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Seasonal variation in nutrient retention in a free water surface constructed wetland monitored with flow-proportional sampling and optical sensors

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Highlights:

- Nitrate retention was estimated by flow-proportional sampling and sensors
- Summer nutrient retention was efficient (%), but was a small part of yearly mass
- Organic nitrogen retention was efficient in the first winter, but not the second
- Sensors are essential for evaluating nutrient dynamics and retention

ABSTRACT

Constructed free water surface wetlands (CWs) are used to reduce nutrient and sediment loads to receiving waters in highly impacted catchments by e.g., agricultural land use. In this paper, we evaluated the retention effectiveness of a Swedish CW in two consecutive hydrological years, 3-4 years after construction respectively. We compared nutrient loads based on concentrations from flow-proportional sampling (C_{fp}) and turbidity and nitrate concentrations measured with optical sensors (C_s). CW's retention was estimated based on differences between inlet and outlet concentrations and flow (Q) at both the inlet and outlet (2Q), or only at the inlet (1Q). In the first year (2012/2013), with a cold winter (mean topsoil temperature -0.2 ^oC), nitrate-nitrogen (NO_3N) retention was 32% (C_{fp} and C_s, 2Q). In the second year, with a mild winter (mean topsoil temp 1.8 ^oC) and less water runoff, the corresponding values were 37% (C_{fp}, 2Q) and 39% (C_s, 2Q). Nitrate-nitrogen retention was significantly correlated to water residence time and temperature, and was most effective relative to the load (80%) in summer and least effective (40%) in winter. Quantitatively, however, summer NO_3N retention contributed only 7% (2Q) or 8% (1Q) of yearly NO_3N mass retention. Particulate-phosphorus (PP) concentrations were significantly correlated with suspended solids (SS) concentrations at both inlet and outlet. Seasonal PP retention (C_{fp}, 2Q) was related to particle residence time estimated from turbidity measurements by sensors, and was less effective in the cold winter (3%) than in the mild winter (32%) (C_{fp}, 2Q). Yearly retention (2Q) as a mean of the two years was: SS 40%, total P 36%, PP 34%, dissolved reactive P 30%, total N 56%, NO_3N 35%, organic N 75%, and organic C 30%. Overall, the wetland satisfactorily removed nutrients from agricultural drainage water. However, longer-term studies over a range of flow and temperature conditions are needed to evaluate climate conditions and hydrological residence time as key factors in nutrient removal efficiency.

Key words: Free water surface constructed wetland, Nutrient balance, Optical sensors, Residence time

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1. Introduction

The European Union (EU) Water Framework Directive (2000/60/EC; European Parliament, 2000) and international commitments such as the Baltic Sea Action Plan (HELCOM, 2014) stress the importance of reducing phosphorus (P) and nitrogen (N) loads from arable land to surface waters in order to improve water quality and reduce eutrophication. Constructed free surface water wetlands (CWs) are commonly used in agricultural areas (e.g. Mendes et al., 2018) and are reported to be effective measures to combat eutrophication caused by nutrient losses from arable land (e.g., Schoumans et al., 2014; Tournebize at al., 2015). However, there is limited quantitative evidence on the real effects of CWs, especially in response to seasonal and long-term variations in hydrometeorological conditions.

The nutrient load to CWs may vary depending on factors such as weather, flow (Q), geology, agricultural land use, and other land management in the catchment. Subsequent nutrient retention depends on physical and biological processes that are controlled by the dimensions, location, and age of the wetlands (Kadlec et al., 2000; Currie et al., 2017). Under Nordic conditions and with high flow in the winter half-year, Braskerud et al. (2000) recommend CWs with a high length:width ratio, in order to promote good hydraulic efficiency and facilitate settling of suspended solids (SS) and sediment-bound P. They found minor N retention (3-15% of input), mainly due to sedimentation of N in organic particles and less to denitrification and direct vegetation uptake (Braskerud, 2002). In contrast, many studies have found that denitrification dominates removal of excess N (e.g., Kadlec and Knight, 1996; Valkama et al., 2017), and internal hydraulic efficiency and water temperature have been used to evaluate wetland attenuation of diffuse agricultural nitrate-N (NO_3N) losses (Tanner and Kadlec, 2013). Retention of N and carbon (C) includes emissions to the air in the form of nitrous oxide (N_2O) or nitric oxide (NO) from denitrification, and methane (CH_4) from decomposition of organic matter (Søvik et al., 2006). Sedimentation of nutrients may be of high importance during seasons when the particle load from agricultural areas is high (autumn and winter), while the other processes may be most intensive in summer due to higher temperature and lower discharge.

Another factor influencing CW effectiveness is landscape position relative to groundwater discharge and recharge areas, but retention based solely on inlet flow is most frequently reported (e.g., Braskerud, 2002; Koviacs et al., 2000) without consideration of groundwater movements to or below the CW. Groundwater seepage to the CW can decrease water retention time (Tanner et al., 2005), while the opposite may occur if water bypasses the CW to a nearby stream or lake.

To accurately evaluate the effect of CWs and other mitigation measures on water quality, automated monitoring approaches at both inlet and outlet are necessary (Bieroza et al., 2019). Flow-proportional composite sampling is typically used in the Nordic countries to quantify nutrient loads from agricultural catchments (Kyllmar et al., 2014). However, increasing numbers of studies are now using high-frequency water quality monitoring with sensors to evaluate the effectiveness of mitigation measures (Valkama, 2018; Koskiaho and Puustinen, 2019). Turbidity is often used as a proxy for suspended matter (SS) (e.g., Gippel, 1995), total P (e.g., Jones et al., 2011), and particulate P (PP) (e.g., Ulén et al., 2012a).

