concentrations were occasionally higher than inflow concentrations during extreme flow events or low flow periods with ice cover. However, seasonal sediment deposition was not correlated with hydraulic load (HL), particle load or concentrations, as deposition was mostly higher than particle load in spring-summer. Annual P accumulation was positively correlated with HL (up to a possible maximum) and negatively with an index for fast flow variations (FFI).

Similar annual P retention (mean 89 kg P ha^{-1} yr^{-1}) in Bergaholm P-wetland was estimated with two independent methods. In contrast, inflow-outflow studies indicated P and particle release in the Nybble P-wetland, while results from sediment plates indicated major sediment accumulation. Measurements of water quality at a point after the deep section indicated that the discrepancy may be attributed to erosion and resuspension in that section. However, further studies are needed to confirm this, and to determine whether it was a temporary phenomenon that will disappear as the wetland bottom stabilises.

In three wetlands with different depth sections, sediment accumulation was higher in deep than in shallow areas. Annual sediment and P accumulation was generally higher in the two P-wetlands than in the other six studied wetlands, and was positively correlated with wetland length to width ratio. Overall, the results suggest that P-wetlands can efficiently retain P lost from agricultural clay soils, provided that HL is not too high or peak-based.

Keywords: Agricultural land, clay soils, constructed wetlands, phosphorus, flow-proportional sampling, retention, sediment accumulation, temporal variations.

Author's address: Pia Kynkäänniemi, SLU, Department of Soil and Environment,
P.O. Box 7014, 750 07 Uppsala, Sweden
E-mail: pia.kynkaanniemi@slu.se

Dedication

To my mother, fortsätt vara stark och kämpa!

Many small wetlands lead to clean water.
Pia Kynkäänniemi

Contents

List of Publications **7**

Abbreviations **9**
Terminology 9

1 Background **11**
1.1 Site selection for constructed wetlands 12
1.2 Wetland size and design 13
1.3 Temporal dynamics and monitoring 15

2 Aims and objectives **17**

3 Site description and study methods **19**
3.1 Location of two P-wetlands 19
3.2 Design of P-wetlands 20
3.2.1 Selection of existing wetlands for retention comparison 22
3.3 Methods to estimate P and particle retention 23
3.3.1 Water flow and water sampling 23
3.3.2 Sediment sampling 25

4 Retention of P and particles **27**
4.1 Water quality dynamics 28
4.1.1 Critical events 30
4.2 Variations in retention 31
4.3 Annual P retention 32
4.4 Particle deposition and accumulation affecting P retention 34
4.4.1 Seasonal particle deposition 34
4.4.2 Annual particle and P accumulation 35
4.4.3 Wetland design affecting P and particle accumulation 37
4.5 Sediment deposition and accumulation in different wetland areas 39

5 Comparison of methods for estimating retention **41**
5.1 Evaluation of monitoring methods 43
5.1.1 Water sampling 43
5.1.2 Sediment sampling 43

6 P-wetlands as a mitigation measure **45**

7 Conclusions 49

8 Recommendations and future research 51

9 Svensk sammanfattning 53

References 55

Acknowledgements 61

List of Publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Kynkäänniemi P., B. Ulén, G. Torstensson and K.S. Tonderski (2013). Phosphorus retention in a newly constructed wetland receiving agricultural drainage water. *Journal of Environmental Quality* 42 (2), 596-605.

II Kynkäänniemi P., K.M. Johannesson, B. Ulén and K.S. Tonderski. Quantification of phosphorus retention in Swedish constructed wetlands – comparison of two independent methods. *Submitted to Ecological Engineering*.

III Kynkäänniemi P., K.M. Johannesson, B. Ulén and K.S. Tonderski. Sediment deposition and resuspension in four Swedish constructed wetlands. *Submitted to Ambio*.

IV Johannesson K.M., P. Kynkäänniemi, B. Ulén, S.E.B. Weisner and K.S. Tonderski (In press). Phosphorus and particle retention in constructed wetlands – a catchment comparison. *Ecological Engineering*.

The contribution of Pia Kynkäänniemi to the papers included in this thesis was as follows:

I Planned the experimental work together with the second and fourth co-authors. Performed the experimental work, data analyses, data interpretation and most of the writing, with some assistance from all co-authors.

II Planned the experimental work together with the co-authors. Performed the field work and laboratory work with the second author. Performed the data analyses, data interpretation and most of the writing with some assistance from the co-authors.

III Planned the experimental work together with the co-authors. Performed the experimental work with the second author. Performed the data analyses, data interpretation and most of the writing with some assistance from the co-authors.

IV Planned the experimental work together with the co-authors. Performed part of the field work and phosphorus analyses with the first author. Performed the GIS analyses and took part in the writing.

Abbreviations

TP	Total phosphorus
DP	Dissolved phosphorus
PP	Particulate phosphorus
TSS	Total suspended solids
Q	Water flow
QP	Flow-proportional composite water sampling
L:W	Length to width ratio
$A_w:A_c$	Wetland area to catchment area ratio
HL	Hydraulic load
P-AL	Ammonium lactate-extractable phosphorus (measure of P status)

Terminology

P-wetlands	Small wetlands designed for phosphorus retention, with an initial deep area followed by a shallow area with emergent plants.
Area-specific retention	Mass of nutrient retained per unit wetland area (kg ha^{-1} yr^{-1})
Relative retention	Mass of nutrient retained divided by nutrient load (%)
Sediment deposition	Amount of particle deposition (kg ha^{-1} yr^{-1}) in cylindrical traps.
Sediment accumulation	Amount of particles and P (kg ha^{-1} yr^{-1}) accumulated on plates anchored to the wetland bottom and exposed to resuspension.
Resuspension	Amount of particles resuspended, calculated as the difference between sediment deposition and accumulation (kg ha^{-1} yr^{-1}).

1 Background

Agriculture in many areas of Sweden and other Nordic countries is currently characterised by high losses of nutrients to waters (Kronvang *et al.*, 2005; Vagstad *et al.*, 2004). Extensive drainage of lakes and wetlands over the past centuries has substantially decreased the water storage capacity in the landscape. As a consequence, natural nutrient retention caused by processes such as denitrification of nitrogen (N), sedimentation of particles and associated phosphorus (P), chemical sorption and biological uptake has declined (Hoffmann *et al.*, 2009). This combination of efficient drainage, increased nutrient leaching from soils and decreased landscape nutrient retention has increased the P and N concentrations in lakes, coastal waters and the Baltic Sea, causing eutrophication and potentially toxic algal and cyanobacterial blooms.

Countries around the Baltic Sea have adopted the Baltic Sea Action Plan (BSAP) with the aim of achieving good ecological status in the Baltic Sea by 2021. According to agreements between the Baltic countries, Sweden must decrease its annual P loads by 530 t and its annual N loads by 9240 t by 2021 (HELCOM, 2014). It has been estimated that agriculture contributes 40% of the P load to the Baltic Sea (Brandt *et al.*, 2009a) and considerable efforts have been directed towards identifying best management practices (BMPs) to decrease these losses. Since the 1990s, environmental subsidies have been available to Swedish landowners for the construction of free water surface wetlands to decrease nutrient losses beyond the field boundary, as a supplement to BMPs carried out in the field. Economic subsidies are also available for the creation and restoration of wetlands that promote biodiversity. According to a data compilation and evaluation by Brandt *et al.* (2009b), 1574 wetlands were constructed in southern Sweden from 1996 to 2006. These comprised one-third of the 12 000 ha target to be achieved by 2010 according to the national environmental quality objective '*Thriving wetlands'*. The evaluation also showed that there had been a lack of focus on optimum placement of the wetlands for effective N and P retention.

1.1 Site selection for constructed wetlands

Most of the wetlands constructed in agricultural areas of Sweden to date have been positioned and designed primarily to increase biodiversity or retain N, rather than retaining P. Therefore, it is important to identify the optimum location and design that would result in high P retention in wetlands constructed specifically to retain P in agricultural runoff. Many wetlands constructed for biodiversity are often located far from the nutrient source, resulting in low loads of nutrients. In a study involving datasets for 17 different wetlands, Braskerud *et al.* (2005) demonstrated that the P load to the wetlands was positively correlated with the area-specific P retention. Studies have shown that 80-90% of the P losses from arable land occur during 10-20% of the year and from 1% of the arable land area (Kleinman *et al.*, 2011; Pionke *et al.*, 2000). It is likely that P retention in wetlands would be more effective if the wetlands were placed in connection with these so-called hot-spot areas. Thus, constructed wetlands should perhaps be located close to the source of P losses. To investigate this question, it is important to identify hot-spot areas and areas where the P losses are known to be high. Wetlands located in catchments with a large proportion of agricultural fields would probably have higher area-specific P removal because the load would be higher. Identifying hot-spots involves studying soil survey results to find fields with high P concentrations in the soil and fields that are susceptible to erosion and losses of particulate P (PP). Soils with a high P content are often located close to animal houses and have received manure over a long period (Figure 1). Pastures with high animal density also tend to have a high risk of P losses.

Depending on the soil type in the specific agricultural area, the main problems with leaching may concern either N or P. High N losses generally occur from sandy or loamy soils (Gustafson, 2012), while in the Baltic area high P losses generally occur from soils sensitive to erosion, clay soils with low friction and silty soils with additional low cohesive forces (Lundekvam & Skoien, 1998). There are clay soils in the area around Lake Mälaren in east-central Sweden that generally have high P losses (Ulén *et al.*, 2007). The P is commonly leached through subsurface drain outflow and surface runoff losses, as both PP and dissolved P (DP). In clay soils with cracks, P can be transported extremely rapidly through macropores to the drains (Jarvis, 2007). Consequently, depending on the soil type in the area, the target nutrient to be retained by a constructed wetland should differ. Most wetlands have been

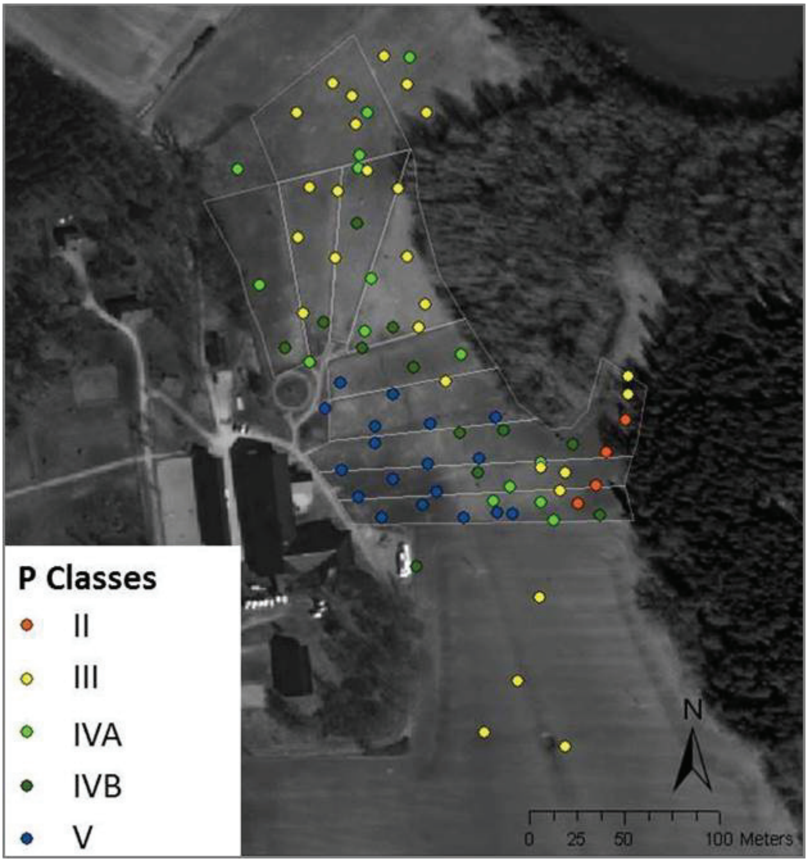

Figure 1. Phosphorus classes in the soil based on P extracted in ammonium lactate (P-AL), demonstrating higher P status (blue) closest to the animal houses than on parts of the paddocks and the arable field further away.

constructed in the south and south-west of Sweden with the aim of retaining N (Brandt *et al.*, 2009b). The nutrient removal efficiency has been evaluated for only few of those wetlands, and there are almost no studies of wetlands in regions with high P losses in east-central Sweden. Hence, important research questions are whether constructed wetlands can retain P lost from those agricultural clay soils; and what the relationship is between retention and P loads under such geohydrological conditions.

1.2 Wetland size and design

One large challenge when dimensioning wetlands treating agricultural runoff is the large variation in hydraulic load (HL) during the year. In agricultural areas, most of the P is lost during periods with high flow, such as snowmelt and autumn rain, when soil particles and associated P are eroded and transported to waters. The higher and more intensive the water discharge, the more particles can be transported. It can be assumed that during high flow periods, a larger wetland area would be needed to allow most of the particles from upstream fields to settle compared with during low flow periods. In practice, it is often difficult to find a landowner willing to give up a large area of productive land to create a wetland occupying *e.g.* 1-2% of the catchment area (A_w:A_c), as recommended for satisfactory *relative* particle retention by Koskiaho (2003) and Puustinen *et al.* (2001). However, it may be possible to construct smaller wetlands that are effective P traps even when receiving high HL with large flow variations. Several studies have shown that in wetlands occupying only 0.03-0.38% of the catchment area (*i.e.* high HL), the *area-specific* P retention is high, 270-600 kg ha^{-1} yr^{-1} (Maynard *et al.*, 2009; Braskerud *et al.*, 2005). Those studies also demonstrated that the area-specific retention increased following increases in area-specific load. However, the relationship was not linear and higher P concentrations in the outflow were observed when HL was high. Since the target is usually to reduce both the total P transport and the outflow P concentration, it is a delicate task to adapt a wetland to a highly variable HL.

