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Published in:
Ecohydrology (Online)

DOI:
10.1002/eco.1683

Publication date:
2016

Document version
Accepted manuscript

Document license
Unspecified

Citation for published version (APA):

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Download date: 16. Nov. 2019
Factors affecting retention of nutrients and organic matter in stormwater ponds

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Keywords
Urban runoff, catchment type, pond type, design, phosphorus

Abstract
Stormwater ponds are a common way to handle urban runoff. Different pond designs have been tested for decades to retain as much water as possible. Lately, also retention of nutrients and organic matter has become increasingly important, to reduce the eutrophication of downstream aquatic systems and thereby e.g. fulfill the European Water Framework Directive. We have examined the load of particulate and dissolved fractions of organic matter, phosphorus, nitrogen and iron in 66 Danish ponds to determine the importance of catchment type (66 ponds) and the retention efficiency of the ponds (39 ponds) dependent on their type, age, size and design. The general trend is that discharge from nutrient enriched and industrial areas is the most polluted, while urban and developing areas are the least polluted. Wet ponds combined with vegetated sand filters have higher retentions of the particulate fractions (40-80
% compared to traditional wet ponds (10-20 %). Generally, optimized retention requires a ratio between pond volume and impermeable catchment area of >250 m³ red.ha (reduced or impermeable hectare). Young ponds have higher retention than older ones, especially regarding the particulate fractions of organic matter, phosphorus and nitrogen where 40-50 % is retained in ponds <5 years, 0-30 % in 5-10 year old ponds and almost nothing in ponds >10 years. For the dissolved fractions, the trend is the same, but with lower retentions. Therefore, management and maintenance should be considered for all ponds, to avoid problems of internal loading, filling and resuspension.

Introduction

Stormwater ponds have been built for decades to reduce the hydraulic load from urban runoff on receiving waters. In this manner erosion of riverbanks, uprooting of plants, forced relocation of fauna and deposition of sand are avoided. The best pond design in moist Northern-temperate climate zones like Denmark is wet ponds and wetlands, whereas infiltration ponds are better in arid or semi-arid climate zones due to long, dry periods with a high evaporation rate (Barbosa & Hvitved-Jacobsen, 2001). Wet ponds are only a possibility in these dry areas where constant water sources, like rivers, are available (Koob et al., 1999).

The stormwater quality is dependent on characteristics of the land use, the surface and the traffic density (Gobel et al., 2007). During a 2-year study of a detention pond Hossain et al. (2005) found that inlet concentrations depended on the factors described above, but also on rain intensity and duration, dry periods and maintenance practice. Because of these factors, retention of SS and heavy metals was highly variable. Approaches have been made to take nutrient retention in ponds into account. A large plant cover containing multiple native species might increase the nutrient retention (Mallin et al., 2002), but during autumn the decaying vegetation releases dissolved inorganic nutrients into the water, which results in an export of nutrients from the ponds (Oberts & Osgood, 1991). The physical pond design mainly ensures retention of large, heavy particles and nutrients bound or adsorbed to these particles, while smaller and lighter particles do not have sufficient time to settle (Egemose & Jensen, 2009, Hvitved-Jacobsen et al., 2010, Muthukrishnan & Selvakumar, 2006). Unfortunately, these particles are the most nutrient-rich (Stone & English, 1993). By combining the pond with a porous filter media (often sand), the retention of smaller particulate and dissolved nutrients can be improved (Hvitved-Jacobsen et al., 2010). However, the particles gradually clog the porous filter structure, and the filter material therefore has to be replaced to keep a satisfactory hydraulic conductivity. The efficiency of the filter mostly depends on pond size, to
ensure sufficient time for sedimentation of particles, otherwise these would clog the filter and reduce its life time (Barbosa & Hvitved-Jacobsen, 2001).

There exists a variety of different methods to design ponds, ranging from simple to complex methods requiring computer modeling (e.g. Koob et al., 1999, Hvitved-Jacobsen et al., 2010, Shamsudin et al., 2014). Most designs focus on either water retention or theoretical treatment efficiency of e.g. particles or phosphorus (P). Persson (2000) and Su et al. (2009) focused on the dispersion of the incoming water in ponds depending on different designs, in order to avoid dead zones and short-circuiting. They separately found that the hydraulic and dispersive performance mostly depend on the location of the inlets and outlets and the length-to-width ratio of the ponds. Another approach is to find out when most of the pollution enters the pond. According to Ellis and Hvitved-Jacobsen (1996) 65-75 % of the total suspended solid (SS) load is discharged with the first 25-30 % of runoff. Based on these results and studies of highway runoff, Barbosa and Hvitved-Jacobsen (2001) suggested that pond design should aim at catching all average rain events and first flush of bigger events, while the rest should be by-passed from a stabilization pond prior to the wet pond.

Worldwide, many different types and sizes of stormwater ponds have been constructed to manage runoff from different catchment types. Unfortunately, the performance of these ponds is rarely tested after construction, nor is the environmental effect on the receiving waters. In the present study, 66 Danish stormwater ponds of varying type and age, located in different catchments, were examined with regard to their loading and retention of nutrients and organic matter. To support the interpretation of the results, iron (Fe) and color were also analyzed, as dissolved inorganic P binds strongly to particulate Fe, but Fe also binds to humic acid (measured as color) reducing the P-adsorption. All ponds have been sampled homogeneously and during the same time of year providing a large database allowing comparisons between the ponds. The discharge from the catchments was also examined as well as the nutrient retention in the ponds.