In this study, we built on previous work in which we evaluated variations in P retention in a CW during the first two years after construction (Kynkäänniemi et al., 2013). The objectives of the present study were to: (i) quantify retention of nutrients and C in the maturing CW over a two-year period using a mass balance approach; (ii) compare retention estimates obtained using flow-proportional sampling and optical sensors; (iii) estimate nutrient retention based on inlet and outlet Q (2Q) and solely on inlet Q (1Q); and (iv) identify any seasonal patterns in nutrient retention. Our hypothesis was that residence time and temperature are key factors controlling P and NO_3N removal efficiency on a seasonal basis.

2. Materials and Methods

2.1. Catchment characteristics

The study was carried out over two hydrological years, 2012/2013 and 2013/2014, which were three and four years, respectively, after construction of the study CW. The CW is situated 15 km south of the city center of Stockholm, Sweden, and it drains to Lake Bornsjön, the reserve drinking water reservoir. The wetland catchment (25.3 ha at the inlet and 25.6 ha at the outlet) is characterized in Johannesson et al. (2015). Mean slope is 3.6% and groundwater dynamics have been recorded in 12 piezometers placed in pairs around the wetland (Kynkäänniemi et al., 2013). Shallow groundwater flows from the southwestern and southeastern slopes and may pass under the CW, since negative hydraulic head has been observed in the narrow area between the CW and the shore of the lake.

The catchment consists of one main cultivated field (6.4 ha), several horse paddocks (in total 2.8 ha), and a farmyard with buildings and forest (11.5 ha) (Fig. 1). The soil under the main field and paddocks is a silty clay (27% clay) and has a high P concentration measured in acid lactate extract (P-AL) (Egnér et al., 1960), especially in the most frequently used paddocks (Parvage et al., 2011) (Fig. 1). In the main field, a water intake to a central well with connecting tile drains remained broken throughout the entire study period. A central culvert collects drainage water from the arable part of the catchment and from a few connected tile drains, which are probably more than 50 years old and provide only essential drainage. The main field was manured with semi-composted horse manure and ploughed under on 10 September 2012, and a winter wheat crop was sown, but survived poorly in the cold winter of 2012-2013. After harvest of this crop in September 2013, structure lime containing 18% active calcium hydroxide (equal to 1 ton CaO ha^{-1}) was applied on the stubble and evenly incorporated into the topsoil by two shallow cultivations. The soil was then left bare until barley was sown in spring 2014.

2.2. *Bergaholm* CW

Bergaholm CW lies next to the main drainage culvert, from which it receives its water. The CW comprises a 1 m deep and 27 m long pond (0.02 ha), followed by two shallow 0.03 m deep vegetated areas (0.03 ha each). Wetland length:width ratio is 14:1 and wetland area (0.08 ha) comprises 0.3% of the catchment area (Kynkäänniemi et al., 2013). Directly after construction (August 2009), the shallow areas were planted with greater pond sedge (*Carex riparia* L.), yellow iris (*Iris pseudacorus* L.), simplestem bur-reed (*Sparganium erectum* L.), and purple loosestrife (*Lythrum salicaria* L.) in the former compacted subsoil (Kynkäänniemi et al., 2013). After three years, the macrophytes were well established, together with frequent cattail (*Thypha latifolia* L.). In summer, filamentous algae (*Cladophora glomerata*) cover the free water surface. The algae were harvested in the first summer after construction (13 July 2010) and contained 0.5% P per dry weight (analyzed by inductively coupled plasma atomic emission spectroscopy (ICP-AES) after oxidative acid wet-combustion in nitric acid; ALS Scandinavia, Luleå, Sweden). In total, the harvested mass was equal to 0.005 kg P per ha catchment area (or 0.6 kg TP ha^{-1} wetland area).

2.3. Precipitation, water flow, and sampling

Topsoil temperature close to the wetland inlet was recorded hourly by a data logger during the study period. Daily precipitation and temperature data were obtained from the national meteorological station at Södertälje (SMHI, 2018), 6 km southeast of Bergaholm CW. These data were complemented with some local data from an observation field situated 1.5 km southwest of the CW. Water flow (Q) was recorded hourly based on water levels at V-notch weirs and load cells at the inlet and outlet wells. Sedimentation of larger soil particles/aggregates occurred in the inlet well, which was emptied a couple of times by hand with a shovel. In a few shorter periods with much accumulated sediment, the water level in the inlet well was adjusted based on the corresponding results from the outlet, since the line was stuttering. The outlet V-notch weir was constructed with one side angled, since the space was narrow. At the highest peak flows (which occurred in total for 31 days in the two-year period), the water level exceeded a critical value and outlet Q was adjusted to 20% of inlet Q. Inlet and outlet flow-proportional water sampling for chemical analyses (C_{fp} concentrations) took place simultaneously based on the inlet flow rate, guided by the data logger as described by Kynkäänniemi et al. (2013). After a water mass equal to 20,000 L (or 0.08 mm) had passed the inlet, a peristaltic pump transferred a subsample (20 mL) to a 20-L glass-bottle placed in a refrigerator. A representative water sample from the stored composite samples was collected biweekly and immediately sent to the laboratory. During the highest water flow peaks, the sampling strategy corresponded to five subsamples per hour. In contrast, flow-proportional samplings were rarely collected in summer months, when the CW outlet was occasionally empty and sampling rate fell to a minimum of five subsamples per month. For eight days in autumn 2013, the electricity was disconnected and all logger functions (near-continuous water flow measurement, water sampling, and hourly recording of the sensor measurements) ceased. For that period, water flow was estimated from a nearby observation field.