The nutrient retention processes for P and N differ, and therefore different wetland designs are required. In Sweden, the focus so far has been to remove N (mostly lost as nitrate from agricultural areas), as it was previously considered the main problem in eutrophication of seas. Constructed wetlands designed for N removal are generally shallow ponds with varying amounts of vegetation (submerged or emergent) to promote denitrification, which is the main removal process for N (Kadlec, 1994). Since P losses also contribute strongly to eutrophication, the focus has recently shifted to P retention in constructed wetlands. Phosphorus is retained by different processes than N, and hence the best location (which also affects the HL) and design of a wetland intended for P removal may differ from those of a wetland designed for effective N removal. In erosion-prone agricultural regions in the Nordic countries, most of the P lost is usually bound to soil particles (PP), with a smaller proportion as DP (Ulén, 2004; Koskiaho, 2003; Uusitalo *et al.*, 2000). Therefore, in those areas the main retention process for P in a wetland would be sedimentation (Braskerud, 2002), but some DP can also be retained by chemical sorption and biological uptake by plants and algae (Reddy *et al.*, 1999). However, plant uptake is only temporary, as most of the P is released to the water during litter decay and only a minor proportion is retained as organic P in the sediment. Furthermore, settled particles and P can be resuspended during hydrological events and P sorbed to sediment can be released if the chemical conditions change due to *e.g.* stagnant water and aerobic conditions (Hoffmann *et al.*, 2009). The location (affecting HL) and design of the wetland are important for the water residence time and for the extent to which the water is spread over the wetland area (hydraulic efficiency). Long, narrow wetlands have higher hydraulic efficiency than circular wetlands, resulting in a longer water retention time (Wörman & Kronnäs, 2005). The problem is to locate and design a small wetland to maximise the retention of inflowing P, while at the same time minimising subsequent resuspension and release of the retained P when flow variations are large.

In regions with sloping topography and high precipitation, resulting in soil erosion, mitigation measures need to focus on reducing particle transport with its associated P. Braskerud (2001b) studied small wetlands (0.03-0.38% of catchment area) installed in agricultural ditches with the aim of slowing down the water velocity and promoting settling. The particle settling (area-specific retention) was found to be high and was attributed to wetland design, which comprised an initial sedimentation basin followed by a shallow vegetation filter. The high P retention in those small wetlands was probably due to the design, in combination with their location in ditches with high transport of particles from the silty soils in the catchment. A subsequent study confirmed that the clay particles eroded as aggregates and also settled as aggregates of the same size as silt particles (Sveistrup *et al.*, 2008). Thus they settled more rapidly than expected, which resulted in higher particle retention at higher hydraulic loads, when the particle loads were also higher. To fulfil the P goals in the BSAP, and in view of the good experiences with constructed wetlands reported by Braskerud (2002), the Swedish Board of Agriculture decided to encourage the construction of such small particle and P trapping wetlands (P-wetlands) in Sweden. Since 2010, these P-wetlands qualify for environmental subsidies. As site-specific factors affect the P retention, the findings reported by Braskerud (2002) may not be applicable in other areas. Retention rates may differ in similar wetlands receiving fine particles transported through the clay soil profile and further via tile drain systems. This was the subject of the research presented in this thesis.

1.3 Temporal dynamics and monitoring

Phosphorus removal efficiency in wetlands receiving non-point source runoff varies considerably, with large variations between wetlands and between years. This is due not only to wetland design and location, but also to annual variations in water flow and P loads (Maynard *et al.*, 2009; Braskerud *et al.*, 2005; Tonderski *et al.*, 2005; Koskiaho *et al.*, 2003). Since P loads are episodic and several processes may be involved in retention, it is important to monitor the temporal pattern during the year.

Both the water flow and the P concentration can change rapidly in agricultural areas. Therefore, accurate estimates of P retention based on mass inflow and outflow require careful measurements of the water flow in both inflow and outflow, and frequent flow-proportional collection of water samples with automatic equipment. However, a large part of the annual transport may occur during periods of snow and minus degrees, when the risk of equipment failure is higher than during other times of the year, potentially resulting in erroneous estimates of annual retention.

As the transformation of P to gaseous form is minimal, all P retained in wetlands can be expected to be found in the sediment. Therefore, an alternative method to estimate annual net P retention could be to measure sediment depth and sample from a reference base (Nolte *et al.*, 2013), *e.g.* an artificial grass mat (Ockenden *et al.*, 2012; Asselman & Middelkoop, 1995) or a plastic-coated plywood plate (Braskerud *et al.*, 2000). The latter approach was used in this thesis to estimate accumulation of particles and associated P on sedimentation plates, as supplement to inflow-outflow measurements.

2 Aims and objectives

The overall aim of this thesis work was to investigate whether small wetlands (relative to catchment area) specifically designed for P retention (P-wetlands) can efficiently retain soil particles and P when constructed in agricultural catchments with clay soils where the main P losses occur through sub-drains.

Specific objectives were to:

I Evaluate the relationship between particle and P retention and water flow and inflow concentration dynamics in two P-wetlands (Papers I & III)

II Critically assess the advantages and disadvantages of estimating particle and particulate P retention with two different, independent methods: i) inflow-outflow balance based on water flow and quality measurements, and ii) measurements and analyses of annually accumulated sediment (Paper II)

III Evaluate P and particle retention in different wetland areas (Papers II & III)

IV Evaluate whether the P retention is higher in P-wetlands than in other wetlands (Paper IV).

Specific research questions addressed were:

- Is particle and P retention related to hydraulic load and inflow concentrations?
- Is particle and P retention related to wetland depth?
- Is particle and P retention related to wetland size and shape?

3 Site description and study methods

3.1 Location of two P-wetlands

Two small P-wetlands were constructed on erosion-prone clay soils in east-central Sweden in locations where the runoff water was known to have high turbidity. A major site selection criterion was that the constructed wetland would occupy 0.3% of the catchment area, in order to obtain a lower HL than for wetlands in regions with generally coarser soil as studied by Braskerud (2002) and Maynard *et al.* (2009). This was deemed necessary to promote high area-specific retention in the study region, where a large proportion of P is transported in drains as very fine or colloidal particles that may be difficult to settle (Ulén, 2004). Another criterion was favourable topography, to facilitate the construction of V-notches for continuous water flow measurements. A final criterion was to find an interested landowner who would help with wetland maintenance.

The first small P-wetland (Bergaholm) was constructed to reduce the P load to Lake Bornsjön. The whole catchment area of Lake Bornsjön, which serves as the reserve drinking water reservoir for Stockholm city, is managed by Stockholm Water Ltd. This company has monitored the P concentrations in streams and culverts to the lake for 30 years. The selected sub-catchment (26 ha) has clay soil (27% clay content) and high P concentrations (mean 0.5 mg L^{-1}) in drainage water running in a small culvert (Parvage *et al.*, 2011). It comprise an 11 ha cultivated field, 3 ha horse paddocks and 12 ha forest (Figure 2). The mean slope of the arable land is 3.6%. The mean animal density in the paddocks is high, 3.8 animal units ha^{-1} and soil P status is higher in the horse paddocks than in the arable field (Figure 1), mean 147 and 86 mg P-AL kg $soil^{-1}$, respectively (Parvage *et al.*, 2011).

Figure 2. The catchment areas of the Bergaholm and Nybble P-wetlands in east-central Sweden.

The second P-wetland (Nybble) was constructed to reduce the P load to the river Kilaån, which discharges into the Baltic Sea. The 44 ha catchment area consists of about 50% arable land, cultivated with cereal crops and ley (Figure 2). The clay content is 22% and the mean slope of the erosive arable land is 4.7%. The arable land is sub-drained with tile drains discharging into a small open stream. There were no animals in the catchment at the time of the study and the soil P status was moderate (mean 75 mg P-AL kg^{-1}).

3.2 Design of P-wetlands

The size recommendation given by the Swedish Board of Agriculture for a wetland to be eligible for the environmental subsidy for P-wetlands is 0.1-0.5% of catchment area. The actual size of the Bergaholm P-wetland is 0.31% of catchment area, while the area of the Nybble wetland had to be lowered to 0.23% to prevent uncontrolled inflow, as a zone with artesian groundwater appeared when constructing the outlet.

The Bergaholm and Nybble P-wetlands were both constructed with a 1 m deep sedimentation basin at the inlet, followed by a shallow (0.3-0.4 m) area planted with emergent macrophytes (Figures 3 & 4). Greater pond sedge (*Carex riparia* C.), yellow iris (*Iris pseudacorus* L.) and branched bur-reed (*Sparganium erectum* L.), locally growing in nearby lakes, were planted to speed up the establishment and to influence the plant community composition. Highly productive plants such as cattail (*Typha* sp.) and reed (*Phragmites* sp.), and tuft-forming plants were avoided, but by the end of the study period *Typha* sp. had colonised both wetlands, along with various species of submerged plants.

Figure 3. The Bergaholm P-wetland, constructed beside a drainage culvert, with an initial deep section (left) followed by a shallow area planted with emergent macrophytes (right). Photo: Pia Kynkäänniemi taken September 2013 and June 2014.

The Bergaholm and Nybble P-wetlands were designed to fit the surrounding terrain and are long, narrow, with a length to width ratio (L:W) of 14 and 11, respectively, in order to promote good hydraulic efficiency. The intention with the narrow shape in combination with a deep inlet pond was to ease maintenance and to facilitate future removal of the P-containing sediment. To reduce the risk of initial erosion of the bare wetland shores, they were covered with coarse-meshed coconut fibre netting.

The Bergaholm P-wetland was constructed in August 2009, by digging beside the drainage pipe (Figure 5). A part of the drainage pipe was cut open and all the water was diverted into the U-shaped wetland, which had been planted immediately after the excavation was completed.

Figure 4. The Nybble P-wetland, constructed in a drainage ditch, with an initial deep section (left) followed by a shallow area with emergent plant species (right). A heap of particles settled at the beginning of the deep pond (left corner of the left-hand photo). Photo: Pia Kynkäänniemi taken May 2013 and August 2014.

Figure 5. Construction of the P-wetlands Bergaholm in August 2009 (left) and Nybble in November 2010 (right). Photo: Pia Kynkäänniemi.

The outflow from the wetland flows back into the drainage pipe and further into the lake.

The Nybble P-wetland was constructed by widening a ditch while the water was still running (Figure 5). Work started in October 2010, but was stopped by early onset of winter. Subsequent snowmelt and a heavy summer rain event caused major erosion that destroyed the outlet, which needed to be reconstructed and the wetland bottom levelled in September 2011. The wetland was planted in June 2011.

3.2.1 Selection of existing wetlands for retention comparison

Six small constructed wetlands of varying age (1-13 years) located in southern Sweden (Figure 6) were selected for comparison of P and particle retention with that in the two new P-wetlands (Paper IV). The selection was based on the criteria: i) expected high P loads (preferably predominantly clay soils and a large proportion of arable land in the catchment); ii) preferably A_w:A_c <0.5%; and iii) an interested landowner. One of these, the Wiggeby wetland, was constructed in spring 2009, also as a long, narrow 1 m deep pond intended to retain particle bound P. It was the smallest wetland studied, with an area representing only 0.04% of the catchment (Table 1). Sparse patches of cattail and sedge colonised spontaneously in the years after construction. The Skilleby wetland was constructed in 2002 to reduce nutrient leaching, but is wide and short, with A_w:A_c 0.36%. It consists of two deep ponds densely colonised by submerged broad-leaved pondweed (*Potamogeton natans* L.). The shallow area between the ponds and also the shores are dominated by dense stands of cattail. The shallow middle area dried out during the studied summers. The Lindevad and Ekströmmen wetlands are also wide and short, and both wetlands were constructed with islands to provide shelter and refuge for waterfowl, as the main aim of the wetlands was to attract birds. In the Lindevad wetland there are two inlets, one of which received sewage water from a single household.

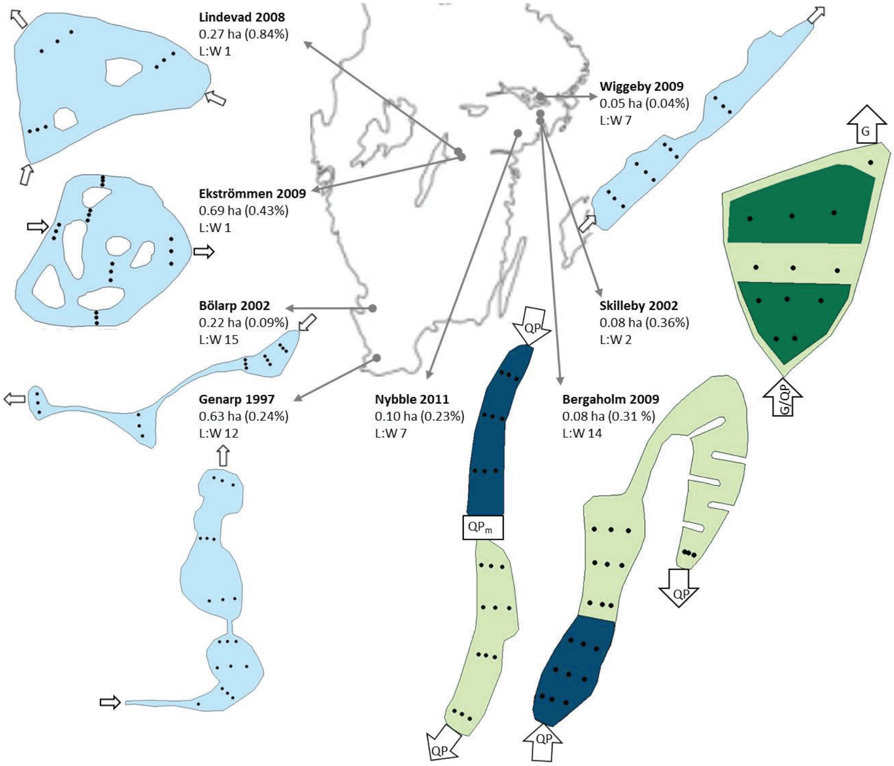

Figure 6. Wetland location and design. Year of construction, wetland area (ha), relative size of the catchment area (A_w:A_c) and wetland length to width ratio (L:W). Circles illustrates sediment sampling points, arrows inlet and outlet, QP flow-proportional and G manual grab sampling of water. Dark blue and green mean depth >1 m and light green <0.5 m. Figures are not to scale.