**Materials and methods**

The 66 ponds are situated in the Municipality of Aabenraa in the Southern part of Denmark (characteristics in Table 1). Half of the ponds are located in the cities of Aabenraa and Padborg, with 22 and 10 ponds, respectively. The remaining 34 ponds are distributed in smaller cities and villages (Figure 1). Based on the dominating land use, the pond catchments have been divided into 6 types: 1) developing areas that contain roads and sewers but have no other
human impact yet, 2) rural areas that mostly comprised of villages in agricultural areas, 3) urban areas, 4) industrial areas, characterized as light industry as Denmark does not host heavy industry, 5) mixed areas of urban and industrial influence and 6) nutrient enriched areas with high nutrient concentrations in runoff due to mistaken connections of sewage pipes to the stormwater system and/or dairy/grain handling industries or similar industries in the catchment. The examined ponds consisted of 46 wet ponds, 7 wet ponds combined with a vegetated sand filter placed within the pond, just before the outlet, 5 ditches, 5 grooves with overflow possibility to a detention area, two subsurface magazines and one dry pond.

Available GIS themes held information of age since construction/renovation, permanent water depth (if wet pond), maximum water depth and slope of banks. The GIS themes also included maps with coordinates of inlet/outlet and polylines of the sewer system and receiving waters. The GIS information allowed calculations of distance between inlet and outlet, pond area, wet volume (only wet ponds) and storage volume. Maps of the sewer system were used to identify the catchment area for each pond, including the drainage coefficient (impermeable area in percentage of total area), calculated in each catchment. Finally, plant cover was estimated visually (coverage in percentage of the total pond area) in the wet ponds during the sampling campaign.

The ponds were sampled during 10 days with rain in December 2011 and January 2012. During the sampling period, precipitation data were retrieved from two national rain gauges; one situated in the center of Aabenraa and the other approx. 7 km south of Aabenraa. The distance between Aabenraa and Padborg is 23 km. Annual precipitation data from 1999-2012 were retrieved from the rain gauge in Aabenraa, except data from 2008-2009 which were left out, due to problems with the rain gauge.

Flow measurements were conducted in the inlet and outlet pipes in one of three ways: 1) velocity measurement with an Ott kleinflügel propeller instrument; 2) direct flow measurement conducted with a measuring cylinder and a timer. This was only possible when the pipe was positioned higher than the water table; 3) simple velocity measurement of travel time and distance for a small floating stick. The latter method was less precise compared to the other methods, and was only used as a last alternative.

Water samples were collected in the inlet and outlet (either in a nearby well or directly in the pipe) and in the middle of the pond. pH, oxygen and temperature was measured by YSI electrodes on site. Known volumes of each water sample were filtered in triplicate on pre-washed, pre-ignited and pre-weighed Whatman GF/C filters (pore size 1.2 µm) for SS, loss of
ignition (LOI), particulate phosphorus (PP) and particulate iron (PFe). SS was measured in triplicate on all three filters (105 °C, 24 h), whereas LOI was measured on one filter (520 °C, 2 h). PP and PFe were measured by boiling the combusted filter in 1 M HCl (1 h) followed by determination of dissolved inorganic phosphorus (DIP) and dissolved iron (DFe) in the extract (Andersen, 1976). The remaining two filters were kept for analysis of heavy metals (Egemose et al. 2015).

The filtered water was analyzed for nitrate (NO₃⁻), nitrite (NO₂⁻), ammonium (NH₄⁺), total dissolved phosphorus (TDP), DIP, DFe, dissolved organic carbon (DOC) and color. NO₃⁻, NO₂⁻ and NH₄⁺ were analyzed spectrophotometrically on a flow injection system (QuickChem 8500 Series, Lachat Instruments, QuickChem method 10-107-041-C). DIP was measured by the molybdenum-blue method (Koroleff, 1983). TDP was measured as DIP after wet oxidation with potassium peroxodisulfate. DFe was measured by the ferrozin method (Gibbs, 1979). DOC was analyzed with infrared spectrophotometry on a TOC 5000 total organic carbon analyzer. Color was measured according to Hongve and Akesson (1996).

Total phosphorus (TP) was measured as TDP on an unfiltered sample. Total nitrogen (TN) was measured as NO₃⁻ on an unfiltered sample after digestion with potassium peroxodisulfate and sodium hydroxide (QuickChem method 31-107-04-3-B).

Retention in percentage was calculated based on measured in- and outlet concentrations and flow. Data were tested for normality using Sapiro-Wilk test, but since data generally did not follow a normal distribution, non-parametric tests (α < 5%) were used. Kruskal-Wallis one-way analysis of variance was used to compare concentrations with pond and/or catchment parameters, and the non-parametric 2-sample Kolmogorov-Smirnov test was used afterwards to find significant differences in specific sample pairs. Spearman’s rank order correlation was used to find correlations between two variables, whereas linear regression was used when an independent and a dependent variable were present. For each parameter, the measured concentrations and/or retentions varied considerable. To prevent remote data points from dragging the average in one direction, we decided to use median values instead of averages throughout the article.
Results

Runoff related to rainfall history

Catchment runoff depends on rainfall history, and hence on the pond inflow. In order to evaluate this correlation, all ponds with more than one inlet (n=22) were left out of the analysis, since it was difficult to calculate the average inflow in these cases. Additionally, ponds without measurable flow the day of sampling (n=19) and ponds with flow >30 l s$^{-1}$ (n=2) were left out of the analysis, leaving 27 ponds for the analysis.