2.4. Water chemical analysis

The water samples were analyzed according to Swedish Standards or the European Committee for Standardization (methods listed by Vattenkemiska laboratoriet, 2019) at two accredited water laboratories at SLU. Total P (TP) was analyzed as soluble molybdate-reactive P after acid oxidation with $K_2S_2O_8$. The particulate-bound phosphorus (PP) fraction was calculated as the difference between TP in filtered and unfiltered water using filters with pore diameter 0.2 µm (Schleicher and Schüll, Dassel, Germany). Dissolved reactive phosphorus (DRP) was analyzed after pre-filtration with the same type of filters. Suspended solids (SS) content was determined after filtration of a certain volume of sample using the same type of filters and by weighing the dried cake captured by the filter. Total nitrogen (TN) was analyzed together with organic carbon (OrgC) using a CN analyzer (Shimadzu). Nitrate-nitrogen and nitrite-nitrogen were analyzed together and referred to as nitrate-nitrogen (NO_3N). Organic N (OrgN) was estimated as the difference between TN and NO_3N and any ammonium-N was neglected, as this N form occurs only in very low concentrations at the study site and is not regularly analyzed.

2.5. Optical sensors

Automated measurements of NO_3N and turbidity (C_s concentrations) were performed with sensors (s::can nitro:lyser Messtechnik, GmbH) placed in the inlet and outlet wells, just beside the inlet and outlet weirs of the CW and approximate two centimeters below the inlet for the autosampler. Sensor measurements are based on absorbance in the UV-visible range (200-750 nm) with measuring range 0-100 mg NO_3N L^{-1} and 0-1000 FTU turbidity. Before each measurement, the windows of the sensor are cleaned with compressed air. To prevent overclogging with sediments, the sensor inlet has been wrapped with a coarse-pored plastic mesh. The instruments were manually controlled and cleaned at least once every 6 months and the base-line was regulated. Concentrations of NO_3N and turbidity (FTU units) were estimated from the corrected value of absorbance and calibrated for NO_3N from bi-weekly water sampling. Turbidity concentrations were re-calculated to SS concentrations based on the lab samples. The re-calculation involved multiplication with a coefficient obtained for each measuring period, since the general SS calibration curve was scattered in the highest range. In the first cold winter, with ice at the inlet, the values of NO_3N fell below zero. These values were removed along with other outliers.

2.6. Data analysis and statistics

Precipitation, water runoff, nutrient transport, and wetland retention were all estimated in mm related to the catchment area. The hydrological year, starting in October, was divided into four seasons: autumn (October-December), winter (January-March), spring (April-June), and summer (July-September). The spring season encompassed any late snowmelt and early-summer drought. The summer season included September, when drought is still frequent at the study site.

The hydrographs from the inlet and outlet were compared and the time delay between distinct peaks at the inlet and outlet was used as an indication of the actual water residence time. It was compared with the theoretical residence time (or detention time), estimated by dividing the wetland volume (380 m^3 under medium to high flow conditions) by the inflow Q. In a corresponding way, the time delay between distinct turbidity peaks at the inlet and outlet was estimated as particle residence time. Nitrate-N concentrations did not show any distinct peaks and no corresponding estimation was made for this parameter. Selected simultaneously sampled nutrient concentrations (C_{fp}) were compared pairwise by regression analysis and using a value of $p<0.01$ for significant correlations. Transport load to the CW was estimated in two ways: i) from concentrations in the composite and flow-proportional samples (C_{fp}) multiplied by Q in the period they represented; and ii) from the values recorded by the sensors (Cs) multiplied by hourly Q. Nutrient retention in the CW was quantified in two ways: from concentrations and Q at the inlet minus concentrations and Q at the outlet (2Q), and from inlet-outlet concentrations and inlet Q only (1Q) and, based on that, the relative retention as a percentage of the inlet load to the CW.

3. Results

3.1. Seasonal variation in weather, hydrology, and wetland water budget

There were distinct differences in weather conditions in the two hydrological years studied. Autumn 2012 was wet, with 200 mm precipitation (Table 1), and was followed by a cold winter, with mean air temperature -4.6 ^{o}C, frozen soil, and main snowmelt in April 2013. Long-lasting (4 months) snow on ice covered the CW. Autumn 2013 was characterized by low runoff and the winter was milder and wetter than in the previous year, with just occasional snow and ice cover on the CW. Water balance demonstrated losses (Table 1). High relative losses was especially the case in summer, when the outlet occasionally dried out, potentially due to seepage losses to the nearby lake and evaporation from the wetland (Tables 2). The number of distinct water flow peaks was 5-13 per season. The seasonal residence time for water (mean of two years), estimated from the time delay of the flow peaks, was: autumn 2.1 h, winter 1.2 h, spring 4.0 h, and summer 7.7 h (Table 1), which in all cases was much shorter than the theoretical residence time (100 h).

3.2. Sampling, concentrations and nutrient ratios

In the episode with the highest flow (Fig. 2a), the turbidity value just reached the upper limit of detection. Large numbers of subsamples (n = 141) were taken over 111 hours. In a moderate episode, subsampling took place at a mean rate of 0.96 samples per hour (Fig. 2b), a frequency close to the hourly recording of turbidity data. In two weeks in winter 2013, the turbidity values at the outlet were much higher than in comparable SS analyses (C_{fp} values). These sensor values were neglected, since the probe, which was placed closer to the bottom than the inlet to the auto-sampler, seemed more sensitive to re-suspension than SS concentrations from flow-proportional water samples (C_{fp}).

We found significant relationships between PP and SS concentrations at both the inlet and the outlet (Fig. 3a). The relative proportion of PP to SS was similar at the inlet (mean 0.12%)

and outlet (mean 0.15%), values typical in drainage water from Swedish clayey soils (Ulén, 2004). In contrast, total N and total organic C (OrgC) concentrations were not significantly related to each other (Fig. 3b). The weight-average ratio was 0.32 at the inlet and 0.20 at the outlet. The regression line between TN and TP concentrations was significant in the first year, but with a low slope (Fig. 3c). In total, N:P ratio was low (8:1 and 3:1 at the inlet and outlet, respectively), which was expected since the CW is located below a marked hotspot for P. In the second year, the regression line was only significant at the outlet. The irregular relationship at the inlet could indicate irregularities from the horse-related activities. The generally higher ratio in the second year (mean 13:1 and 14:1 at the inlet and outlet, respectively; Fig. 3d) may be an effect of structure-liming of the non-grazed arable land reducing P transport.