It was the largest wetland relative to catchment area (0.84%) of those selected for the study (Figure 6) and emergent and submerged plants had colonised in patches (Table 1 in Paper IV). The Ekströmmen wetland was the second largest (0.43%) and at the time of the study there was no vegetation in the wetland. The Bölarp wetland was the second smallest (0.09%), while the Genarp wetland was intermediate (0.24%). Both the Bölarp and Genarp wetlands are long and narrow, and are primarily constructed for N retention. However, Bölarp has a more dense plant cover.

3.3 Methods to estimate P and particle retention

3.3.1 Water flow and water sampling

In order to study the temporal dynamics of water flow, P concentration and retention in the newly constructed Bergaholm and Nybble P-wetlands (Papers I

& III), water flow was measured continuously and flow-proportional composite water samples (QP) were collected every fortnight at the wetland inlet and outlet (Figure 6). The composite sample contained several subsamples, each approximately 20 mL, taken with an autosampler after 20 000 L of water had passed through the wetland. In the Nybble wetland, additional flow-proportional samples were collected between the deep and the shallow sections, so there were three points with flow-proportional water sampling. To further investigate the relationship between retention and water flow and quality changes during critical snowmelt events, high-frequency time-proportional composite samples were collected in the Bergaholm wetland during snowmelt 2010 in addition to the fortnightly flow-proportional sampling (Paper I).

For the short periods when there were technical problems with the water measurements in the Bergaholm wetland, manual adjustments were made using data on the water flow pattern measured in a nearby small observation field, comprising approximately 18% of the Bergaholm wetland catchment area (Paper I). In some winter periods, ice lifted the trunk for water displacement and caused overestimation of the water flow in the Nybble wetland. Therefore, the recorded extreme peaks were lowered to the daily maximum runoff in the larger river basin where the Nybble wetland is located, using runoff data from the Swedish Meteorological and Hydrological Institute (Paper II).

There was a need for maintenance, by regularly shovelling away accumulated sediment from the inlet well in the Bergaholm wetland and in front of the pipe connecting the ditch in Nybble with the well in which water level measurements were made, as this would otherwise have disturbed the water flow measurements.

Water flow measurements were also performed and water samples taken in the Skilleby wetland, to determine the water quality changes (Paper III). In the Skilleby wetland, water flow was only measured at the inlet and the pressure transducer malfunctioned in the first year of the study period. Therefore, the flow from the Bergaholm wetland was used for area-proportional flow estimation in the first year (Paper II). The pressure transducer at Skilleby was placed in an open ditch with no insulation during winter and therefore extreme peaks during winter were recorded. Therefore as was done for Nybble wetland, extreme peaks in the Skilleby wetland were lowered to the maximum daily runoff in the larger river basin (Paper II). In the Skilleby wetland, flow-proportional samples were only taken at the inlet, in years two and three of the study, as the water flow equipment malfunctioned in the first year of observations. During that year, manual grab samples (G) were taken at both the inlet and outlet. The outlet was sampled manually during the whole period (Figure 6).

The composite flow-proportional samples were stored in a refrigerator below 8˚C in a sampling hut at Bergaholm and in the sampling well below ground at Nybble. They were collected and sent to the laboratory every week or every two weeks. Total P (TP), DP and total suspended solids (TSS) were analysed according to European Committee for Standardisation methods (ECS, 1996) in a SWEDAC-accredited laboratory, using membrane filters with 0.2 µm pore size for measurements of TSS and for filtering before DP analysis. The difference between TP in non-filtered and TP in filtered water was considered to be particulate P (PP). By subtracting DP and PP from TP, the proportion of other P (OP) was estimated. Particle and P transport (kg) in and out of the wetlands was calculated by multiplying the accumulated water flow for each sampling period (m^3) by the concentration (mg L^{-1}). Linear interpolation was made between concentrations from manual grab samples (Paper II). Area-specific retention (kg ha^{-1} wetland area) was estimated by subtracting transport out of the wetland from the load entering the wetland and dividing by the surface area of the wetland. Relative retention (%) was calculated by dividing the retention by the load.

The retention estimates based on water flow and water quality data in the three wetlands were compared with an independent monitoring method, *i.e.* sampling sediment accumulation on plates (Paper II) and also related to estimates of seasonal sediment deposition (Paper III).

3.3.2 Sediment sampling

In Paper IV, sediment and P accumulation were estimated for Bergaholm and Nybble, and the six other wetlands (Papers II & III). Sediment plates (plastic-covered plywood 40 cm x 40 cm or 25 cm x 25 cm) were anchored to the bottom in 3-7 transects located along the flow path from inlet to outlet (Figure 6). The plates were set level with the sediment surface and thereby exposed to any processes causing resuspension, and the accumulated amount of sediment was assumed to represent net annual particle retention. In addition, sediment deposition in different parts of the wetlands and in different seasons was studied. That study included the Bergaholm, Nybble, Skilleby and Wiggeby wetlands and examined how differences between wetlands in terms of design and hydrological variations affected sediment deposition and resuspension, which determine the overall particle retention. For the purpose of the study, sediment traps (plastic cylinders 11 cm high and 7.5 cm diameter) were placed adjacent to the plates at the bottom of the wetlands to measure

Figure 7. Annual sediment accumulation on plates. Mineral sediment in the Bergaholm wetland (left), larger particles in the first transect in the Nybble wetland (middle) and poor accumulation of mainly organic sediment in the Wiggeby wetland (right).

sediment deposition in a similar way to that described by Braskerud *et al.* (2000). The traps were dug down into the wetland sediment, with the edge approximately 2 cm above the sediment surface, acting as a collector for suspended solids by lowering water turbulence inside the cylinders (Figure 2 in Paper III). The intention was that the walls would prevent the captured sediment in the bottom of the traps from being resuspended and transported away. The plates were left in the wetlands for one year and lifted up in the summer each year (Figure 7). At that time the sediment depth was measured and a sediment sample collected from a defined area in the most undisturbed part of each plate. Traps were sampled (all material) three times a year, representing the autumn, winter (including the snowmelt period) and spring-summer seasons. The dry weight (DW kg m^{-2}) of each sediment sample was determined. In the samples from the plates, the TP content was analysed according to Andersen (1976) and as recommended by Svendsen *et al.* (1993), with the exception that the samples were digested in an autoclave (120°C and 200 kPa) instead of being boiled on a hot plate (Papers II and IV).

Particle deposition and accumulation and P accumulation (kg m^{-2}) were estimated by interpolating between the amount at each sampling point over the whole wetland surface area using the local deterministic interpolation method Inverse Distance Weighted (IDW) in ArcGIS 10.1 (Papers II-IV). Annual area-specific resuspension (kg m^{-2} yr^{-1}) was calculated as the difference between sediment deposition and accumulation. Relative resuspension (%) was calculated by dividing annual resuspension by annual sediment deposition.

4 Retention of P and particles

The Bergaholm and Nybble P-wetlands were located in the same climate zone, 95 km apart. Precipitation, temperature and snow cover for sites near the Bergaholm wetland were obtained from the meteorological climate station Södertälje and snow cover data from Norsborg (Figure 8). The first winter was cold, with snow cover up to 0.5 m deep, which caused extremely intense snowmelt in March 2010 (Figure 8). The second winter was also cold and with much snow, but the snowmelt occurred in stages, with a short event in January and the main event in March and April 2011. The third winter was mild, with snow for a shorter period and snowmelt from January to April. Autumn 2012 was rainy and December 2012 cold, with snowmelt in the end of the month and in January 2013. The final snowmelt in the fourth winter was in April 2013, after two months with up to 0.2 m deep snow. Generally, the HL was higher for the Nybble wetland than for Bergaholm (Table 1). In the Bergaholm wetland, the water retention time varied from a few hours during snowmelt up to 1000 days during the extremely low flow in summer, with a median of 7 days (Paper I).

The Bergaholm P-wetland is located just 30 m from the shores of Lake Bornsjön. The water inflow was always higher than the outflow and the pattern of pressure levels in piezometers indicated that some water from the wetland infiltrated into the groundwater all year round (Paper I). In contrast, the area immediately downstream of the Nybble wetland outlet was constantly wet, indicating groundwater discharge close to the outlet. This resulted in higher outflow than inflow during some periods (Figure 2 in Paper II), but not overall.

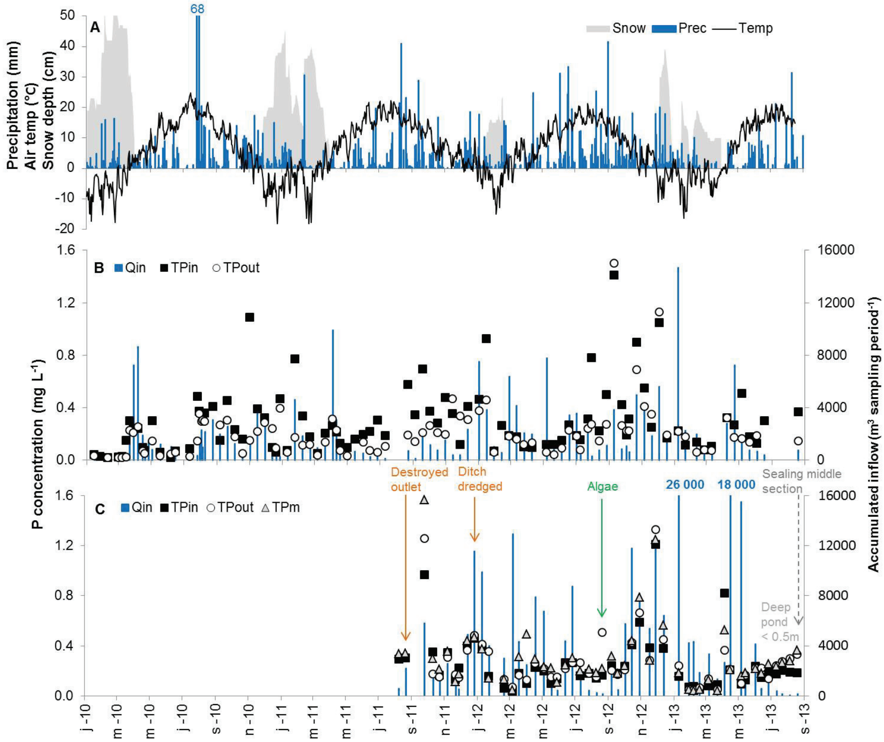

Figure 8. A) Daily precipitation (mm), air temperature (°C) and snow cover (cm) at the meteorological stations near Bergaholm. Accumulated inflow for each period (m^3), total P (TP) inflow (in) and outflow (out) concentrations (mg L^{-1}) in B) the Bergaholm P-wetland and C) the Nybble P-wetland, and in the middle section between the deep and the shallow area (m) in Nybble.

4.1 Water quality dynamics

The mean inflow concentrations to the Bergaholm and Nybble wetlands was approximately 0.3 mg TP L^{-1} and 0.1 mg DP L^{-1}, respectively, showing that around two-thirds of the P was bound to particles. This was confirmed by the high suspended solids concentrations (Table 1 in Paper II). However, this varied considerably throughout the year. In the Bergaholm wetland, DP inflow concentrations exceeded 50% of TP frequently during snowmelt and until autumn, while in Nybble a similar DP to TP distribution was only observed every August and September. The higher DP concentrations that occurred more regularly in the Bergaholm wetland were probably due to the high P-AL concentration in the catchment topsoil and a high degree of P saturation caused by long-term manure loading to the soil (Parvage *et al.*, 2011).

The TP concentrations were low during the high snowmelt flow in January and April 2013, while they were higher in the beginning of snowmelt (Figure 8). In addition, it is known that snowmelt runoff from clay soils is characterised by a high proportion of DP (Ulén, 2003; Turtola, 1999). Total P inflow concentrations were also high, above 1 mg L^{-1}, in November-December 2012 in both wetlands and the high flow caused high outflow concentrations. Outflow TP concentrations were occasionally higher than those in inflow, *e.g.* in high flow events in autumn and snowmelt, in summer after intensive rain events flushing out algae and during periods of ice cover in winter (Figure 3 in Paper I). Release of DP from sediments has been reported in other studies with algae mats in late summer (Palmer-Felgate *et al.*, 2011) and during periods of ice cover and anoxic conditions causing a release of iron-bound P in a wetland receiving agricultural runoff with high concentrations of P (Johannesson *et al.*, 2011). General summer outflow concentrations were below 0.05 mg L^{-1}, which resulted in low transport of bioavailable P to Lake Bornsjön during the period that is most critical for lake water quality. This was a favourable effect of the Bergaholm P-wetland.