As the study was conducted during 2 months, the precipitation history differed. In order to take this into account the amount of water (m$^3$) falling on the impermeable catchment area was calculated for each pond at different time periods prior to sampling. This method was described in Egemose et al. (2011). Linear regressions between precipitation history at previous time steps (30 minutes to 7 days) and the measured flow showed significant correlations (p<0.001) for all 16 time periods analyzed (Figure 2A). Coefficients of determination ranged between 0.37 and 0.79, and did not show any clear tendencies to either increase or decrease. The resolution of the precipitation data was 1 hour. Using precipitation data with a lower resolution would give a slightly worse but still significant fit, e.g. the previous 5 days with a resolution of 1 hour ($R^2=0.67$, p<0.001) and 1 day ($R^2=0.64$, p<0.001). Only one rain gauge located in Aabenraa (approx. 27 km from the furthermost pond) provided precipitation data for this analysis. By using a resolution of 1 h, precipitation from the previous 5 days and only ponds close to the rain gauge (n=20), the fit was slightly better ($R^2=0.71$, p<0.001). These results showed that runoff to ponds can be predicted more precisely by using a nearby rain gauge with high resolution and knowledge of precipitation history.

The size of the impermeable catchment area was correlated to the measured runoff (Figure 2B), where a significant linear regression existed for impermeable area >1 ha (n=21, p<0.001), but not for areas <1 ha (n=6, p=0.697). The ratio between impermeable area and total catchment area also correlated linearly with the measured flow (impermeable areas <20 %, n=5, p=0.029, impermeable areas >20 %, n=22, p < 0.001). This clearly showed that runoff also depends on the size of the impermeable area.

Calculation of annual precipitation and the yearly number of rainy days were performed for the period 1999-2012 in Aabenraa (Table 2). On average, it rained 153 days year$^{-1}$ corresponding to 822 mm year$^{-1}$, mainly dominated by small rain events below 10 mm day$^{-1}$.
and even below 5 mm day\(^{-1}\) (86 and 63 \%, respectively). Days with more than 50 mm rain only occurred 4 times during the 14 years data set.

**Catchment influence on inlet concentrations**

The measured inlet concentrations varied dependent on parameter and catchment type, with the following concentrations of particulate matter and nutrients: SS (4-58 mg l\(^{-1}\)), LOI (2-35 mg l\(^{-1}\)), NO\(_3^−\) (395-1116 µg l\(^{-1}\)), PP (24-173 µg l\(^{-1}\)), TDP (22-108 µg l\(^{-1}\)). TFe also varied (370-2201 µg l\(^{-1}\)), resulting in a TFe:TP ratio of 6-12. The 6 different catchment types were proven to influence the inlet concentrations (Table 3). The highest concentrations came from nutrient enriched catchments, and were 200-500 \% higher than those from the second highest catchment type, except DOC, NO\(_3^−\) and DFe where the highest concentrations came from developing, urban and rural catchments, respectively. Ponds with industrial and mixed catchments were very alike, and only differed for NO\(_3^−\). Urban, rural and developing catchments had the lowest inlet concentrations, with developing areas most frequently receiving the lowest concentrations.

Industrial, urban and rural catchments were represented with 15-19 ponds per catchment type, while nutrient enriched, mixed and developing catchments were represented with 4-6 ponds. The latter is problematic for the Kruskal-Wallis analysis as groups of less than 5 are too small to give a statistically-sound chi-squared distribution, and the statistics should therefore be used with caution. The test showed significant differences between catchment types for 8 of the 15 measured parameters, namely SS, LOI, NO\(_2^−\), NH\(_4^+\), PN, TP, PP and TFe (Table 3). For all 8 parameters nutrient enriched and urban catchments were significantly different. Nutrient enriched and developing catchments, and also industrial and urban catchments, were significantly different concerning the particulate parameters (SS, LOI, TP and PP), while the other combinations of catchment types varied dependent on parameter.

Catchment size (both total and impermeable area) and the drainage coefficient showed significant differences between catchment types. Generally, mixed and industrial catchments were largest (24-31 ha, 11-14 red. ha (reduced or impermeable hectare)) and had the highest drainage coefficient (39-45 \%), while rural and developing catchments were smallest (5-9 ha, 3 red. ha) and had the lowest drainage coefficient (5-25 \%). Nutrient enriched and urban catchments were in between (11-13 ha, 3-6 red. ha, 30-38 \%). The size of the impermeable area and the drainage coefficient affected the inlet concentrations (Figure 3). The particulate parameters (SS, LOI and PP) increased with increasing impermeable area and drainage coefficient. The only exception was that PP remained on the same level up to an impermeable area of 35 \%, whereafter it increased. There were no trends for the dissolved parameters (NO\(_3^−\)
and TDP), when plotted against impermeable area and drainage coefficient, with concentrations of 0.6-1.3 mg NO$_3$-$l^{-1}$ and 20-33 µg TDP $l^{-1}$. This meant that while the particulate parameters showed an increasing trend, when plotted against impermeable area and drainage coefficient, the dissolved parameters varied, indicating that they depended on neither impermeable area nor drainage coefficient. There were strong positive correlations between total area and the concentration of SS, LOI, TFe and PFe, between impermeable area and SS, LOI, PP, TFe, PFe and DFe, and between drainage coefficient and NO$_2^-$, NH$_4^+$, TFe and PFe. In addition, total area, impermeable area and drainage coefficient correlated positively with each other.