3.3. Hysteresis patterns, transport, and retention of SS, TP, and PP

The hourly turbidity concentrations demonstrated clock-wise hysteresis, with higher values in the rising limb of the flow (Fig. 2a and b). Therefore, the mean composite SS concentration (and corresponding SS transport) might have been underestimated. However, estimated SS inlet transport load to the CW was generally in good agreement when based on flow-proportional sampling or sensors (Table 1). Yearly SS load to the CW was high, roughly corresponding to 200-400 kg ha^{-1} from the catchment area. The broken inlet well in the main field, and grazing and trampling by horses and their manure load to the soil in the paddocks, might have contributed to the high SS load from this silty clay soil. In the second year of the study, SS load was more than 50% lower, which may have been a consequence of different weather conditions and recent structure-liming of the main field.

Mean residence time for particles (4.6 hours, based on turbidity peaks) was slightly longer than for water (Table 1). This short residence time suggests limited settling of particles of clay size, but this contradicts the substantial SS retention in most seasons (Table 1). Based on the sensors, mean SS retention for the entire period was estimated to be 170 kg ha^{-1}yr^{-1}, which was lower than the value obtained from flow-proportional water sampling (260 kg ha^{-1} yr^{-1}). The main differences were recorded in October-December 2012 and April-June 2013 (Table 1), seasons with high load and much snowmelt, respectively, when outflow Q might have included much re-suspension of particles over-recorded by the sensor. Quantitatively, SS retention (C_{fp}) was highest in autumn 2012/2013, but most effective in relative terms in summer 2013/2014 (Table 2).

Estimation of load and retention of TP and PP from analyses of water samples showed that PP transport constituted 68% of TP transport from the catchment. Absolute TP retention (not shown) and PP retention (Table 1) were estimated to be high in the first autumn, but low in the following winter. In contrast, relative retention of TP was highest in summer and lowest in winter, as was relative retention of PP (85-94% in summer and 2-30% in winter) (Table 2). On average for both years, TP retention was estimated to be 21-36% and PP retention 29-34% (1Q and 2Q) (Table 3). Relative PP retention increased significantly with particle residence time in the CW on a seasonal basis (Fig. 4a). In absolute amounts, most retention occurred in autumn (mean 0.08 kg ha^{-1} quaternary^{-1}) and least in summer (mean 0.01 kg ha^{-1} quaternary^{-1}).

3.4. Nitrate-N transport and retention, estimated with two techniques

Similar loads of NO_3N (mean 2.7 kg ha^{-1} yr^{-1}) were estimated to be transported from the catchment when using the automatic flow-proportional sampling technique and the sensors. Such low losses from agriculture-dominated catchments are typical for this type of soil and similar to losses from a nearby observation field (Ulén and Persson, 1999). In the first year (2012/2013) with its cold winter (mean topsoil temperature -0.2 ^{o}C), NO_3N load to the CW was 1.6 kg ha^{-1} yr^{-1} according to both techniques. The two retention estimates were also similar, 0.5 (C_{fp}) and 0.4 (C_s) kg ha^{-1} yr^{-1}. In the following year with mild winter (mean topsoil temperature 1.8 ^{o}C) and with less water runoff, the NO_3N load to the CW was 3.9 kg ha^{-1} yr^{-1} (according to both techniques) and the two retention estimates were again similar, 1.4 (C_{fp}) and 1.5 (C_s) kg ha^{-1} yr^{-1}. Nitrate-N retention was significantly correlated to water residence time and soil temperature in different seasons (Fig. 4b). Relative retention was most effective (> 90%) in summer 2012/13 and least effective in both winters (23-35%) (Table 2). However, in quantitative terms summer NO_3N retention contributed only 7% of yearly NO_3N retention, as estimated from measured Q values at the outlet or 8% as estimated from the inlet only.

3.5. Transport and retention of OrgN, OrgC and DRP

A huge input of OrgN (5 kg ha^{-1} yr^{-1}) occurred during the first year, which amounted to 80% of TN. Most of the OrgN (83%) was retained in the CW, while total NO_3N retention was lower (33%). In the second year, the OrgN input was moderate (0.3 kg ha^{-1} yr^{-1}) and amounted to 13% of TN input. Less OrgN (20%) was retained in the CW, while NO_3N retention was similar (36%). OrgN was most effectively retained in the first autumn and winter (82 and 94%), but not the second (Table 2). Input of OrgC was quantitatively 22 kg ha^{-1} yr^{-1} the first year and 21 kg ha^{-1} yr^{-1} the second. Retention (7 kg ha^{-1} yr^{-1} OrgC) occurred together with 4 kg ha^{-1} yr^{-1} OrgN (C/N ratio 2:1) in the first year. In the second year retention was 11 kg ha^{-1} yr^{-1} OrgC and 0.1 kg ha^{-1} yr^{-1} OrgN (C/N ratio 90:1). Seasonally OrgN retention varied more than OrgC retention (Table 2).

Relative retention of DRP was quite often similar to PP retention but was higher in winter 2013 and lower in spring 2013, spring 2014 and summer 2014 (Table 2).