In Bergaholm wetland, the mean outflow TP and DP concentrations were lower than the inflow concentrations, while no difference was observed in Nybble. On the other hand, in the Nybble wetland the concentrations of TP and particles were higher at the middle sampling point (between the deep and shallow sections) than in the inflow, but also than in the outflow. A 150-m road ditch was dredged in late December 2011, causing high transport of particles which settled at the inlet of the Nybble wetland (Figure 4; Figure 5 in Paper III). At a rough estimate, the amount of soil that settled in the heap was approximately 2 t (Paper III). The dredging occurred in the end of a two-week sampling period, but surprisingly enough no extreme increase in the inflow concentrations of TP and TSS was observed. Large particles (sand) were visually observed in the heap and in the first sediment sampling transect (Figure 4 & 7). These large particles were probably excluded from the thin suction tube for water sampling (4 mm in diameter), though they may have actually caused a high TSS inflow concentration. The larger particles were only found in the first sediment sampling transect and were probably not resuspended. On the other hand, the heap of particles probably acted as a source of finer particles within the wetland in subsequent years, which may have contributed to the higher TP and TSS concentrations at the middle sampling point after periods of high flow (Figure 8). There was never any accumulation of particles in the bottom of this sampling well, suggesting that any eroded/resuspended particles were so small that they did not settle even during low flow periods. In contrast, particles settled in the inlet sampling well in the Bergaholm wetland, and had to be regularly removed. The Nybble wetland was constructed by widening a ditch while the water was still running (Figure 5), which may have contributed to subsequent erosion from the wetland bottom and sections between the different wetland levels. Furthermore, it was found that the pipe conducting the water from the deep section to the sampling well in the middle was installed with the inlet lower than planned, and close to the wetland bottom. The water velocity increases close to a pipe inlet and, if placed close to the sediment surface, particles can be eroded in this section, which most likely also contributed to the higher concentrations at the middle sampling point in the Nybble wetland. In August 2013, an attempt was made to decrease this erosion at the pipe, and the sediment was shovelled away by hand, with the intention of increasing the distance to the bottom. In addition, a rubber cloth was attached to the wetland bottom. However, this was in the end of this study period and thereby no effect of this could be seen here. The internal erosion was larger than expected, indicating that timing of the excavation and ensuring that the construction is carried out properly are very important. Luckily the wetland captured the large particles that eroded from the dredged ditch, but the heap of particles should have been removed to avoid further resuspension and P transport downstream.

4.1.1 Critical events

High-frequency time-proportional sampling during snowmelt 2010 in the Bergaholm P-wetland revealed diurnal variations in concentrations (Figure 4 in Paper I), and also showed that P retention was correlated with inflow, air temperature and the P concentration during snowmelt. This indicated that the Bergaholm wetland was able to function as a P trap even during periods with simultaneous high flow and high P concentrations. However, there seemed to be a water flow threshold ($Q>130\ m^3\ h^{-1}$) above which the Bergaholm wetland did not function as a sink for P and particles. An extreme episode with a flow peak of 4428 $m^3\ h^{-1}$ was reported for one of the wetlands in the study by Braskerud (2001a), which generally received a 10-fold higher HL than the Bergaholm wetland. Flush-out of particles occurred at a higher water velocity in that wetland, which could be explained by the larger particles in the inflow settling at the same rate as silt particles (Sveistrup *et al.*, 2008).

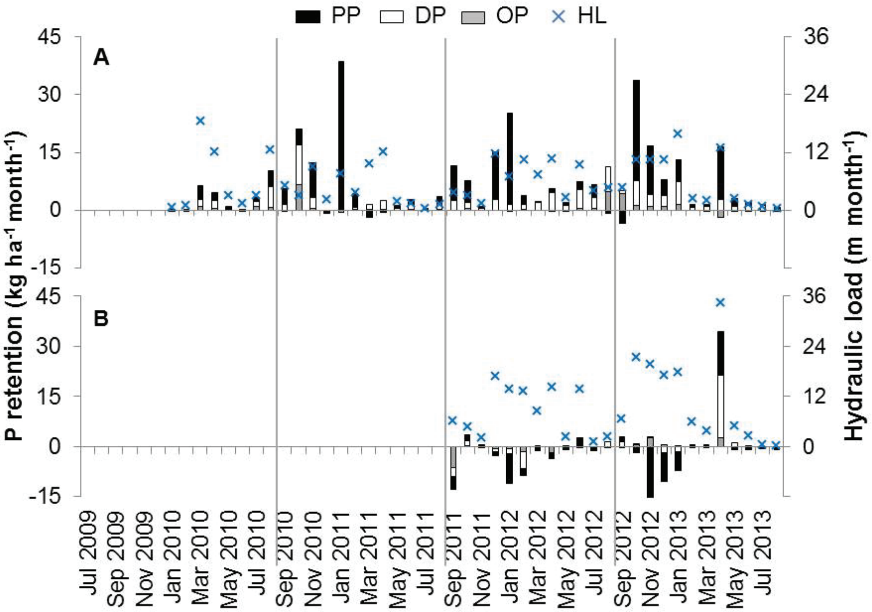

Figure 9. Monthly area-specific P retention (kg ha^{-1} month^{-1}) in A) the Bergaholm and B) the Nybble P-wetlands. Crosses indicate hydraulic load (HL) and bars indicate particulate P (PP), dissolved P (DP) and other P (OP).

4.2 Variations in retention

The higher outflow than inflow concentrations, in combination with the occasional contribution of groundwater close to the Nybble outlet, resulted in higher transport out of the wetland and estimated release of P and particles during most of the first two years after wetland construction in 2011 (Figure 9). The mean annual release was -10 kg P ha^{-1} yr^{-1} and -18 t TSS ha^{-1} yr^{-1}. Due to the higher concentrations at the middle sampling point, the retention was also calculated specifically for that second section of the wetland, *i.e.* the shallow area with emergent plants. This section was estimated to retain 66 kg TP ha^{-1} yr^{-1} and 43 t TSS ha^{-1} yr^{-1}, which corresponded to relative retention of 8 and 24 %, respectively, of the load at the middle sampling point.

The Bergaholm P-wetland acted as a net P and TSS sink on an annual basis, retaining on average for the first 3.5 years 89 kg TP ha^{-1} yr^{-1} and 37 t TSS ha^{-1} yr^{-1}. This corresponded to 36% of the load (Table 1 in Paper II). The P was mainly retained as PP rather than DP (22 and 11% of TP, respectively), which agreed with observations from other wetlands (Braskerud *et al.*, 2005), although conflicting results have been reported. For example, Tanner and Sukias (2011) reported poor P removal in three wetlands where DP was the dominant P form in the inflow and found in fact the wetlands acted as net sources of P on an annual basis during establishment.

In the Bergaholm wetland, the highest monthly retention of TP was 38 kg ha^{-1} in January 2011 (Figure 9), when there was a short snowmelt event which resulted in a high load of PP. In contrast, during the major snowmelt in March the same year, both the P load and the retention were lower, even though the hydraulic load was higher. The reason was that the PP fraction in the inflow was lower than in January. As expected, some of the variation in monthly TP retention was explained by the load variations (Figure 6 in Paper I). This correlation between area-specific P load and retention generally applies to nutrient removal observed in other treatment wetlands (Braskerud *et al.*, 2005; Kadlec, 2005). The monthly TP retention was commonly higher during autumn than in summer (Paper I), confirming that the seasonality in P load is an important factor for P retention in wetlands (Richardson, 1985). High flow events during spring and autumn are important for P retention, as the loss of P and particles from arable fields is usually highest at those times.

4.3 Annual P retention

A previous analysis of P retention using inflow-outflow balance data from 17 wetlands in the cold temperate climate of Scandinavia, Switzerland and Illinois showed that site-specific factors affected P retention (Braskerud *et al.*, 2005). There was a large variation in retention efficiency, with annual average P removal varying between 1 and 88%. The most important factors for P retention were wetland size, age and catchment area characteristics. In the present thesis, the mean annual P retention in the Bergaholm and Nybble P-wetlands was compared with that in these wetlands and some additional wetlands from Sweden (Table 1). The retention estimate for the Nybble wetland is difficult to compare and therefore both the estimated release for the total wetland area and the retention for the last shallow area are shown, in order to demonstrate the effect of internal erosion/resuspension.

The measured P retention of 89 kg ha^{-1} yr^{-1} in the Bergaholm P-wetland was lower than that in the seven wetlands in Norway on silty soils, but higher than that in the other wetlands located in cold temperate climates with different design and soil type. The P-wetlands studied by Braskerud (2002) had up to 10-fold higher P load, due to higher HL, and large particles in the inflow settled fast (Sveistrup *et al.*, 2008). However, the P loads to the Bergaholm and Nybble P-wetlands (250 and 390 kg P ha^{-1} wetland area yr^{-1}) were higher than those reported for many other wetlands constructed in agricultural areas

Table 1. *Wetland area, relative size to catchment (A_w:A_c), hydraulic load (HL), total P inflow concentration (TP_{in}) and retention in the Swedish (Swe), Finnish (Fin), Norwegian (Nor), Swiss (SWZ) and U.S. wetlands compared. Sorted by area-specific P retention.*

Wetland	Area (m^2)	A_w:A_c (%)	HL (m yr^{-1})	TP_{in} (mg L^{-1})	TP retention (kg ha^{-1} yr^{-1})	(%)	Reference
Nor: Leirvollbekk	2000	1.00	124	1.53	1562	83	(Braskerud et al., 2005)
Nor: Kinn	350	0.07	683	0.35	578	29	(Braskerud *et al.*, 2005)
Nor: Berg	900	0.06	620	0.18	513	43	(Braskerud *et al.*, 2005)
Nor: Grautholen	840	0.38	285	0.39	462	42	(Braskerud *et al.*, 2005)
Nor: Flatabekken	890	0.09	648	0.22	373	27	(Braskerud *et al.*, 2005)
Nor: Skuterud	2300	0.05	917	0.19	272	16	(Braskerud *et al.*, 2005)
Nor: Lier	1200	0.15	241	0.60	269	20	(Blankenberg *et al.*, 2013)
Swe: Lilla Böslid	4100	0.06	416	0.20	200	24	(Weisner *et al.*, unpublished)
Swe: Bergaholm	800	0.31	70	0.29	89	36	(Paper II)
Swe: Bölarp	2200	0.05	270	0.07	73	38	(Weisner *et al.*, unpublished)
Swe: Nybble	1010	0.23	119	0.26	-17/66[a]	-4/8[a]	(Paper II)
U.S.: ORWRP 1	10000	n.d.	54	0.17	56	62	(Nairn & Mitsch, 2000)
U.S.: ORWRP 2	10000	n.d.	54	0.16	52	58	(Nairn & Mitsch, 2000)
Swe: Slogstorp	6500	0.10	597	0.07	47	12	(Wedding, 2004)
Swe: Västerby	400	0.01	4190	0.07	39	1	(Uusi-Kämppä *et al.*, 2000)
Swe: Genarp	10000	0.30	80	0.12	27	28	(Wedding, 2004)
Swe: Edenberga	2200	0.23	57	0.08	25	57	(Weisner *et al.*, unpublished)
Fin: Hovi	6000	5.00	7	0.51	24	62	(Koskiaho *et al.*, 2003)
U.S.: Tardiff	6100	8.71	2	2.15	18	88	(Higgins *et al.*, 1993)
Swe: Råbytorp	7500	0.20	137	0.12	16	10	(Wedding, 2004)
Swz: Sonnhof	2350	1.15	34	0.14	11	23	(Reinhardt *et al.*, 2005)
U.S.: Wetland1	1600	4.26	11	0.10	10	68	(Kovacic *et al.*, 2006)
U.S.: Barnstable1	13000	9.29	6	n.d.	8	24	(Jordan *et al.*, 2003)
Fin: Alastro	4800	0.53	47	0.12	6	7	(Koskiaho *et al.*, 2003)
U.S.: Wetland2	4000	3.25	16	0.48	6	44	(Kovacic *et al.*, 2006)
U.S.: WetlandA	6000	4.00	15	0.20	4	23	(Kovacic *et al.*, 2000)
Swe: Stene	21000	2.18	7	0.24	3	17	(Johannesson *et al.*, 2011)
U.S.: WetlandB	3000	6.00	9	0.12	2	23	(Kovacic *et al.*, 2000)
Fin: Flytträsk	600000	3.03	14	0.07	2	15	(Koskiaho *et al.*, 2003)

[a]Retention estimated for total wetland area and for the shallow area with emergent plants.

(Reinhardt *et al.*, 2005; Jordan *et al.*, 2003; Koskiaho *et al.*, 2003; Kovacic *et al.*, 2000; Higgins *et al.*, 1993). In a warmer climate, high P retention (82-173 kg ha^{-1} yr^{-1}) mainly in DP form, has been observed (Maynard *et al.*, 2009).

A positive relationship between area-specific P load and P retention was found by Braskerud *et al.* (2005). However, those authors also found a negative correlation between area-specific P load and relative P retention (% of load). The Bergaholm P-wetland retained 36% of the incoming P, which was more than in three of the five P-wetlands in Norway (21-44%) with much higher P loads (Braskerud, 2002). It was also higher than in most previously studied wetlands in Sweden (10-38%), Finland (7-62%), Switzerland (23%) and U.S. (23-88%) (Table 1). There were four exceptions with higher mean annual relative efficiency. Those were wetlands with low HL, three out of four of which also received high inflow P concentrations (Kovacic *et al.*, 2006; Braskerud *et al.*, 2005; Koskiaho *et al.*, 2003; Higgins *et al.*, 1993). In summary, the comparison indicated that the design of the P-wetlands facilitated P removal. However, the Alastro wetland in Finland had a similar design (0.5% of catchment area; narrow, deep section followed by a shallow section), but the relative retention efficiency was only 7%. In that wetland, the inflow P concentration was lower and the lower L:W (5) may have impaired its hydraulic efficiency (Persson & Wittgren, 2003). Considering that the present study covered the first years after wetland construction (when the bottom surface was not stabilised) and included extreme snowmelt events with low residence times, P was retained quite well in the Bergaholm P-wetland. In contrast, the retention in the Nybble P-wetland was not adequate and the wetland obviously needed more years to stabilise. However, in that wetland water sampling could have been misleading as there was great accumulation of particles and P on the plates (further discussed below and in Chapter 5). Moreover, the higher concentration of particles and TP at the middle sampling point than in the inlet indicated erosion and/or resuspension of particles and P in the deep area.