Measurements of pH, oxygen and color in runoff did not vary significantly between catchment types. Median pH values varied from 6.9-7.7, with nutrient enriched catchments having the lowest value and mixed and developing catchments the highest, while industrial, urban and rural catchments were in between with pH 7.2-7.4. The median oxygen saturation was above 80 % for all catchments, with lowest values in runoff from nutrient enriched, industrial and mixed catchments (83.4-86.7 %) and highest values from urban, rural and developing areas (90.8-93.6 %). The median inlet concentrations of color varied from 11.0-17.3 Pt units $l^{-1}$ with the lowest concentrations observed in urban and developing areas and the highest in industrial catchments.

The measured parameters also correlated with each other. Especially the particulate fractions correlated with each other. For instance, a significant positive correlation existed between SS and LOI, and both of them correlated positively with PP and PFe. Positive correlations also existed between PP, PFe and PN. Concerning the dissolved fractions, there were significant positive correlations between DIP, DFe and fractions of N. DOC correlated negatively with SS and LOI, and positively with TN, PN, DFe and color. Color showed similar trends by correlating positively with different fractions of Fe and N.

A comparison of inlet and outlet concentrations of SS, TN and TP (Figure 4) showed that high concentrations in and out of the ponds went together for TN and mostly for TP, whereas SS varied without trends. As seen in Table 3, TP mainly consisted of PP whereas TN mainly consisted of dissolved N. SS and TP had varying inlet concentrations depending on catchment type and more homogenous outlet concentrations. On the other hand, inlet and outlet concentrations of TN were very similar regardless of the catchment type.
Retention in ponds

Pond geometry, age and type were important for the retention. Parallel ponds and ponds with no outlet or with joint inlet and outlet were left out of this analysis, since it was impossible to calculate the retention. In addition, ponds without flow measurements were left out, since flow was required to find the retention. This left 39 ponds for analyzing retention (Table 4). None of the retentions differed significantly between pond types, probably due to the very low number of ponds in 3 of the 4 pond types (27 out of 39 ponds were wet ponds). Trends of different retention between pond types were though seen (Table 4, Figure 5). Wet ponds with filters were generally best at retaining SS, LOI, TP, PP, TDP, DIP, NO₃⁻ and NO₂⁻. On the other hand, this pond type seemed to be less efficient regarding DOC, NH₄⁺ and DFe. Wet ponds had a fairly good retention, especially regarding DIP, DFe and particulate fractions except PFe. Ditches only had a reasonable retention of DOC and NO₂⁻. It seemed that grooves with storage did neither retain nor release the measured parameters. Generally, none of the pond types seemed able to retain NH₄⁺ and TFe (the latter mostly due to poor PFe retention).

Apart from pond types, the pond age proved to affect the retention. Age since construction correlated negative with retention of SS, TP and TDP. Age since renovation correlated negative with SS, TP, LOI and PP (Figure 6C), but it also correlated positively with NH₄⁺, indicating that NH₄⁺ was the only parameter that was retained better in old ponds. Pond geometry also affected the retention, especially volume, since it correlated positively with SS, LOI, all P fractions and DFe. Area correlated positively with SS, LOI, TDP and DFe, while depth only correlated positively with TN. Ratio between pond volume and impermeable area correlated positively with SS, PP, TDP and DIP (Figure 6B). On the other hand, no significant correlations were found for neither distance between inlet and outlet, plant coverage nor storage area, -volume and -depth. Attention should be paid to three parameters showing important trends (Figure 6). The distance between inlet and outlet, and the ratio between pond volume and impermeable area shared the same trend, the higher the distance or ratio, the better the retention of SS, LOI, NO₃⁻, PP and TDP. Number of years since renovation gave the opposite trend, indicating that younger ponds have higher retention. Pond retention was generally efficient (>30 %) the first 5 years for newly constructed or renovated ponds, whereupon the retention drops significantly to <10 % for all 5 parameters.
Discussion

Runoff related to rainfall history

Significant linear regressions between precipitation history and measured inflow were found. The conversion from mm to m$^3$, based on the impermeable area, made it possible to compare different sized catchments. The distance from the individual pond to the rain gauge has a small influence on the fit, since a shorter distance is equivalent to a smaller uncertainty in precipitation history. The regressions are though significant (p<0.001) independent of the distance, which may be due to the fact that the furthermost pond was only approx. 27 km away from the rain gauge and that most of the ponds are situated relatively close to the rain gauge.