3.6. Retention related to water flow at both inlet and outlet, or only to water flow at inlet

Seepage may account for a substantial part of the reduction in NO_3N concentrations, with NO_3N being lost by groundwater moving below the CW. Similarly, some DRP may be lost by seepage to the lake. Relative retention estimated from recorded outlet Q (2Q) was: SS 42%, TP 36%, PP 34%, DRP 30%, TN 56%, NO_3N 35%, OrgN 75%, and OrgC 30%, as a mean of the two years (Table 3). These figures also include uncertainties in the water balance caused by evaporation and in estimating water flow during the highest peaks at the outlet. Corresponding retention based solely on inlet Q (1Q) may be regarded as the minimum value and was: SS 27%, TP 21%, PP 29%, DRP 14%, TN 47%, NO_3N 22%, OrgN 71%, and OrgC 14%. In total for the two years, estimated relative retention of PP (29-34%) and OrgN (71-77%) was rather similar based on either inlet or outlet Q, while estimated retention of the dissolved nutrients DRP (14-30%) and NO_3N (22-35%) was more affected by the water balance (Table 3). Even when the retention data were based on these minimum values, the Bergaholm CW appeared to remove most nutrients from agricultural drainage water in a rather satisfactory way.

4. Discussion

4.1. Transport and retention of SS and P

Clock-wise hysteresis (Fig. 2) is an indication of accumulation of sediments and their subsequent mobilization in storm events. After re-mobilization, most of this material probably re-settles close the inlet, where the main accumulation of sediment in the Bergaholm CW occurs according to previous measurements on sedimentation plates (Geranmayeh et al., 2018). The outflow SS concentration may include internal erosion and SS re-suspension at the outlet. However, these processes were indicated to be of minor importance, since the amount of SS retained was similar to the amount that settled on the plates each year. Based on the large amounts, settling occurred faster than the theoretical gravimetrical sedimentation of clay-sized particles. Hence our findings support the suggestion by Braskerud (2002) that settling velocities of soil material may be higher than that of single particles, since they may be mobilized and transported by water in aggregate form. This is supported by the fact that soil aggregates have been observed in leachate from a nearby experimental field (Simonsson et al., 2019) with a similar soil type as the Bergaholm catchment. Clear SS retention during most of the year was indicated by the sensor data in Bergaholm CW, which is in agreement with findings from the Finnish wetland Gateway (Valkama et al., 2017). Those authors observed that SS removal rate was reduced during the flow peaks, but that the CW did not lose all its retention capacity. In contrast, internal erosion and re-suspension of particles has been found to cause more or less temporary negative retention in some other Swedish wetlands (Geranmayeh et al., 2018).

The two shallow ponds of the Bergaholm CW contain many macrophytes with periphyton, fauna, and microorganisms, and are more complicated to define than the inlet pond, which is designed for particle settlement. In studies of similar wetlands, macrophytes have been observed to inhibit re-suspension of sediment (Braskerud, 2002). The plants also return nutrients as litter, a form that is more susceptible to leaching than settled soil. Lack of TP removal in summer is proposed to be a consequence of P release from decaying plant biomass (Beutel et al., 2014), However, no such effect was indicated in the present study, where DRP was reasonably effectively reduced in all seasons.

4.2. Transport and retention of N and C

A surprising finding was the large input and retention of OrgN in the first study year. This high input cannot be attributed solely to the horse paddocks in the catchment, since this form of N has been shown to represent only 10% of TN leaching in lysimeter studies on clayey paddock soils (Parvage et al., 2015). In the first study year, the N retention comprised 4.2 kg ha^{-1} OrgN and 1.5 kg ha^{-1} NO_3N, i.e., denitrification was not the main process for N retention. In the second study year, input and retention of OrgN were lower. Since OrgN was retained without any clear accompanying C retention, the suggestion by Braskerud (2002) that OrgN settles together with OrgC could not be verified here. Future studies should examine long-term retention of OrgN related to OrgC and the relative importance of NO_3N and OrgN retention.

In relative terms, NO_3N retention (35% estimated from inlet and outlet Q; 22% estimated solely from inlet Q) (Table 3) was: higher than reported for five small Norwegian CWs (maximum 9%) primarily designed for P retention (Braskerud, 2002), higher than in the Finnish CW Gateway (13%) (Valkama et al., 2017), similar to that in the Finnish wetland Rantamo-Setteili CW (27%), and lower than in the Finnish wetland Hovi CW (69%) (Koskiaho and Puustinen, 2019). Nitrogen removal can generally be expected to increase as vegetation becomes established and C becomes available for effective denitrification, with maturity of vegetation reported to be an important explanatory factor for the effectiveness of NO_3N retention (Koskiaho and Puustinen, 2019). Both Finnish studies cited above have also found NO_3N retention to be of quantitative importance even in winter periods, although the effectiveness decreases with decreasing temperature (Valkama et al., 2017; Koskiaho and Puustinen, 2019).

4.3. Quantification and expression of retention

Load estimation based on flow-proportional sampling during periods with a long residence time can potentially be of lower precision, since the ideal technique would always be to follow the same water parcel passing through the wetland. Nevertheless, the water sampling strategy applied in this study, with simultaneous water sampling at the inlet and outlet, may have satisfactory accuracy, since the water residence time was estimated to be just a few hours during high flow conditions. A disadvantage with the sensors used in the present study was that they needed frequent calibration, since NO_3N measurement was easily disturbed by accumulated sediment, especially at the inlet well. However, using the sensor technique offers possibilities to monitor NO_3N dynamics much more closely in time than the evaluations comparing three-month seasons presented here.

Nutrient retention is commonly expressed based on mass load or as effectiveness related to inlet load, both of which are reported in the present study. Specific retention related to the wetland area is another option, but has the disadvantage that the area of small wetlands can change within years. Yet another option is to report the CW effectiveness as an outlet concentration with importance for downstream water eutrophication (Braskerud et al., 2005). Retention is commonly reported on an annual basis, and with a significant regression between retention and load. However, it is important to take into consideration the seasonal pattern and variability of flow in order to calculate effectiveness accurately (Tanner and Kadlec, 2013). The critical residence time for particle settling, microbial denitrification, and other processes is not considered in reporting on an annual basis. The CW:catchment area ratio is usually reported and is suggested to be an important explanatory factor for NO_3N retention effectiveness (Koskiaho and Puustinen, 2019). However, more careful studies of the groundwater dynamics are necessary for assessments in relation to CW hydraulics. In the present study, we found temperature to be an explanatory factor for N retention effectiveness, while winter temperature may only have an indirect effect on PP settling, e.g., related to snow and ice cover on the CW or to snowmelt with low pH, which may release P from soil particles by ion-exchange (Ulén et al., 2012b). Future studies should examine retention over a range of flow and temperature conditions and evaluate climate conditions and hydrological residence time as factors in nutrient removal efficiency.