4.4 Particle deposition and accumulation affecting P retention

4.4.1 Seasonal particle deposition

The seasonal deposition in traps in Bergaholm, Nybble and Skilleby wetland was compared with seasonal inflowing water and its quality (Paper III). During the spring-summer season, sediment deposition was mostly higher than the particle load estimated from water sampling. This discrepancy could not be explained by seasonal differences in HL, particle load or TSS concentration. Fennessy *et al.* (1994) also reported much higher sediment deposition than inflow of suspended particles in four wetlands, due to resuspension and internal production of organic matter. The organic carbon content of the sediment accumulated on plates in the shallow sections with emergent macrophytes in the Bergaholm and Skilleby wetlands was significantly higher than that of the sediment accumulated in the deep sections (Paper IV), directly indicating deposition of internally generated organic material in the wetlands. Even though the deep sections in the Skilleby wetland were colonised by submerged plants, the carbon content was higher in the sediment from the areas dominated by dense stands of *Typha* sp., supporting the suggestion that plant organic carbon also contributed to the measured sediment accumulation.

Traps capture not only the particles in the inflow, but also the sediment particles that have been resuspended and redeposited. Hence, part of the measured sediment deposition could be due to resuspension in the newly constructed wetlands and internal erosion from the sides and bottom. Particles can also be resuspended through bioturbation, caused by either sediment-living invertebrates (which are more active in summer) or by animals trampling on the edges of the wetlands. For instance, wild boars have been observed rooting along the side of the Bergaholm wetland, while in the Skilleby wetland large numbers of invertebrates were found in the traps. Furthermore, Fennessy *et al.* (1994) speculated that declining water depth over the growing season may lead to increased sediment recirculation from wind-generated waves in sections with open waters. It is possible that this process occurred in the deep area of the Nybble wetland when the water level declined during summer and the pond almost dried out.

4.4.2 Annual particle and P accumulation

The annual particle retention in the Bergaholm and Nybble P-wetlands was also estimated as sediment accumulation using sediment plates and the results compared with those from six other wetlands not specifically designed for high P and particle retention (Papers II-IV). Those wetlands are all situated in catchments with clay soils except for Bölarp, where the catchment consists of loamy soils. Phosphorus accumulation was strongly correlated (Pearson coefficient 0.92) with particle accumulation (Paper II), and was highest in the Nybble P-wetland (240 kg P ha^{-1} yr^{-1}) and third highest in Bergaholm (90 kg ha^{-1} yr^{-1}). The particle size of the settled sediment was larger in Bölarp than in the Bergaholm P-wetland, while P accumulation was lower in the former (Table 2). Similarly, Ockenden *et al.* (2014) found that sediment P concentrations were inversely related to the median particle size of the settled sediment in a study of sediment accumulation in 10 small field wetlands

Table 2. *Construction year, wetland purpose, wetland relative size to catchment area (A_w:A_c), wetland length to width ratio (L:W), number of sampling years, mean clay content of the accumulated sediment, mean annual P (kg ha^{-1} yr^{-1}) and particle accumulation and sediment resuspension (t ha^{-1} yr^{-1}) based on sediment sampling in the studied wetlands.*

Wetland	Construction year	Construction purpose	A_w:A_c (%)	L:W	Sampling years	Clay (%)	Accumulation P	Accumulation Particles	Resusp
Nybble	2011	Retain P	0.23	11	2	n.d.	240	230	1680 (87%)
Bergaholm	2009	Retain P	0.31	14	4	41	90	60	280 (83%)
Skilleby	2003	Retain N&P	0.36	2	3	84	20	20	95 (84%)
Wiggeby	2009	Retain P	0.04	7	3	53	10	10	30 (77%)
Lindevad	2008	Birds	0.84	1	2	n.d.	30	40	n.d.
Ekströmmen	2009	Birds	0.43	1	2	68	50	50	n.d.
Bölarp	2002	Retain N	0.09	15	2	13	80	70	n.d.
Genarp	1997	Retain N	0.24	12	2	35	180	110	n.d.

(0.02-0.11% of catchment area) in the U.K. Furthermore, those authors found that among very small wetlands, the sediment and P accumulation rates were highest in wetlands located in catchments with sandy soils and lowest in catchments with clay soils. They also concluded that careful selection of site is important in order to maximise the potential of wetlands to intercept runoff and associated sediment and P transport.

The annual retention estimates for the Nybble wetland diverged considerably from the annual release of particles and P estimated with inflow-outflow balance calculations. Some of the accumulated sediment on the plates in the Nybble wetland comprised eroded and resuspended particles that had resettled, thus not only representing inflowing particles. Advantages and disadvantages of the different sampling methods are further discussed in Chapter 5.

In Paper III, the role of resuspension for particle retention was investigated in the Nybble, Bergaholm, Skilleby and Wiggeby wetlands. The area-specific resuspension was calculated as the difference between sediment deposition and accumulation and was higher in Nybble (1680 t ha yr^{-1}) than in Bergaholm (280 t ha yr^{-1}). The area-specific resuspension was found to be strongly correlated with sediment deposition (Table 2 in Paper III). Annual sediment deposition, accumulation and area-specific resuspension were negatively correlated with fast flow index. Therefore, not only HL, but also a flow pattern with *e.g.* high peaks, can be decisive for sediment deposition and accumulation.

Most of the sediment deposited in the Nybble, Bergaholm, Skilleby and Wiggeby wetlands was resuspended (77-87%) and there was no significant difference in relative resuspension between the wetlands that could explain the difference in sediment accumulation. All wetlands except Skilleby were newly constructed, and there could have been erosion problems along the wetland shores and bottom after construction.

The annual accumulation of sediment on plates in the deep section in the Nybble P-wetland was on average 5.5 cm yr^{-1} in the first two years after construction, much probably due to the incidental soil transport after dredging of the road ditch upstream. In the Bergaholm P-wetland, on average 3.5 cm yr^{-1} accumulated in the deep area in the first four years. The sediment in the deep section in the Nybble wetland will need to be removed earlier than that in the Bergaholm wetland, in order to avoid having a very shallow pond. However, it is difficult to recommend any general interval for this type of maintenance of P-wetlands based only on two short-term studies.

4.4.3 Wetland design affecting P and particle accumulation

In Paper IV, particle and P accumulation in Bergaholm and six other small wetlands was investigated with the aim of relating P retention to catchment characteristics and two wetland design characteristics, size in relation to catchment area (A_w:A_c) and shape (L:W). The influence of these wetland factors on particle deposition in sediment traps and on resuspension was also investigated in the Bergaholm, Nybble, Skilleby and Wiggeby wetlands (Paper III). Hydraulic load and design are important factors for nutrient retention in wetlands (Koskiaho, 2006; Arheimer & Wittgren, 2002). Hydraulic load is commonly negatively correlated with A_w:A_c, but neither P nor particle accumulation was correlated with A_w:A_c in Papers III and IV. Hydraulic load was positively correlated with particle retention for the Bergaholm, Nybble and Skilleby wetlands, where water flow was actually measured (Paper III). No such correlation was observed when using modelled water flow data for the seven wetlands studied in Paper IV (excluding Nybble). The reason may have been that two wetlands, Wiggeby and Bölarp, were very small (A_w:A_c 0.04 and 0.09, respectively) and thus had exceptionally high HL (>250 m yr^{-1}), while the others had low or moderate HL (Figure 10). A strong correlation between P retention and HL was observed only on including the wetlands with HL <250 m yr^{-1} (here corresponding to A_w:A_c >0.1%). The HL in all these wetlands was lower than that (440-1200 m yr^{-1}) in the wetlands studied by Braskerud (2001b), where sediment accumulation was high (150-750 t ha^{-1} yr^{-1}). Braskerud suggested that the inflow contained particles of larger size than clay or aggregated particles and that these might have settled more easily than fine clay, as discussed above. In Paper IV, the Wiggeby wetland received a high HL in combination with very fine particles from the catchment clay soil. There might be an upper limit to HL if a wetland is to serve as a trap for P transported

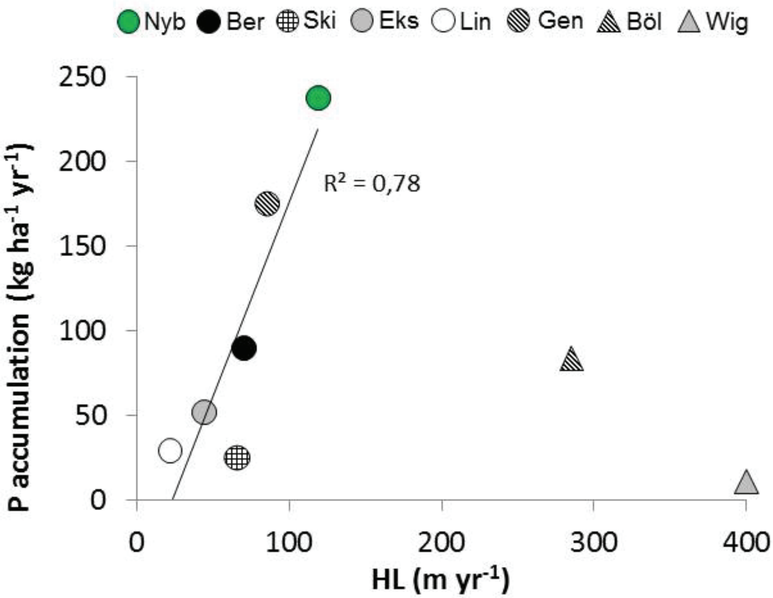

Figure 10. Correlation between annual P accumulation on sediment plates and hydraulic load (HL). Hydraulic load measured for the Nybble, Bergaholm and Skilleby wetlands (Paper II), previous years HL values for Wiggeby (Olli *et al.*, 2009), Bölarp and Genarp (Weisner *et al.*, unpublished) and modelled HL for the Lindevad and Ekströmmen wetlands (Paper IV). Wiggeby and Bölarp were excluded from the regression and are marked as triangles.

from agricultural soils rich in clay. Based on the results presented in Paper IV, a HL of 300 and 400 m yr^{-1} had a detrimental effect on annual P accumulation (Figure 10). This would suggest that wetlands constructed in southern Sweden, should be larger than 0.1% of the catchment area in order to retain substantial amounts of P transported from agricultural clay soils. However, a more precise minimum wetland size remains to be determined.

Phosphorus and particle accumulation on plates was positively correlated with wetland L:W ratio, with Pearson correlation coefficient 0.61 and 0.54, respectively (Paper IV). When combined with a fixed factor for the HL classification (high for Wiggeby and Bölarp and low for Bergaholm, Skilleby, Wiggeby, Ekströmmen and Lindevad) in a multiple regression analysis, L:W explained 74 and 59%, respectively, of the remaining variation in P and particle accumulation. As discussed above, even though the HL and P load in the Skilleby wetland were similar to those in Bergaholm, the P accumulation was three-fold lower. This was probably because the triangular shape (low L:W) resulted in a lower effective volume (Persson & Wittgren, 2003). Long, narrow wetlands have better hydraulic efficiency and longer retention time than circular wetlands (Wörman & Kronnäs, 2005). The low L:W in combination with the inappropriate location of the inlet and outlet in the Skilleby wetland probably caused preferential water flow along the right-hand side from the inlet to the outlet. Even though there were no statistically significant differences between sediment deposition or accumulation within transects, the results from the data interpolation supported this suggestion (Figure 7 in Paper III). This could be counteracted by installing embankments, thereby increasing the distance to the outlet, *i.e.* the flow path. However, HL had a larger influence on the retention results than L:W ratio, as seen from the low accumulation in the Wiggeby wetland with its L:W of 7 (Figure 10).

4.5 Sediment deposition and accumulation in different wetland areas

Differences in sediment deposition and accumulation in different deep (approximately 1.0 m) and shallow (<0.5 m) areas, within the Bergaholm, Nybble and Skilleby wetlands were investigated in Paper III. As expected, the sediment accumulation was significantly higher in the first deep areas than in the shallow areas in all three wetlands (Bergaholm shown in Figure 11). When water from the drainage pipe or ditch enters the deep area, the water velocity is reduced and particles and associated P should sink faster. In the P-wetlands studied by Braskerud *et al.* (2000), 50% of the total sediment retained was captured in the initial 30% of the area. Distance from the inlet could be an important factor, as a decrease in sediment accumulation with distance from the inlet has been shown in other studies (Johannesson *et al.*, 2011; Braskerud *et al.*, 2000). No consistent decrease from the inlet and outlet could be observed in any of the four wetlands in Paper III (including Wiggeby with its uniform depth profile) during the 2 to 4 year study period. However, in the two wetlands with the highest L:W (Bergaholm and Bölarp), there was a significant decrease in sediment accumulation with distance from the inlet in two of the years (Paper IV). In Bergaholm (Figure 11; Figure 4 in Paper III), the difference between the deep and shallow areas emphasised the value of an initial deeper section, slowing down the inflow water velocity. Furthermore, as concluded by Braskerud *et al.* (2000), the shallow area with emergent plants would be filled up quickly if there was no efficient sedimentation basin first. The Wiggeby wetland consisted of only a deep area, but the much smaller size made it unsuitable for comparison of accumulation rates. However, the wetland should not be too deep, as the particles would not have time to settle in a small wetland during high-flow events. The shallow area following the deep basin provides a short settling distance for small clay particles and the plant stems and detritus can act as a filter. The relative clay content in the sediment

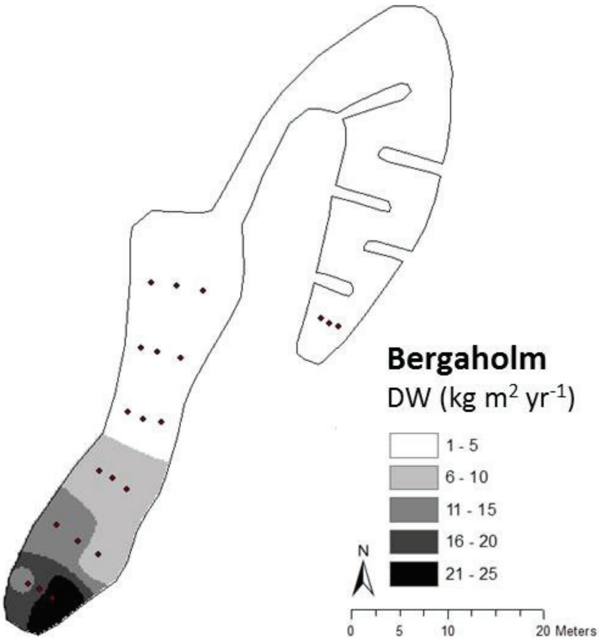

Figure 11. Sediment accumulation pattern in the Bergaholm P-wetland. More sediment (dry weight, DW) settled in the deep area than in the shallow area.

increased with distance from the inlet in the wetlands studied by Braskerud *et al.* (2000). In the present study, it was observed that clay particles (<2 µm) had settled in the wetlands (Table 2), but further analyses are needed to determine whether fine clay particles measured on filters (<0.2 µm) had settled. Furthermore, a detailed study of the particle size distribution in the different transects would be valuable, especially to understand internal erosion and/or resuspension in the Nybble wetland. This would also be interesting to confirm the assumption that more of the settled material remained (lower relative resuspension) in the deep area of the Bergaholm wetland in the first years, because larger particles settled close to the inlet and were less prone to resuspension than smaller particles, which probably settled in the shallow area. Furthermore, the vegetation was not dense until the last year of this study and therefore was unable to stabilise the sediment in the first years. In a study of four planted constructed wetlands in Norway, Braskerud (2001a) observed 40% resuspension in parts planted with emergent plants during early years, but five years after construction this resuspension had decreased to low levels. Only the Skilleby wetland was older, with fully established vegetation, and in this wetland the area-specific resuspension was lower in the shallow sections with dense plant stands than in the deep sections. This could be interpreted as confirmation of a positive influence of plants in decreasing resuspension.