We expected to find correlations between impermeable area and runoff and there seems to be two trends; one for small areas and one for larger areas. This is probably caused by the varying travel distance for any raindrop from catchment surface to pond inlet, as the mean of this distance is shorter for smaller areas. The largest impermeable catchment was 47.8 ha (Table 1). Since most of the ponds are situated in small cities (21,900 inhabitants in Aabenraa) compared to European countries, there may be a third correlation trend for larger cities.

Beside differences in travelling distance, the impermeable areas differed regarding size/shape, material and age. This might explain the irregular behavior of the determination coefficients in Figure 2A. The determination coefficients varied a lot with precipitation up to 24 hours before sampling, indicating that the catchment were of great importance for the runoff e.g. due to initial losses to wetting, storage and interception. From 1 to 7 days the best fit was achieved when using precipitation from the previous 5 days, which was also observed by Egemose et al. (2011). This indicated that factors concerning the impermeable area were evened out after 1 day.

Mallin et al. (2002) found that rainfall history affects the level of SS (the day of sampling plus one day before) and nutrients (the day of sampling plus two days before). We observed a similar significant and positive trend for SS, N and P, but they are all discharged within 1 day. Our results showed that the dissolved fraction was discharged faster than the particulate fraction, indicating accumulation of particulate matter in the catchment. By knowing the correlation between rainfall history and SS, N and P for a specific catchment, the annual load to an existing or new pond could be calculated. It hereby becomes possible to choose a pond type and size that fits the likely inlet load and ensures a sufficient retention.
**Catchment influence on inlet concentrations**

Gobel et al. (2007) divided urban surface runoff into rainwater runoff, roof runoff (different materials) and runoff from traffic areas (different traffic intensities). We were interested in the concentrations entering the ponds and not the concentrations derived from specific parts of the catchment. Therefore, we chose a different approach and categorized the catchment types more generally based on specific activities/land uses. The median concentrations usually decreased in the following order: Nutrient enriched >> mixed and industrial > rural and urban > developing, meaning that the areas most affected by human activities (traffic and industry) are generally receiving the highest concentrations.

Even though many of the studied ponds have high retentions, the outlet concentrations tend to depend much on the inlet concentration and thereby indirectly on catchment type. For some parameters, a high inlet concentration equals a corresponding high outlet concentration, whereas the concentrations varied more for other parameters. More advanced treatment might therefore be required to ensure low outlet concentrations from ponds in industrial or nutrient enriched catchments compared to developing catchments.

The measured concentrations are in accordance with extensive literature reviews on stormwater runoff (e.g. Gobel et al., 2007, Makepeace et al., 1995), though our concentrations are in the lower end of the intervals. This is probably due to lower traffic intensities in the relatively small cities in the municipality of Aabenraa. The measured pH values are similar to what Gobel et al. (2007) found in trafficked areas independent of traffic intensity, but higher than what he found for roof runoff, which indicates that the runoff from the studied catchments are mostly influenced by roads and car parks. Regarding oxygen, we found high concentrations independent of catchment types, as sampling was conducted in winter with fully aerated inlet water and low oxygen consumption/production in the ponds. In summer we might have seen large differences among the catchment types as oxygen concentrations are mainly driven by temperature dependent mineralization/photosynthetic processes.

Significant differences between catchment types were found for total area and drainage coefficient. Industrial areas tend to have fewer ponds per ha than urban areas, which is explained by bigger ponds in industrial areas (median area >1500 m$^2$) compared to urban areas (median area <800 m$^2$). The concentrations of SS, LOI and PP increased with increasing impermeable area and drainage coefficient, probably because the larger catchments are dominated by industrial activities and a higher/heavier traffic load, whereas the smaller catchments are dominated by rural areas with less traffic.
The developing catchments tend to have more ponds per ha than older catchments. This is a general tendency in Denmark, with construction of more ponds to prevent flooding of urban areas and to reduce the hydraulic load on receiving waters. By constructing more ponds per ha the annual loading on each pond becomes smaller. This may increase the retention and prolong the time before renovation is required (Figure 6C).

SS is a simple and useful indicator for PP, PFe and PN through strong correlations between these parameters. TN and TP can also be useful indicators, since they correlate with particulate and dissolved fractions of nutrients, Fe and organic matter. This is in accordance with Ingvertsen et al. (2011), who suggested 8 indicator parameters including i.e. TN, TP and the fine fraction of SS (<63 µm).