4. Conclusions

At 3-4 years after establishment and with full development of rooted macrophytes in the vegetated part, Bergaholm free water surface CW was found to act satisfactorily as a sink for P, especially in PP form. Much of the TP retention is in PP form in this CW, located in a catchment with an arable silty clay soil. Total N retention was even higher than TP retention. In one study year, a majority of the TN retention in the CW was in the form of OrgN with unknown source.

Sensors proved useful for studying the impacts of e.g., temperature and actual particle dynamics. Hysteresis was observed in the turbidity/water flow relationship, indicating that the sensor technique may also be useful for mass balance studies. However, an automatic flow-proportional water sampling technique has the advantage of not requiring frequent field calibration and it is easy to include multiple P and N fractions in the analysis.

Assessments of nutrient retention in CWs should be based on both inlet and outlet water flow measurements, especially when studying dissolved forms of P and N. In Bergaholm CW, negative retention occurred in short, rare periods in winter and spring. Phosphorus (both PP and DRP) and NO_3N retention was most effective in summer, but this represented only a minor part of annual amount retained. Cold winter conditions impaired PP retention, but had only a limited effect on TN retention.

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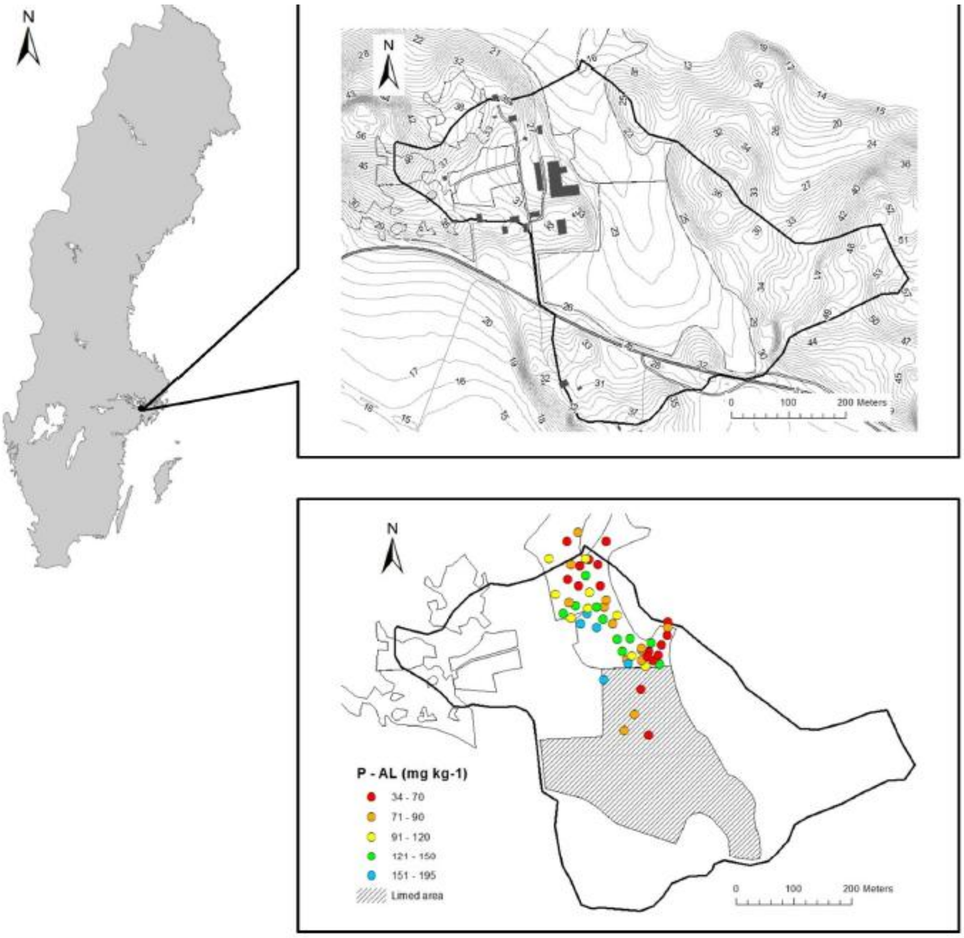
Figure capture

Fig. 1. Maps of Bergaholm catchment showing the topographical location and topsoil concentrations of ammonium lactate-extracted phosphorus (P-AL). The area close to the wetland inlet is used as horse paddocks and the cross-hatched area to the south is an arable field.

Fig. 2. Two episodes with clock-wise hysteresis at the wetland inlet: a) 06:00 h on 18 Oct to 20:00 h on 22 Oct 2012 (141 subsamples for flow-proportional sampling concentrations (C_{fp}) and 111 for sensor concentrations (C_s)) and b) 03:00 h on 8 Jan to 20:00 h on 9 Jan 2014 (43 subsamples for C_{fp} and 45 for C_s). Maximum turbidity was recorded one hour before maximum water flow in both cases.

Fig 3. Autumn-winter (October-April) concentrations of a) particulate phosphorus (PP) related to suspended solids (SS), and b) total nitrogen (TN) related to total organic carbon (OrgC) in two hydrological years (2012-2014), c) concentrations of total nitrogen (TN) related to total phosphorus (TP) 2012/2013, and d) concentration of TN related to TP 2013/2014 at the wetland inlet and outlet. Filled circles represent inlet concentrations and unfilled circles outlet concentrations. Significant ($p<0.01$) relationships at the outlet are marked as solid lines, non-significant as broken.