5 Comparison of methods for estimating retention

In Paper II, estimates of P and particle retention obtained with two monitoring methods (water and sediment sampling) were compared. When flow-proportional water sampling was used at both inlet and outlet, the results from the two methods should agree well, as shown for the Bergaholm wetland (Figure 12) and also as reported previously for particle retention (Braskerud *et al.*, 2000) and particle and P retention (Blankenberg *et al.*, 2013).

The results for the Skilleby wetland demonstrated the large uncertainty introduced when relying on water quality results obtained from grab samples in studies of non-point source wetlands with large and rapid variations in both inflow and concentrations. There was no significant difference between particle concentrations in the inflow and outflow when samples were collected as grab samples at these points. In contrast, when inflow was sampled flow-proportionally, the mean annual inflow concentration was 75% higher than when grab sampling had been used simultaneously. In addition, the manually sampled outflow concentrations were lower than the inflow concentrations obtained, when the inflow had been sampled flow-proportionally. This resulted in retention estimates (88 kg P ha^{-1} yr^{-1}) that were higher than those based on sediment accumulation (25 kg P ha^{-1} yr^{-1}; Table 1 in Paper II). Hence, measuring with different techniques at the inlet and outlet should be avoided, as the results cannot be compared.

The need to use flow-proportional sampling, as opposed to grab sampling, in order to get good estimates of P load and retention was clearly confirmed for the wetlands studied here. The rapid hourly variations observed in concentrations of P and suspended solids in the Bergaholm wetland during snowmelt (year 2010, Paper I) further confirmed the importance of using flow-proportional sampling. In addition, the time delay between the flow increase at

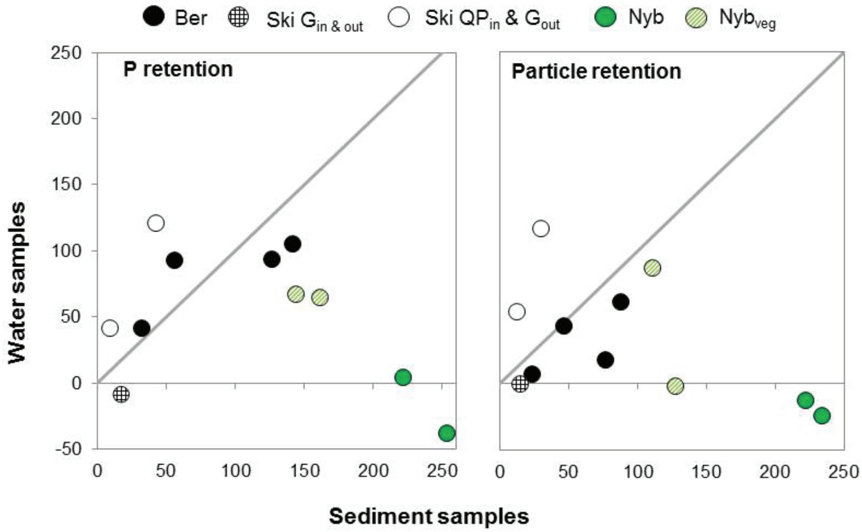

Figure 12. Relationship between estimates of (left) P retention (kg ha^{-1} yr^{-1}) and (right) particle retention (t ha^{-1} yr^{-1}) with water sampling and sediment accumulation on plates. Nyb$_{veg}$ is the estimate for only the shallow area with plants in the Nybble wetland. In the first year in the Skilleby wetland, grab sampling (G) was performed at both the inlet and outlet, while in the two following years flow-proportional sampling (QP) was performed at the inlet and grab sampling at the outlet. The line represents a 1:1 relationship.

the inlet and outlet emphasised the importance of conducting water flow measurements at both inlet and outlet.

The retention estimates based on water sampling in the Nybble wetland indicated overall release of both P and particles, while sediment sampling indicated substantial sediment accumulation (Figure 12). However, the large pile of particles observed at the Nybble wetland inlet and the large amount that settled on the plates may indicate erosion and resuspension, resulting in active transport of particles close to the bottom. Therefore, the sediment sampling may have overestimated the retention in Nybble, and may not represent retention of inflowing particles and P. The P accumulation (150 kg P ha^{-1} yr^{-1}, light green circles in Figure 12), in the shallow area downstream of the deep pond might better represent the retention, as the water sampling also indicated retention (66 kg P ha^{-1} yr^{-1}) for that area. Similarly, Johannesson *et al.* (2011) found a large discrepancy between estimates based on water quality and flow data and sediment sampling, and concluded that for improved estimates of P retention efficiency in wetlands, measurement of sediment accumulation is a good supplement to inflow-outflow studies. Sediment sampling can also be used for determination of spatial variability and estimation of resuspension (Paper III) to improve the understanding of the internal wetland processes. On the other hand, water sampling is needed for investigations of the P dynamics and load calculations. Furthermore, water sampling enables retention to be estimated for dissolved nutrients such as N, which is not possible with sediment sampling, as the main retention process is denitrification. Further studies are needed to determine how long is needed for wetland stabilisation (*e.g.* of Nybble) and to understand the internal erosion and resuspension.

5.1 Evaluation of monitoring methods

A cost comparison was made between estimating P retention based on sediment sampling with 21 sediment plates and flow-proportional water sampling at the wetland inlet and outlet (Paper II). Including the capital investment needed for the sampling equipment, flow-proportional sampling was 60-fold more expensive than sediment sampling. Excluding the investment in equipment, flow-proportional sampling was three-fold more expensive than sediment sampling.

5.1.1 Water sampling

As proven in Paper I & II and also by others (*e.g.* Reddy *et al.*, 1999), accurate water flow monitoring at both inlet and outlet is essential for reliable estimates of P load and retention. To ensure that the water flow at the wetland inlet represents the total inflow, ditches were constructed along the Bergaholm and Nybble wetlands to prevent water from the catchment area entering the wetlands from the side. Despite this, the water balance was not complete due to *e.g.* groundwater discharge and seepage.

The uncertainty of water flow measurements in a stable section has been indicated to be around 10% (Harmel *et al.*, 2006). In addition, there are uncertainties caused by sample storage before analysis and the P analysis method used (at least 10% for the laboratory used in this thesis). Since grab sampling at the surface or 15 cm above the stream bottom generally revealed similar P concentrations (Harmel *et al.*, 2006), the placement of the sampling tubes (in the middle of the water section in the present study) should be of less importance for the estimated retention based on water sampling.

5.1.2 Sediment sampling

When sampling deposited and accumulated sediment with traps and plates, there are other difficulties. The sedimentation deposition can be overestimated when using traps (Kozerski & Leuschner, 1999), because the turbulence and flow velocity are low in the cylinders, which allows particles to settle faster than they would do outside the cylinder. In contrast, when estimating sediment accumulation on plates and when the sediment contains large amounts of organic material, there is a risk of losing sediment when lifting up the plates in deep areas, thereby underestimating sediment accumulation. That is also a risk when there is low accumulation, as in the Wiggeby wetland (Figure 12). Furthermore, if the deep areas are densely vegetated with submerged vegetation that obstructs lifting the sediment plates, more sediment can be lost. On the other hand, the organic sediment is produced within the wetland itself and does not represent material originating from the catchment. In clay soil areas, settled material may stay in place on a plate owing to the cohesive forces between the clay particles. In the studied wetlands, most sediment on the plates was mineral (Figure 7) and generally only the edges of the large plates were disturbed. The sediment depth was measured and samples collected from the undisturbed areas. However, this method may not be appropriate in wetlands located in catchments dominated by soils with high organic content, due to low mineral inputs (Nolte *et al.*, 2013). Artificial grass mats (Ockenden *et al.*, 2014; Hoffmann *et al.*, 2009; Asselman & Middelkoop, 1995) could also be used and would probably cause lower losses of sediment upon lifting the plates. On the other hand, they are probably more suitable for flooded grassland or marshlands, as they do not represent the bare clay bottom surface present in the constructed wetlands in this thesis.

Other observed disturbances were high flow events in combination with a gravel-covered bottom, which tipped the plates, and ice lifting and moving the plates during winter. Physical disturbance of the equipment by drift ice and bioturbation caused by burrowing animals and grazing livestock have been mentioned by others (Nolte *et al.*, 2013). There were no fish or crayfish in the studied wetlands, but birds and wild boars contributed to bioturbation. Furthermore, invertebrates such as *Asellus aquaticus* and larvae of *Trichoptera*, *Chironomidae*, *Ephemeroptera* and *Odonatoptera* were observed and could have caused bioturbation to a lesser extent.

Another uncertainty was the method used for interpolating between sampling points, which did not take into account the morphometry of the wetland, *i.e.* different depths in different parts of the wetland or the slope of the wetland shores. The results from the interpolation method were compared with those results from a simpler method for estimating total sediment accumulation (multiplying the mean for all sampling points by the wetland area). Particle accumulation was usually estimated to be higher with the simpler method, as tested here for the Bergaholm, Nybble and Skilleby wetlands (Paper II).

6 P-wetlands as a mitigation measure

To achieve good ecological status in Swedish lakes and the Baltic Sea, mitigation measures such as catch crops, buffer strips and wetlands are being promoted with the help of environmental subsides to reduce the nutrient losses from agricultural areas. The best approach is to reduce losses of P at the very source, *i.e.* from agricultural fields. However, some losses will occur and targeted measures adjacent to watercourses are needed to capture those in the most efficient way. In areas with erosion problems and surface runoff, buffer strips could reduce PP at the field edge, but could also increase the DP losses (Stutter *et al.*, 2009; Uusi-Kämppä *et al.*, 2000), especially in the winter when frozen plant material releases DP (Uusi-Kämppä, 2007). As shown in this thesis, it is mainly P bound to particles that is retained in the studied P-wetlands and also dissolved P, but to a lesser extent. Unlike buffer strips, P-wetlands can also capture the P losses in sub-drained areas. In Sweden, the buffer strips may currently be placed along water courses, regardless of the slope of the field or surface runoff, and may end up in areas where the reduction in P losses is low. Buffer strips, P-wetlands and similar measures need to be implemented and sited where they are most effective. Studies have shown that the relative retention increases with a wider buffer strip and that the upper part of the buffer strip is most effective in mitigating TP loads in fields with silt and sand soils (no difference for clay), as sedimentation is the most important retention process (Syversen *et al.*, 2001; Uusi-Kämppä *et al.*, 2000). However, it might be more effective to widen the ditch to a P-wetland instead of having a buffer strip, as this might allow P from subsurface drains to settle. In addition, it is important to capture the particles and associated P and return them to agricultural fields. It is much easier to capture and retrieve the P from small wetlands than from a lake or from the Baltic Sea. The P accumulation was high in the P-wetlands studied here, especially in deep areas of those

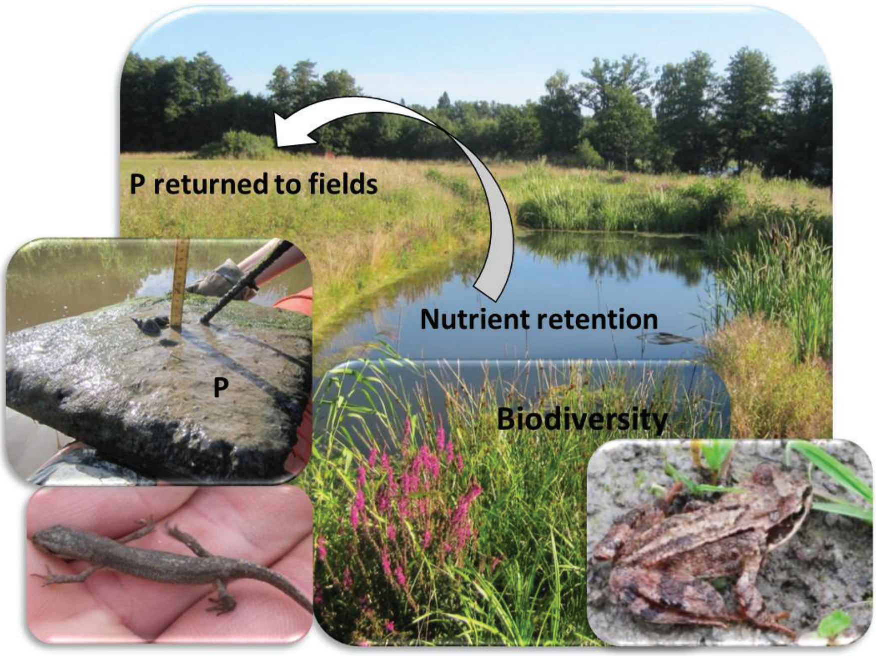

Figure 13. P-wetlands have many functions: reducing P losses, recycling P and increasing biodiversity.

wetlands (Paper III). Furthermore, the P content in the sediments was higher than that in the soil of the catchment area (Paper IV).