Retention in ponds

The results indicate that retention in the ponds depends in part on pond type. The wet ponds make up most of our data foundation. The reason for the relative low retention in these is probably that first flush is not included in the samples (point measurements in the middle of the event). The retention is primarily dominated by sedimentation and adsorption. Since this pond type includes many of the oldest ponds, the overall retention potential is smaller than for newer ponds, especially concerning dissolved nutrients. Wet ponds with filters had the best retention, especially concerning the particulate fractions due to sedimentation in the pond, followed by filtration and adsorption in the filter just before discharge. Ponds of this type are also the newest, which may also explain the good retention of dissolved nutrients. Ditches tend to discharge previously retained nutrients and organic matter, including any nearby dead vegetation and leaf fall. This is logical based on the long and shallow design which causes short retention time and high flow rate (Persson, 2000, Su et al., 2009) that will flush everything out of the ditch each time it rains. Grooves with storage are open pipes that allow excess runoff to overflow a small area before returning to the sewer system into the same open pipes. Therefore, it makes good sense that they neither retain nor release nutrients and organic matter. Common for all examined pond types is that they do not retain TFe (mostly due to poor PFe retention). Birch et al. (2005) observed that i.e. Fe is discharged in higher concentrations than it enters the pond, probably due to leaching from clay materials. The inability to retain TFe can be good for the downstream water quality, as the remaining Fe in the water acts as binding capacity for remaining P. The potential binding capacity is though not in the pond.
Retention tends to correlate with distance between inlet and outlet and storage capacity. This is expected as both parameters are directly connected to the retention time in the pond and the larger the pond, the better the retention. This is mainly connected to the significant correlation between retention and ratio between pond volume and impermeable catchment area, but also to longer distance between inlet and outlet and hence a longer retention time. These findings are of great importance for consultants when designing new ponds but also when restoring old ponds. Age since construction and age since renovation both correlate significantly with retention, as less material can be resuspended and mineralized in new ponds. To keep a high removal efficiency in ponds, managers should make maintenance plans including sediment removal, already from the design phase. During summer, vegetation will slow down the water and thereby prolong the distance between inlet and outlet, and they will take up dissolved nutrients from the water. This effect is smaller during winter due to vegetation decay, and as expected, we did not see any trends towards a connection between plant cover and retention (Oberts & Osgood, 1991). It may though be different in summer (Mallin et al., 2002).

**Conclusion**

The results from 66 stormwater ponds showed typical inlet and outlet concentrations for different catchment types. Industrial and very nutrient enriched areas should have a high priority since they contribute with higher concentrations into, but also out of, the ponds compared to urban and developing areas. To ensure optimal retention, and as little influence on the receiving water as possible, attention should be paid to pond type, size and age. In moist climates like Denmark a wet pond combined with vegetated sand filter will be optimal, alternatively just a wet pond. We suggest that the distance between inlet and outlet should be at least 50 m, but preferable >80 m, whereas the ratio between pond volume and impermeable catchment area should be >250 m³ red.ha⁻¹, which is in accordance with e.g. Hvidtved-Jacobsen et al. (2010). The suggested requirements ensure a long retention time and use of the whole water body. Unfortunately, many existing ponds have a poor retention due to non-functional design. During heavy rain events, first flush will be flushed directly through these small ponds and into the receiving waters inducing negative effects. Finally, the age since either construction or renovation should be less than 5 years for optimal retention, and management and maintenance should be considered for older ponds.

By respecting these few guidelines the pond should be able to retain >80 % SS, >60 % LOI, >80 % NO₃⁻, >40 % PP and >50 % TDP.
Acknowledgement

Thanks to Arwos (owner of the ponds), for fruitful cooperation and for providing background data and information. We thank lab technicians at University of Southern Denmark for help with chemical analysis. The study was supported by 1) Industrial/commercial PhD project (Melanie J. Sønderup) granted by the Danish Ministry of Science, Innovation and Higher Education FI case number 11-109519, 2) Centre for Lake Restoration - a Villum Kann Rasmussen Centre of Excellence and 3) Oticon Scholarship Award granted to Anna Grudinina.

References


Table 1. Characteristics of the 66 stormwater ponds. Wet = wet retention pond, filter = wet retention pond followed by a vegetated sand filter, groove = groove with overflow possibility to a detention area, ditch = ditch with detention capacity, closed = Subsurface magazines with detention capacity, dry = dry detention pond. Areas, volumes and ages are all given as range (1st line) and median (2nd line, bold).

<table>
<thead>
<tr>
<th>Catchment type</th>
<th>No. of ponds</th>
<th>Pond type</th>
<th>Total catchment area [ha]</th>
<th>Reduced catchment area [red. ha]</th>
<th>Pond volume [m³]</th>
<th>Year of construction</th>
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<tr>
<td>Developing</td>
<td>5</td>
<td>3 wet, 2 filter</td>
<td>3.4-28.4 5.4</td>
<td>0.2-9.9 1.0</td>
<td>84-3322 554</td>
<td>1971-2011 2008</td>
</tr>
<tr>
<td>Rural</td>
<td>19</td>
<td>15 wet, 2 grooves, 1 ditch, 1 closed</td>
<td>2.4-19.1 9.0</td>
<td>0.4-5.7 2.5</td>
<td>15-1451 286</td>
<td>1975-2010 2003</td>
</tr>
<tr>
<td>Urban</td>
<td>15</td>
<td>9 wet, 3 ditch, 2 grooves, 1 filter</td>
<td>0.6-65.9 11.3</td>
<td>0.2-19.8 3.1</td>
<td>18-633 200</td>
<td>1970-2007 1990</td>
</tr>
<tr>
<td>Mixed</td>
<td>6</td>
<td>6 wet</td>
<td>12.4-68.1 31.1</td>
<td>7.0-27.0 13.8</td>
<td>28-1261 569</td>
<td>1960-2007 1994</td>
</tr>
<tr>
<td>Industrial</td>
<td>17</td>
<td>11 wet, 4 filter, 1 dry, 1 groove</td>
<td>1-95.6 23.5</td>
<td>0.6-47.8 10.6</td>
<td>1159-5209 2371</td>
<td>1975-2009 1993</td>
</tr>
<tr>
<td>Nutrient enriched</td>
<td>4</td>
<td>2 wet, 1 closed, 1 ditch</td>
<td>8.5-18.8 13.2</td>
<td>2.6-10.1 5.6</td>
<td>43-1398 354</td>
<td>1979-2006 1998</td>
</tr>
</tbody>
</table>

Table 2. Annual precipitation data from the rain gauge positioned in the center of Aabenraa available from 1999-2012. Direct addition of data is not possible due to average values.