Fig 4. Seasonal retention, estimated from inlet and outlet water flow, of a) particulate phosphorus (PP) related to the mean particle residence time from turbidity peaks, and b) nitrate nitrogen (NO_3N) related to mean water residence time (hours) multiplied by soil temperature. Both relationships are significant ($p<0.01$).



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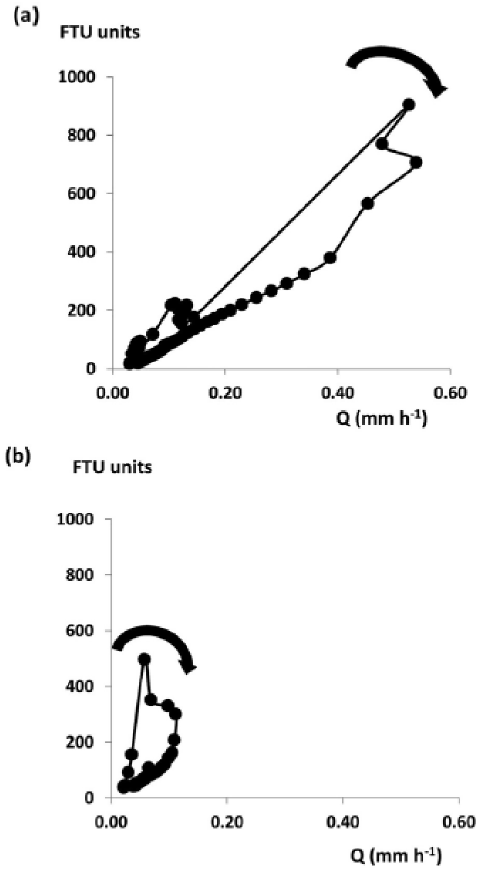

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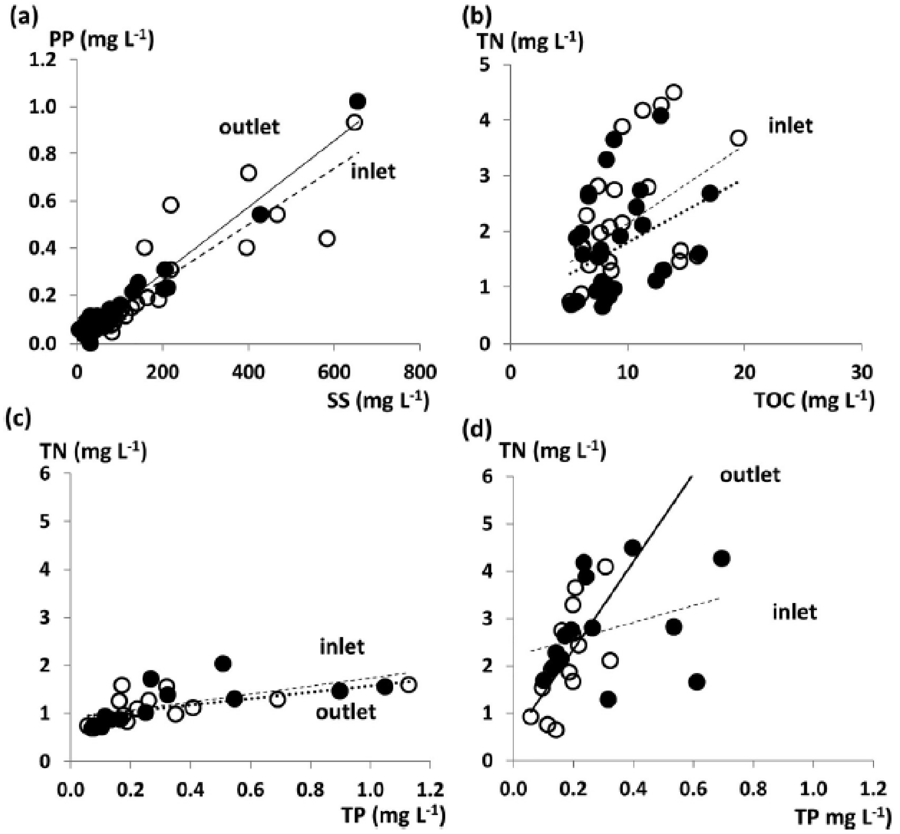

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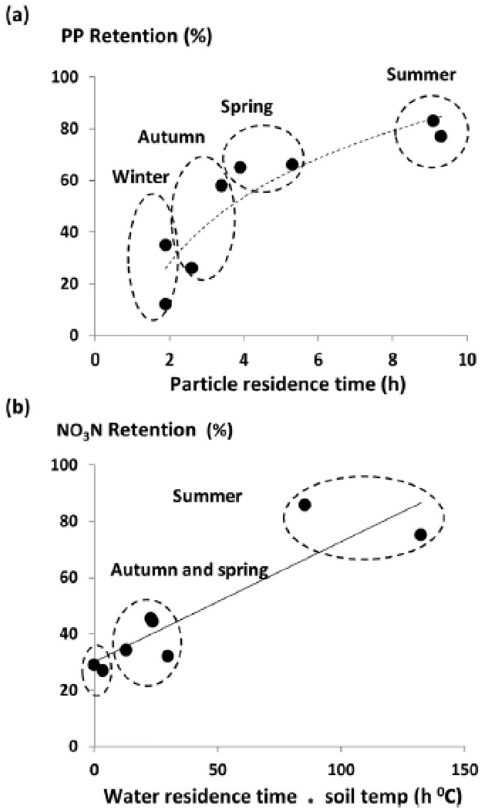

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Table 1

Meteorological and hydrochemical parameters, including mean delay in flow peaks (Qpeak), mean delay in turbidity (Turb) peaks, inlet load, and free water surface constructed wetland (CW) retention of suspended solids (SS), particulate phosphorus (PP), and nitrate nitrogen (NO_3N) in two hydrological years (2012/2013 and 2013/2014). All load estimations are related to catchment area. Inlet load and retention of SS and NO_3N are based on: (i) flow-proportional sampling and inlet and outlet water flow (2Q) and (ii) hourly recordings of FTU units and NO_3N concentrations measured by sensors and 2Q.