When a P-wetland is constructed in a ditch, less land (or no land at all if constructed in a ditch ravine like the Nybble wetland) is used than if a sub-drain has to be cut open. Specifically, a long, narrow shape decreases the excavation costs, especially if the area is not very flat, while also improving the retention in the wetland. It is better to design the wetland with a hydraulically efficient shape instead of creating the same area but with parts where the water is not always spread, even though the extra digging might increase the cost. Furthermore, a larger shallow area might not be better than digging more or deeper to increase the sedimentation basin. In addition, the timing of excavation should preferably be set to summer to reduce the erosion risk and the cost of reconstruction. It is also favourable to place the P-wetlands closer to the source of P, where the P concentration in the incoming water is high and the amount of water is lower than further down in the catchment. This allows for smaller wetlands to be constructed, which is favourable since the cost of digging is one of the limiting factors for wetland construction. Even though targeted for P and particle retention, N was also reduced in the P-wetlands studied here (data not shown). Furthermore, creating an aquatic habitat in a dry, drained landscape always adds diversity (Figure 13), but the extent of this benefit was not evaluated in this thesis.

Hansson *et al.* (2012) studied landowners' incentives for constructing wetlands in an agricultural area in southern Sweden and found that the main reason for not creating a wetland was that the land was suitable for food production, classified as productive. Landowners could be encouraged to construct wetlands on productive land by adequate subsidies, in order to increase qualities of the landscape and obtain other beneficial functions. The landowners surveyed by Hansson *et al.* (2012) reported that sufficient knowledge and good experiences could also motivate them. In contrast, lack of knowledge about wetlands and unclear information regarding the nutrient reduction effectiveness would have the opposite effect. Furthermore, costs that are not covered by subsidies, the costly and time-consuming application procedures involved in applying for wetland construction permits and environmental subsidies, and burdensome maintenance requirements were cited as factors that prevent wetland construction. More information is needed so that farmers and consultants can construct P-wetlands at appropriate sites, based on hydrology and soil texture information, to ensure that P retention efficiency is sufficiently high to justify the subsidies paid.

7 Conclusions

- Monthly area-specific P retention was positively correlated with P load in the specially designed Bergaholm P-wetland.
- Occasions when P concentrations were higher in outflow than inflow coincided with extreme flow events or periods with low flow and ice cover, but net monthly losses of total P were only rarely observed in the Bergaholm P-wetland.
- Seasonal sediment deposition could not be explained by seasonal variations in hydraulic load, particle load or concentrations, since seasonal sediment deposition was mostly larger than the measured particle load in spring-summer.
- Annual sediment deposition, accumulation and area-specific resuspension were negatively correlated with fast flow index, demonstrating the importance of hydraulic load characteristics and not only annual hydraulic load.
- Similar retention estimates for the Bergaholm wetland were obtained with two independent study methods. Retention of particles and P was higher in this newly constructed P-wetland (89 kg P ha^{-1} yr^{-1}) than in other previously investigated wetlands in Sweden. This suggests that adapting wetland design and location to general hydraulic load and soil conditions can promote P retention.
- In contrast, the two-year study of the Nybble P-wetland produced quite contradictory retention estimates with the two independent study methods. Water flow and quality measurements indicated annual losses of P and particles from the wetland, while sampling of annual accumulation of sediment indicated substantial particle and P retention. This discrepancy is probably attributed to erosion and/or resuspension of the settled material in the first, deeper part of this wetland.

- Sediment sampling was a good supplement to inflow-outflow studies and substantially improved the understanding of particle movement in the wetlands and the interpretation of the results from water quality data.
- The results for the Skilleby wetland clearly emphasised the importance of flow-proportional water sampling for accurate estimates of P load and retention.
- In three wetlands with different depth sections, sediment accumulation was higher in deep areas than in shallow areas, demonstrating the importance for the P retention of a deep section to promote particle settling.
- Particle and associated P accumulation was low in two wetlands with hydraulic load of 300 and 400 m yr^{-1}, *i.e.* wetlands smaller than 0.1% of the catchment area. This suggests that above a certain maximum hydraulic load, the P retention will decrease in wetlands located in regions with clay soils. Based on this thesis, a rule-of-thumb would be that in southern Sweden, wetlands for P retention should be larger than 0.1% of the catchment area.
- Phosphorus accumulation was positively correlated with wetland length to width ratio (L:W).

8 Recommendations and future research

There is generally a lack of accurate data on how efficient wetlands are in reducing P losses from agricultural areas, especially P-wetlands. Possible upper limit of hydraulic load to which P accumulation may be positively affected and the dependence of fast flow variations needs further studies. Further research studies are also needed to determine whether erosion and resuspension in the second P-wetland here studied were temporary phenomenon that will disappear as the wetland bottom stabilises. Therefore, monitoring of wetlands should continue and should be improved in order to allow carefully assessments related to hydrology. When landowners in Sweden construct a wetland, they are contracted to keep the wetland for at least 20 years. Wetlands are dynamic ecosystems that are constantly changing and require maintenance, but there is still a lack of long-term monitoring. The retention varies between years and no wetland has been evaluated during all the 20 years of the wetland 'lifetime'. Therefore, it is important to determine the dynamics of different P fractions (including dissolved forms) and loads, in order to improve the design, management and placement of wetlands. Long time series of carefully measured data are also valuable to improve modelling of wetland retention and placement. In order to obtain useful data and understanding of wetlands, there should be a national monitoring programme, instead of individual short-term, scattered projects. Grab sampling once a month is not sufficient to capture the event-based transport of P and particles. Therefore, if the purpose is to estimate annual area-specific P retention, sediment sampling is recommended over grab sampling. However, it is more valuable for the understanding of wetland retention dynamics, and also more cost-effective, to continue careful measurements where expensive equipment and electricity are already installed (even though only partly) than to start investigating new wetlands for a few years. In particular, if the intention is to continue measuring P loads and retention in the Skilleby wetland, the outlet sampling also needs to be flow-proportional for accurate retention estimates. If only annual retention is of interest, a cheaper alternative is to continue with sediment sampling. To improve the retention in the Skilleby wetland, the flow path of the water should be changed by redirecting it with embankments or moving soil in the shallow middle area.

To avoid the need for reconstruction of wetlands, initial excavation should not be done during winter. It is better to wait and start excavating in summer, when the soil is dry and the water flow low. Then the wetland can be slowly filled with water.

To further optimise the design of P-wetlands, studies are needed on whether a larger deep area in relation to total wetland size increases the retention. Moreover, investigations are needed on the particle sizes settling in different wetland areas and whether settling of small particles could be increased by enhancing flocculation/aggregation of colloidal particles.

For the multifunctional value of P-wetlands, it would also be valuable to investigate how to return the accumulated P-containing sediment in the easiest way to agricultural fields and how well the crops can utilise the P it contains. The P-wetlands studied here have not yet been assessed for increased biodiversity. Other positive functions, *e.g.* N retention, or negative effects as emissions of greenhouse gases, should also be investigated.

9 Svensk sammanfattning

Fosforförluster från jordbruksområden bidrar till övergödningen av insjöar och hav och kan orsaka giftiga blomningar av alger och cyanobakterier, inte minst i Östersjön. Den här avhandlingen undersökte ifall små våtmarker med en initial djupdel följt av en grunddel med övervattensvegetation, kan avskilja jordpartiklar och fosfor som transporterats från lerjordar i jordbruksområden. Två långsmala sådana s.k. fosfordammar (Bergaholm och Nybble) anlades med en yta som motsvarar 0.2-0.3% av tillrinningsområdet och jämfördes med sex andra våtmarker av varierande form och anläggningssyfte. Avskiljningen uppskattades med två oberoende metoder: flödesproportionell vattenprovtagning vid inlopp och utlopp samt provtagning av ackumulerat sediment på plattor. Dessutom beräknades resuspension av partiklar som skillnaden mellan deposition av partiklar i fällor i form av cylindrar nedgrävda i botten och ackumulerat på plattor som förankrats på ytan av våtmarkens botten.

I Bergaholm fosfordamm, var fosforavskiljningen per våtmarksyta och månad hög när fosforbelastningen var hög. Fosforkoncentrationen i utflödet var högre än i inflödet vid ett fåtal högflödesperioder samt perioder med lågflöde och istäcke, som orsakade lågt släpp av fosfor vid dessa tillfällen.

Säsongsdepositionen av sediment i de studerade våtmarkerna var högre än den uppmätta belastningen av partiklar under vår-sommar säsongen. Depositionen kunde därmed inte enkelt förklaras av variationer i hydraulisk belastning, eller inflödeskoncentrationen av partiklar. Den årliga ackumuleringen av fosfor på sediment plattor ökade med den hydrauliska belastningen, men bara upp till en viss gräns. Däremot minskade ackumuleringen av sediment om flödesvariationen var alltför kraftig med många markanta flödestoppar.

I Bergaholm fosfordamm, var fosforavskiljningen densamma oberoende om den uppskattades med analys av fosfor i ackumulerat sediment eller i vattenprover. Medelavskiljningen för fyra år var 89 kg P ha^{-1} $år^{-1}$. Däremot indikerade vattenproverna ett släpp av fosfor och partiklar i Nybble fosfordamm, medan sedimentplattorna visade på en stor ackumulation av sediment. Mätningar av vattenkvalitén i en provpunkt mellan den djupa och grunda våtmarksdelen indikerade att den stora skillnaden mellan metoderna skulle kunna bero på intern belastning orsakad av erosion av våtmarkens botten och kanter. Dessutom muddrades ett vägdike uppströms som orsakade ett inflöde av jord som lagrades i en hög vid inloppet och senare resuspenderades och transporterades inom våtmarken. Fortsatta studier behövs dock för att bekräfta detta, samt för att utvärdera ifall det var ett tillfälligt fenomen som kommer att försvinna när våtmarkens botten stabiliserats.

I de två fosfordammarna samt Skilleby våtmark som har sektioner med olika djup, var sedimentackumuleringen högre i de djupa våtmarksdelarna jämfört med de grunda. Den årliga fosforackumuleringen var generellt högre i de två fosfordammarna än i de övriga sex våtmarkerna som studerats här. Dessutom var ackumuleringen av fosfor i sedimentet positivt korrelerad med våtmarkers längdbreddförhållande. Våtmarker med syftet att fånga fosfor som läckt från jordbruksområden bör därför utformas långsmala med en initial djupdel och den hydrauliska belastningen bör inte vara alltför hög eller för pikig.

References

Andersen, J.M. (1976). Ignition method for determination of total phosphorus in lake sediments. *Water Research* 10, 329-331.

Arheimer, B. & Wittgren, H.B. (2002). Modelling nitrogen removal in potential wetlands at the catchment scale. *Ecological Engineering* 19, 63-80.

Asselman, N.E.M. & Middelkoop, H. (1995). Floodplain sedimentation - quantities, patterns and processes. *Earth Surface Processes and Landforms* 20, 481-499.

Blankenberg, A.G.B., Deelstra, J., Øgaard, A.F. & Pedersen, R. (2013). Phosphorus and sediment retention in a constructed wetland. In: Bechmann, M., et al. (ed.) *Agriculture and Environment – Long-term monitoring in Norway* p. 299-314. Akademiska Publishing Trondheim, Norway.

Brandt, M., Ejhed, H. & Rapp, L. (2009a). Nutrient loads to the Swedish marine environment in 2006. *Swedish Environmental Protection Agency Report 5995*, Stockholm, Sweden.

Brandt, M., Arheimer, B., Gustavsson, H., Pers, C., Rosberg, J., Sundström, M. & Thorén, A.K. (2009b). Uppföljning av effekten av anlagda våtmarker i jordbrukslandskapet på belastning av kväve och fosfor. (In Swedish with English abstract). *Swedish Environmental Protection Agency Report* 6309, Stockholm, Sweden.

Braskerud, B.C. (2001a). Sedimentation in small constructed wetlands: retention of particles, phosphorus and nitrogen in streams from arable watersheds. *Doctor Thesis* 2001:10, Agricultural University of Norway, Ås, Norway.

Braskerud, B.C. (2001b). The influence of vegetation on sedimentation and resuspension of soil particles in small constructed wetlands. *Journal of Environmental Quality* 30, 1447-1457.

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

Braskerud, B.C., Lundekvam, H. & Krogstad, T. (2000). The impact of hydraulic load and aggregation on sedimentation of soil particles in small constructed wetlands. *Journal of Environmental Quality* 29, 2013-2020.

Braskerud, B.C., Tonderski, K.S., Wedding, B., Bakke, R., Blankenberg, A.G.B., Ulén, B. & 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.

ECS (1996). Water Quality. Determination of phosphorus. Ammonium-molybdate spectrometric method. *European Standards* EN 1189, European Committee for Standardization. Brussels, Belgium.

Fennessy, M.S., Brueske, C.C. & Mitsch, W.J. (1994). Sediment deposition patterns in restored fresh-water wetlands using sediment traps. *Ecological Engineering* 3, 409-428.

Gustafson, A. (2012). Leaching losses of nitrogen from agricultural soils in the Baltic Sea Area. In: Jakobsson, C. (ed.). *Sustainable Agriculture and Health* pp. 65-81, Uppsala Univeristy, Uppsala, Sweden.

Hansson, A., Pedersen, E. & Weisner, S.E.B. (2012). Landowners' incentives for constructing wetlands in an agricultural area in south Sweden. *Journal of Environmental Management* 113, 271-278.

HELCOM. 2014. The Baltic Sea Action Plan. http://helcom.fi/baltic-sea-action-plan. Last visited 23 Jan 2014.

Harmel, R.D., Cooper, R.J., Slade, R.M., Haney, R.L. & Arnold, J.G. (2006). Cumulative uncertainty in measured streamflow and water quality data for small watersheds. Transactions of the *American Society of Agricultural and Biological Engineers* 49, 689-701.

Higgins, M.J., Rock, C.A., Bouchard, R. & Wengrezynek, B. (1993). Controlling agricultural runoff by use of constructed wetlands. In: Moshiri, G.A. (ed.) *Constructed Wetlands for Water Quality Improvement* p. 359-367, Lewis Publishers, Boca Raton, FL, U.S.A.

Hoffmann, C.C., Kjaergaard, C., Uusi-Kämppä, J., Hansen, H.C.B. & Kronvang, B. (2009). Phosphorus retention in riparian buffers: Review of their efficiency. *Journal of Environmental Quality* 38, 1942-1955.

Jarvis, N.J. (2007). A review of non-equilibrium water flow and solute transport in soil macropores: principles, controlling factors and consequences for water quality. *European Journal of Soil Science* 58, 523-546.

Johannesson, K.M., Andersson, J.L. & Tonderski, K.S. (2011). Efficiency of a constructed wetland for retention of sediment-associated phosphorus. *Hydrobiologia* 674, 179-190.

Jordan, T.E., Whigham, D.F., Hofmockel, K.H. & Pittek, M.A. (2003). Nutrient and sediment removal by a restored wetland receiving agricultural runoff. *Journal of Environmental Quality* 32, 1534-1547.

Kadlec, R.H. (1994). Wetlands for water polishing: free water surface wetlands. In: Mitsch, W.J. (Ed.) *Global Wetlands: Old and New*. Elsevier Science B.V.

Kadlec, R.H. (2005). Phosphorus removal in emergent free surface wetlands. Journal of *Environmental Science and Health Part a-Toxic/Hazardous Substances & Environmental Engineering* 40, 1293-1306.

Kleinman, P.J.A., Sharpley, A.N., McDowell, R.W., Flaten, D.N., Buda, A.R., Tao, L., Bergström, L. & Zhu, Q. (2011). Managing agricultural phosphorus for water quality protection: principles for progress. *Plant and Soil* 349, 169-182.

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

Koskiaho, J. (2006). Retention performance and hydraulic design of constructed wetlands treating runoff waters from arable land. *Doctoral Thesis* 2006: C252, University of Oulu, Oulu, Finland.

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

Kovacic, D.A., David, M.B., Gentry, L.E., Starks, K.M. & Cooke, R.A. (2000). Effectiveness of constructed wetlands in reducing nitrogen and phosphorus export from agricultural tile drainage. *Journal of Environmental Quality* 29, 1262-1274.

Kovacic, D.A., Twait, R.M., Wallace, M.P. & Bowling, J.M. (2006). Use of created wetlands to improve water quality in the Midwest - Lake Bloomington case study. *Ecological Engineering* 28, 258-270.

Kozerski, H.P. & Leuschner, K. (1999). Plate sediment traps for slowly moving waters. *Water Research* 33, 2913-2922.

Kronvang, B., Bechmann, M., Lundekvam, H., Behrendt, H., Rubaek, G.H., Schoumans, O.F., Syversen, N., Andersen, H.E. & Hoffmann, C.C. (2005). Phosphorus losses from agricultural areas in river basins: Effects and uncertainties of targeted mitigation measures. *Journal of Environmental Quality* 34, 2129-2144.

Lundekvam, H. & Skoien, S. (1998). Soil erosion in Norway. An overview of measurements from soil loss plots. *Soil Use and Management* 14, 84-89.

Maynard, J.J., O'Geen, A.T. & Dahlgren, R.A. (2009). Spatial relationships of phosphorus sorption in a seasonally saturated constructed wetland soil. *Soil Science Society of America Journal* 73, 1741-1753.

Nairn, R.W. & Mitsch, W.J. (2000). Phosphorus removal in created wetland ponds receiving river overflow. *Ecological Engineering* 14, 107-126.

Nolte, S., Koppenaal, E.C., Esselink, P., Dijkema, K.S., Schuerch, M., De Groot, A.V., Bakker, J.P. & Temmerman, S. (2013). Measuring sedimentation in tidal marshes: a review on methods and their applicability in biogeomorphological studies. *Journal of Coastal Conservation* 17, 301-325.

Ockenden, M.C., Deasy, C., Quinton, J.N., Bailey, A.P., Surridge, B. & Stoate, C. (2012). Evaluation of field wetlands for mitigation of diffuse pollution from agriculture: Sediment retention, cost and effectiveness. *Environmental Science & Policy* 24, 110-119.

Ockenden, M.C., Deasy, C., Quinton, J.N., Surridge, B. & Stoate, C. (2014). Keeping agricultural soil out of rivers: Evidence of sediment and nutrient accumulation within field wetlands in the UK. *Journal of Environmental Management* 135, 54-62.

Olli, G., Darracq, A. & Destouni, G. (2009). Field study of phosphorous transport and retention in drainage reaches. *Journal of Hydrology* 365, 46-55.

Palmer-Felgate, E.J., Mortimer, R.J.G., Krom, M.D., Jarvie, H.P., Williams, R.J., Spraggs, R.E. & Stratford, C.J. (2011). Internal loading of phosphorus in a sedimentation pond of a treatment wetland: Effect of a phytoplankton crash. *Science of the Total Environment* 409, 2222-2232.

Parvage, M.M., Kirchmann, H., Kynkäänniemi, P. & Ulén, B. (2011). Impact of horse grazing and feeding on phosphorus concentrations in soil and drainage water. *Soil Use and Management* 27, 367-375.

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

Pionke, H.B., Gburek, W.J. & Sharpley, A.N. (2000). Critical source area controls on water quality in an agricultural watershed located in the Chesapeake Basin. *Ecological Engineering* 14, 325-335.

Puustinen, M., Koskiaho, J., Gran, V., Jormola, J., Maijala, T., Mikkola-Roos, M., Puumala, M., Riihimäki, J., Räty, M. & Sammalkorpi, I. (2001). *Constructed wetlands for agricultural water protection- Final report of the VESIKOT-project.* (In Finnish with English summary). The Finnish Environment 499. Finnish Environment Institute, Helsinki, Finland.

Reddy, K.R., Kadlec, R.H., Flaig, E. & Gale, P.M. (1999). Phosphorus retention in streams and wetlands: A review. *Critical Reviews in Environmental Science and Technology* 29, 83-146.

Reinhardt, M., Gachter, R., Wehrli, B. & Muller, B. (2005). Phosphorus retention in small constructed wetlands treating agricultural drainage water. *Journal of Environmental Quality* 34, 1251-1259.

Richardson, C.J. (1985). Mechanisms controlling phosphorus retention capacity in fresh-water wetlands. *Science* 228, 1424-1427.

Stutter, M.I., Langan, S.J. & Lumsdon, D.G. (2009). Vegetated buffer strips can lead to increased release of phosphorus to waters: a biogeochemical assessment of the mechanisms. *Environmental Science & Technology* 43, 1858-1863.

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

Svendsen, L.M., Rebsdorf, A. & Nornberg, P. (1993). Comparison of methods for analysis of organic and inorganic phosphorus in river sediment. *Water Research* 27, 77-83.

Syversen, N., Oygarden, L. & Salbu, B. (2001). Cesium-134 as a tracer to study particle transport processes within a small catchment with a buffer zone. *Journal of Environmental Quality* 30, 1771-1783.

Tanner C.C. and J.P.S. Sukias. (2011). Multiyear nutrient removal performance of three constructed wetlands intercepting tile drain flows from grazed pastures. *Journal of Environmental Quality* 40, 620–633.

Tonderski, K.S., Arheimer, B. & Pers, C.B. (2005). Modeling the impact of potential wetlands on phosphorus retention in a Swedish catchment. *Ambio* 34, 544-551.

Turtola, E. (1999). Phosphorus in surface runoff and drainage water affected by cultivation practices. *Doctoral Thesis,* Agricultural Research Centre of Finland, Jokioinen, Finland.

Ulén, B. (2003). Concentrations and transport of different forms of phosphorus during snowmelt runoff from an illite clay soil. *Hydrological Processes* 17, 747-758.

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., Bechmann, M., Fölster, J., Jarvie, H.P. & Tunney, H. (2007). Agriculture as a phosphorus source for eutrophication in the north-west European countries, Norway, Sweden, United Kingdom and Ireland: a review. *Soil Use and Management* 23, 5-15.

Uusi-Kämppä, J. (2007). Effects of freezing and thawing on DRP losses from buffer zones. Diffuse phosphorus loss: risk assessment, mitigation options and ecological effects in river basins. The 5th International Phosphorus Workshop, Faculty of Agricultural Sciences, University of Aarhus, Denmark.

Uusi-Kämppä, J., Braskerud, B., Jansson, H., Syversen, N. & Uusitalo, R. (2000). Buffer zones and constructed wetlands as filters for agricultural phosphorus. *Journal of Environmental Quality* 29, 151-158.

Uusitalo, R., Yli-Halla, M. & Turtola, E. (2000). Suspended soil as a source of potentially bioavailable phosphorus in surface runoff waters from clay soils. *Water Research* 34, 2477-2482.

Vagstad, N., Stalnacke, P., Andersen, H.E., Deelstra, J., Jansons, V., Kyllmar, K., Loigu, E., Rekolainen, S. & Tumas, R. (2004). Regional variations in diffuse nitrogen losses from agriculture in the Nordic and Baltic regions. *Hydrology and Earth System Sciences* 8, 651-662.

Wedding, B. (2004). Nutrient reduction in newly constructed ponds. (In Swedish) Hölje å projektet & Kävlingeå-projektet. Ekologigruppen, Landskrona, Sweden.

Weisner, S.E.B., Johannesson, K.M. & Tonderski, K.S. (unpublished). Nutrient retention in wetlands constructed in agricultural areas. New measurements and evaluations of wetlands constructed within the Rural program. (In Swedish with English summary). *The Swedish Board of Agriculture Report*.

Wörman, A. & Kronnäs, V. (2005). Effect of pond shape and vegetation heterogeneity on flow and treatment performance of constructed wetlands. *Journal of Hydrology* 301, 123-138.

Acknowledgements

I would like to express my sincere gratitude to everyone who helped me during my PhD years, especially the following people:

My main supervisor *Barbro Ulén*, for helping me to apply for funding for this project, for always being there and for giving immediate comments.

My supervisor *Karin Tonderski*, for critical discussions and guidance.

My supervisor *Lars Bergström*, for good advice within research, support and uplifting comments.

My partner in NERD *Karin Johannesson*, for being a fantastic colleague, encouraging and providing a lot of laughter, in the lab and muddy field - through rain, cold and ice! Thanks for being a wonderful friend and for the fabulous time at the courses in Denmark, the laboratory in Lancaster and the conferences in Berlin, Jokioinen, Seville, Venice, Uppsala and Nantes ☺ Hoping for continued collaboration!

The landowners Stockholm Vatten AB and *Rolf Hallström* for giving me the opportunity to construct the wetlands, *Håkan Eriksson*, *the Biodynamic Research Institute* and the other landowners in the Southern Sweden for allowing access to the wetlands, *Rolf, Johan Frank*, *Håkan* and *Wijnand Koker* for the help in the field and water sampling.

My technical support: *Gunnar Torstensson*, *Maria Blomberg* and *Göran Johansson* at SLU and *Bengt Norén* at In Situ Instruments AB, for the help with the construction of the wetlands and installing the monitoring equipment. *Jonas Andersson* at WRS Uppsala AB, for the technical design of the P-wetlands, *Jonas Engkvist* of Torparens Entreprenad AB and *Gustav Ribers* at Mariedahls schakt, for constructing the P-wetlands. *Anki Eriksson* and *Frank Schmieder* for helping out in the fieldwork. *Stefan Ekberg* and *the others* at our laboratory, for analysing the water samples. *Ragnar Persson* and *Håkan Karlsson*, for mediating between me and my computer. *Claudia Von Brömsen* for statistical support and *Mary McAfee* for language revision.

My colleagues, especially *Helena Aronsson, Karin Blombäck and Dennis Collentine*, for encouragement, support and being inspiring teachers, supervisors and colleagues, *Annika*, for the support and guidance on the life as a PhD student, *Ana Mingot*, *Maria S* and *Matthew*, for the friendly support during ups and downs and the silly discussions making any day brighter, even though my cup is often suddenly empty ☺

All the *PhD students* and the *P group*, for interesting discussions and seminars that broadened my knowledge.

All the nice people in the Dept. of Aquatic Science and Assessment, *Nilo, Ana*, *Salar* and especially *Brian* for helping me with GIS.

Charlotte Kjaergaard, Carlos Arias and *the other organisers* of the wetland courses at Aarhus University, for the interesting and very fun courses and all new nice *wetland colleagues* around the world that I met at these courses and at conferences, especially *Joachim Audet*: welcome to Uppsala!

Clare Deasy, *Mary Ockenden* and *Ben Surridge* at Lancaster University, for welcoming and introducing us to their research in the laboratory and field.

My friends *Sofia, Linda*, *Sara-Lina*, *Karin*, *Saramin* and *Angelica*, for being the best friends that anyone could ever wish for, through good and bad times ♥ *Mattias, Lena* and *Olle*, for giving me energy and lovely dance moments ☺

My father *Kauko* and mother *Sirpa*, tack för att ni har gett mig den "finska Sisun", envisheten som gör det möjligt att fullfölja allt. Minä rakastan teitä!

Finally, *Aidin Geranmayeh* for field and laboratory work, but most of all for believing and encouraging me in my work, for giving me new perspectives that I could never imagine and for bringing joy and love to my life! مرسي عشق من