<table>
<thead>
<tr>
<th>Precipitation [mm year⁻¹]</th>
<th>Days with precipitation</th>
<th>No. of events &lt;5 mm d⁻¹</th>
<th>No. of events &lt;10 mm d⁻¹</th>
<th>No. of events &gt;10 mm d⁻¹</th>
<th>No. of events &gt;50 mm d⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min.</td>
<td>639</td>
<td>123</td>
<td>81</td>
<td>110</td>
<td>12</td>
</tr>
<tr>
<td>Max.</td>
<td>990</td>
<td>195</td>
<td>128</td>
<td>171</td>
<td>36</td>
</tr>
<tr>
<td>Avg.</td>
<td>822</td>
<td>153</td>
<td>96</td>
<td>132</td>
<td>21</td>
</tr>
</tbody>
</table>
Table 3. Median inlet concentrations for all 66 ponds and the 6 catchment types. Note that particulate and dissolved fractions of the same parameter do not add up to total concentration of the same parameter due to median values. The highest concentration of each parameter is marked by gray background. Parameters with bold are indicating that at least 2 of the catchment types are significantly different, specified with superscript letters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>All n=66</th>
<th>Nutrient enriched n=4</th>
<th>Industrial n=17</th>
<th>Mixed n=6</th>
<th>Urban n=15</th>
<th>Rural n=19</th>
<th>Developing n=5</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS</td>
<td>mg l(^{-1})</td>
<td>7.9</td>
<td>57.8(^{A,B})</td>
<td>12.9(^{C})</td>
<td>16.0</td>
<td>5.9(^{A,C})</td>
<td>6.8</td>
<td>4.0(^{B})</td>
</tr>
<tr>
<td>LOI</td>
<td>mg l(^{-1})</td>
<td>5.0</td>
<td>34.8(^{A,B})</td>
<td>9.8(^{C})</td>
<td>9.3</td>
<td>4.6(^{A,C})</td>
<td>3.5</td>
<td>2.0(^{B})</td>
</tr>
<tr>
<td>DOC</td>
<td>mg l(^{-1})</td>
<td>3.8</td>
<td>4.3</td>
<td>4.3</td>
<td>3.3</td>
<td>3.6</td>
<td>4.0</td>
<td>4.8</td>
</tr>
<tr>
<td>TN</td>
<td>µg l(^{-1})</td>
<td>1240</td>
<td>2533</td>
<td>1247</td>
<td>1577</td>
<td>1210</td>
<td>1233</td>
<td>629</td>
</tr>
<tr>
<td>NO(_3^+)</td>
<td>µg l(^{-1})</td>
<td>750</td>
<td>754</td>
<td>440</td>
<td>926</td>
<td>1116</td>
<td>885</td>
<td>395</td>
</tr>
<tr>
<td>NO(_2^-)</td>
<td>µg l(^{-1})</td>
<td>8</td>
<td>44(^{A,B})</td>
<td>10(^{C})</td>
<td>12</td>
<td>6(^{A,D})</td>
<td>9(^{B,D})</td>
<td>4(^{C})</td>
</tr>
<tr>
<td>NH(_4^+)</td>
<td>µg l(^{-1})</td>
<td>89</td>
<td>639(^{A,B,C,D})</td>
<td>113(^{A,E})</td>
<td>98</td>
<td>71(^{B,E})</td>
<td>95(^{C,F})</td>
<td>52(^{D,F})</td>
</tr>
<tr>
<td>PN</td>
<td>µg l(^{-1})</td>
<td>220</td>
<td>785(^{A})</td>
<td>325(^{B})</td>
<td>350(^{C})</td>
<td>16(^{A,B,C})</td>
<td>194</td>
<td>19</td>
</tr>
<tr>
<td>TP</td>
<td>µg l(^{-1})</td>
<td>60</td>
<td>372(^{A,B})</td>
<td>107(^{C})</td>
<td>121</td>
<td>41(^{A,C})</td>
<td>62</td>
<td>32(^{B})</td>
</tr>
<tr>
<td>TDP</td>
<td>µg l(^{-1})</td>
<td>28</td>
<td>108</td>
<td>34</td>
<td>33</td>
<td>22</td>
<td>32</td>
<td>27</td>
</tr>
<tr>
<td>DIP</td>
<td>µg l(^{-1})</td>
<td>25</td>
<td>103</td>
<td>31</td>
<td>28</td>
<td>21</td>
<td>31</td>
<td>21</td>
</tr>
<tr>
<td>PP</td>
<td>µg l(^{-1})</td>
<td>37</td>
<td>173(^{A,B})</td>
<td>86(^{C})</td>
<td>87</td>
<td>24(^{A,C})</td>
<td>42</td>
<td>25(^{B})</td>
</tr>
<tr>
<td>TFe</td>
<td>µg l(^{-1})</td>
<td>456</td>
<td>2201(^{A})</td>
<td>660</td>
<td>677</td>
<td>370(^{A})</td>
<td>443</td>
<td>381</td>
</tr>
<tr>
<td>DFe</td>
<td>µg l(^{-1})</td>
<td>111</td>
<td>125</td>
<td>117</td>
<td>93</td>
<td>36</td>
<td>170</td>
<td>131</td>
</tr>
<tr>
<td>PFe</td>
<td>µg l(^{-1})</td>
<td>287</td>
<td>372</td>
<td>349</td>
<td>369</td>
<td>216</td>
<td>286</td>
<td>217</td>
</tr>
</tbody>
</table>
Table 4. Median retentions (%) for 39 ponds and 4 pond types. The highest retention for each parameter is marked by gray background.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>All n=39</th>
<th>Wet n=27</th>
<th>Wet with filter n=4</th>
<th>Ditch n=4</th>
<th>Groove with storage n=4</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS</td>
<td>6.1</td>
<td>11.1</td>
<td>79.2</td>
<td>-83.1</td>
<td>0.3</td>
</tr>
<tr>
<td>LOI</td>
<td>8.3</td>
<td>21.3</td>
<td>62.4</td>
<td>-88.8</td>
<td>0.7</td>
</tr>
<tr>
<td>DOC</td>
<td>8.0</td>
<td>9.7</td>
<td>-2.5</td>
<td>15.2</td>
<td>-2.7</td>
</tr>
<tr>
<td>TN</td>
<td>7.2</td>
<td>9.5</td>
<td>57.6</td>
<td>5.0</td>
<td>-0.4</td>
</tr>
<tr>
<td>NO\textsubscript{3}^{-}</td>
<td>8.9</td>
<td>12.7</td>
<td>78.5</td>
<td>5.0</td>
<td>0.3</td>
</tr>
<tr>
<td>NO\textsubscript{2}^{-}</td>
<td>0.2</td>
<td>0.2</td>
<td>24.2</td>
<td>19.4</td>
<td>-14.7</td>
</tr>
<tr>
<td>NH\textsubscript{4}^{+}</td>
<td>-12.1</td>
<td>-21.5</td>
<td>-7.7</td>
<td>-10.4</td>
<td>-1.1</td>
</tr>
<tr>
<td>PN</td>
<td>0.9</td>
<td>23.5</td>
<td>22.1</td>
<td>6.5</td>
<td>-10.4</td>
</tr>
<tr>
<td>TP</td>
<td>3.9</td>
<td>3.8</td>
<td>54.7</td>
<td>-55.6</td>
<td>4.7</td>
</tr>
<tr>
<td>PP</td>
<td>3.0</td>
<td>21.6</td>
<td>37.2</td>
<td>-84.4</td>
<td>-0.6</td>
</tr>
<tr>
<td>TDP</td>
<td>4.1</td>
<td>-2.3</td>
<td>47.9</td>
<td>-4.4</td>
<td>7.7</td>
</tr>
<tr>
<td>DIP</td>
<td>12.2</td>
<td>15.2</td>
<td>51.4</td>
<td>6.0</td>
<td>-9.7</td>
</tr>
<tr>
<td>TFe</td>
<td>-0.8</td>
<td>-0.2</td>
<td>-4.0</td>
<td>-46.4</td>
<td>2.8</td>
</tr>
<tr>
<td>DFe</td>
<td>15.4</td>
<td>15.9</td>
<td>0.0</td>
<td>-3.1</td>
<td>14.5</td>
</tr>
<tr>
<td>PFe</td>
<td>-0.9</td>
<td>-0.9</td>
<td>32.4</td>
<td>-75.6</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Figure captions