Hydrological year	Autumn Oct-Dec		Winter Jan-March		Spring April-June		Summer July-Sept	
	12/13	13/14	12/13	13/14	12/13	13/14	12/13	13/14
Air temperature (°C)	2.0	4.7	−4.6	1.2	10.8	9.8	15.1	15.3
Soil temperature (°C)	4.6	5.6	−0.2	1.8	8.8	6.0	14.2	14.2
Precipitation (mm)	222	159	68	146	121	126	162	181
Runoff inlet (mm)	98	25	47	74	47	25	3	4
Mean detention time (days)	0.6	5.4	2.9	1.9	2.8	6.3	52	38
Mean Qpeak delay (hours)	1.4	4.2	0.4	1.9	1.1	6.8	9.3	6.0
Runoff outlet (mm)	76	19	39	63	46	19	1	2
Seepage + other losses (mm)	21	6	8	10	1	6	2	2
Mean Turb peak delay (hours)	2.6	3.9	1.9	1.9	3.4	5.3	9.3	9.1
SS (i) inlet (kg ha^{-1} $quarter^{-1}$)	332	70	35	95	81	11	2	10
SS (ii) inlet (kg ha^{-1} $quarter^{-1}$)	314	91	35	96	62	10	3	8
SS (i) retention (kg ha^{-1} $quarter^{-1}$)	96	52	13	35	53	5	2	8
SS (ii) retention (kg ha^{-1} $quarter^{-1}$)	44	71	–[a]	26	16	4	2	7
PP inlet (kg ha^{-1} $quarter^{-1}$)	0.45	0.08	0.04	0.12	0.09	0.03	0.002	0.02
PP retention (kg ha^{-1} $quarter^{-1}$)	0.11	0.05	0.01	0.04	0.05	0.02	0.002	0.02
NO_3N (i) inlet (kg ha^{-1} $quarter^{-1}$)	0.59	0.81	0.29	2.2	0.64	0.82	0.04	0.11
NO_3N (ii) inlet (kg ha^{-1} $quarter^{-1}$)	0.56	0.87	0.30	2.2	0.63	0.81	0.05	0.07
NO_3N (i) retention (kg ha^{-1} $quarter^{-1}$)	0.21	0.34	0.08	0.59	0.19	0.39	0.03	0.10
NO_3N (ii) retention (kg ha^{-1} $quarter^{-1}$)	0.15[b]	0.35	0.11[b]	0.86	0.10	0.28	0.04	0.06

[a] Possible particle re-suspension at outlet measured by the sensors, but not the automatic sampler.

[b] Concentrations based on method (i) for 1–2 months with periodically disturbed recording by the sensor.

Table 2

Water balance of the free water surface constructed wetland (CW) with quarterly seepage and other losses (%) relative to inlet runoff, and wetland retention of suspended solids (SS), total phosphorus (TP), particulate P (PP), dissolved reactive P (DRP), total nitrogen (TN), nitrate N (NO_3N), organic N (OrgN), and organic carbon (OrgC). Retention of SS and NO_3N are based on flow-proportional sampling and inlet and outlet water flow (2Q). Values in brackets are SS and NO_3N retention based on values from sensors and 2Q.

Hydrological year	Autumn		Winter		Spring		Summer	
	Oct-Dec		Jan-March		April-June		July-Sept	
	12/13	13/14	12/13	13/14	12/13	13/14	12/13	13/14
Water balance								
Seepage + other losses (%)	22	24	16	14	1	24	61	51
Wetland retention								
SS (%)	(11) 26	75 (78)	37	(27) 35	(25) 66	(43) 47	(67) 92	(81) 84
TP (%)	37	56	16	39	37	65	84	84
PP (%)	24	66	2	30	58	66	94	85
DRP (%)	31	64	26	37	23	36	92	36
TN (%)	73	42	85	33	20	49	80	82
NO_3N (%)	(25) 35	(41) 44	27 (35)	23 (33)	(21) 30	(33) 48	(92) 95	(65) 85
OrgN (%)	82	32	94	< 0	< 0	27	59	78
OrgC (%)	34	35	43	19	8	30	54	69

Table 3

Mean seasonal retention by the free water surface constructed wetland (CW) of suspended solids (SS), total phosphorus (TP), particulate P (PP), dissolved reactive P (DRP), total nitrogen (TN), nitrate N (NO_3N) organic N (OrgN), and organic carbon (OrgC) in two hydrological years (2012/13, 2013/14) and in total in the two-year period, estimated from runoff at inlet and at outlet (2Q), and from inlet runoff only (1Q).

	Inlet and outlet Q (2Q)					Inlet Q only (1Q)				
	Autumn Oct-Dec	Winter Jan-March	Spring April-June	Summer July-Sept	Two years Oct-Sept	Autumn Oct-Dec	Winter Jan-March	Spring April-June	Summer July-Sept	Two years Oct-Sept
SS (%)	37	37	63	84	40	19	28	60	75	27
TP (%)	32	25	54	84	36	12	13	48	67	21
PP (%)	30	24	60	83	34	13	13	54	75	29
DRP (%)	37	37	63	84	30	13	13	11	94	14
TN (%)	66	54	36	92	56	57	46	27	64	47
NO_3N (%)	39	37	40	82	35	21	15	33	78	22
OrgN (%)	80	81	3	73	75	75	78	15	42	71
OrgC (%)	36	28	16	94	30	16	17	< 0	91	14