Figure 1. Map of Denmark (left), the grey area represents the studied municipality. The distribution of ponds (black diamonds) in the study area (right), with identification of the 2 largest cities, Aabenraa and Padborg.

Figure 2. First linear regressions were made between accumulated runoff volume from the catchments before sampling (m\textsuperscript{3}) and the measured flow (l s\textsuperscript{-1}) – regressions are not shown. The resulting coefficient of determination (R\textsuperscript{2}) is shown on the primary y-axis and the ratio between flow and runoff volume is shown on the secondary y-axis. Hereby the same parameters are shown in 2 different ways. On the x-axis is A) Accumulation periods before sampling ranging from 30 minutes to 7 days, and B) Importance of impermeable area in red.ha and %.

Figure 3. Median runoff concentrations for 5 parameters (SS, LOI, NO\textsubscript{3}^{-}, PP and TDP) divided into intervals of impermeable area (ha, left) and drainage coefficient (%). Notice the different units for each parameter given in the legend box.
Figure 4. Median in- and outlet concentrations of SS, TN and TP for the 6 catchment types. For inlet n=66 and for outlet n=64 ponds. Direct subtraction of data to produce retention is not possible due to median values.

Figure 5. Median retentions in the ponds for 5 parameters (SS, LOI, NO₃⁻, PP and TDP) divided into pond type.

Figure 6. Median retentions in the ponds for 5 parameters (SS, LOI, NO₃⁻, PP and TDP) divided into A) distance between in- and outlet (m), B) ratio between pond volume (m³) and impermeable area (red. ha) and C) age since renovation (year).
Figures

Figure 1:

Figure 2:

Figure 3:
Figure 4:
Figure 5:

Figure 6: