ECOHYDROLOGY
Ecohydrol. **9**, 796–806 (2016)
Published online 9 October 2015 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/eco.1683

Factors affecting retention of nutrients and organic matter in stormwater ponds

Melanie J. Sønderup,[1,2]* Sara Egemose,[1] Anders S. Hansen,[3] Anna Grudinina,[4] Martin H. Madsen[5] and Mogens R. Flindt[1]

[1] *Department of Biology, University of Southern Denmark, Campusvej 55, Odense M DK-5230, Denmark*
[2] *Arwos A/S, Forsyningsvejen 2, Aabenraa DK-6200, Denmark*
[3] *Ramboll Denmark A/S, Vejle Division, Lysholt Allé 10, Vejle DK-7100, Denmark*
[4] *Herning Vand A/S, Ålykkevej 5, Herning DK-7400, Denmark*
[5] *EnviDan, Vejlsøvej 23, Silkeborg DK-8600, Denmark*

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. fulfil 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 results showed 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 with traditional wet ponds (10–20%). Generally, optimized retention requires a ratio between pond volume and impermeable catchment area of $>250\,m^3$ 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. Here, 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.

KEY WORDS urban runoff; catchment type; pond type; design; phosphorus

Received 3 September 2014; Revised 16 August 2015; Accepted 17 August 2015

INTRODUCTION

Stormwater ponds have been constructed 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 and 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 water quality of stormwater is dependent on characteristics of the land use, the surface material 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 not only on the factors described previously but also on rain intensity and duration, dry periods and maintenance practice. Because of these factors, retention of suspended solids (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 and 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 and Jensen, 2009; Hvitved-Jacobsen *et al*., 2010; Muthukrishnan and

*Correspondence to: Melanie J. Sønderup, Department of Biology, University of Southern Denmark, Campusvej 55, Odense M DK-5230, Denmark.
E-mail: melanie@biology.sdu.dk

Selvakumar, 2006). Unfortunately, these particles are the most nutrient-rich (Stone and 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, before they reach the filter area. Otherwise, these particles would clog the filter and reduce its lifetime (Barbosa and Hvitved-Jacobsen, 2001).

There exists a variety of different methods to design ponds, ranging from simple to complex methods requiring computer modelling (e.g. Koob *et al*., 1999; Hvitved-Jacobsen *et al*., 2010; Shamsudin *et al*., 2014; Sønderup *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 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 colour were also analysed, as dissolved inorganic P binds strongly to particulate Fe, but Fe also binds to humic acid (measured as colour) 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 I). 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 were divided into six types: (1) developing areas that contained roads and sewers but had no other human impact yet; (2) rural areas that mostly composed 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, seven wet ponds combined with a vegetated sand filter placed within the pond, just before the outlet, five ditches, five grooves

Table I. Characteristics of the 66 stormwater ponds.

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

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 and median (bold).

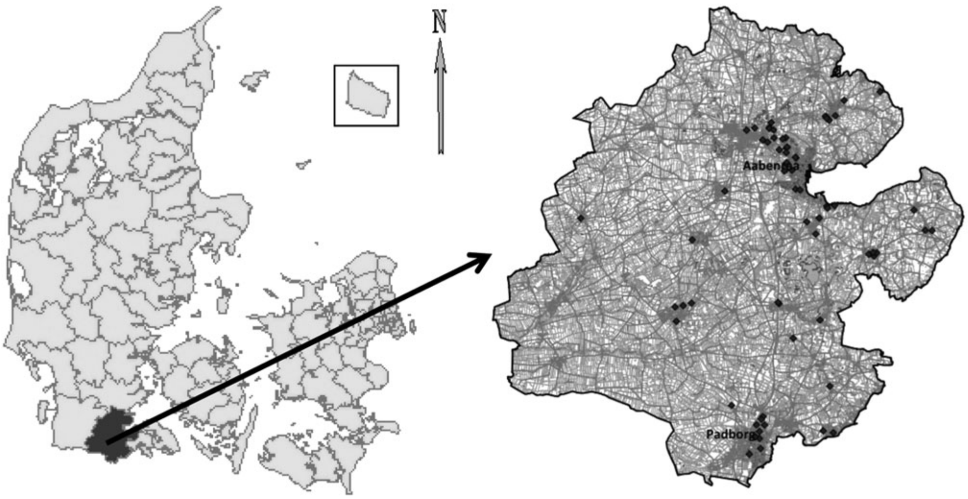

Figure 1. Map of Denmark (left), the dark grey area represents the studied municipality. The distribution of ponds (black diamonds) in the study area (right), with identification of the two largest cities, Aabenraa and Padborg.

with overflow possibility to a detention area, two subsurface magazines and one dry pond.

Available Geographic Information System (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 centre of Aabenraa and the other approximately 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 that were left out, because of problems with the rain gauge.

Flow measurements were conducted in the inlet and outlet pipes in one of the 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 and (3) simple velocity measurement of travel time and distance for a small floating stick. The latter method was less precise compared with 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 were 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 were 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 analysed for nitrate (NO_3^-), nitrite (NO_2^-), ammonium (NH_4^+), total dissolved phosphorus (TDP), DIP, DFe, dissolved organic carbon (DOC) and colour. NO_3^-, NO_2^- and NH_4^+ were analysed 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 analysed with infrared spectrophotometry on a total organic carbon 5000 analyser. Colour 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 NO_3^- 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 inlet and outlet concentrations and flow. Data were statistically tested for normality using Sapiro–Wilk test, but because data generally did not follow a normal distribution, nonparametric tests ($\alpha < 5\%$) were used. Kruskal–Wallis one-way analysis of variance was used to compare concentrations with pond and/or catchment parameters, and the nonparametric two-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 considerably. 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, because it was difficult to calculate the average inflow in these cases. Additionally, ponds without measurable flow on 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 by Egemose *et al.* (2011). Linear regressions between precipitation history at previous time steps (30 min to 7 days) and the measured flow showed significant correlations ($p < 0.001$) for all 16 time periods analysed (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 h. 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 h ($R^2 = 0.67$, $p < 0.001$) and 1 day ($R^2 = 0.64$, $p < 0.001$). Only one rain gauge located in Aabenraa (approximately 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 II). 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 four times during the 14 years data set.

Catchment influence on inlet concentrations

The measured inlet concentrations varied depending on parameter and catchment type, with the following concentrations

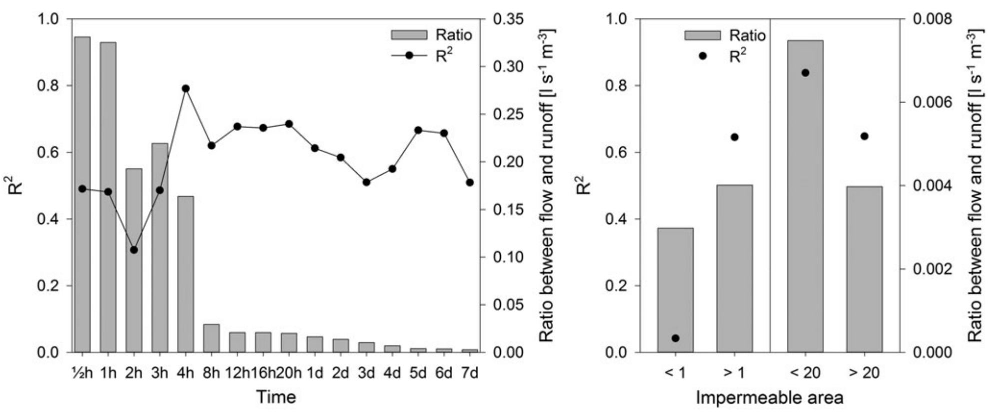

Figure 2. First linear regressions were made between accumulated runoff volume from the catchments before sampling (m^3) and the measured flow ($l\,s^{-1}$) – regressions are not shown. The resulting coefficient of determination (R^2) is shown on the primary *y*-axis, and the ratio between flow and runoff volume is shown on the secondary *y*-axis. Hereby, the same parameters are shown in two different ways. On the *x*-axis is (A) accumulation periods before sampling ranging from 30 min to 7 days and (B) importance of impermeable area in reduced or impermeable hectare and percent.

Table II. Annual precipitation data from the rain gauge positioned in the centre of Aabenraa available from 1999–2012.

	Precipitation (mm year^{-1})	Days with precipitation	No. of events <5 mm day^{-1}	No. of events <10 mm day^{-1}	No. of events >10 mm day^{-1}	No. of events >50 mm day^{-1}
Minimum	639	123	81	110	12	0
Maximum	990	195	128	171	36	1
Average	822	153	96	132	21	0.3

Direct addition of data is not possible due to average values.

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}) and TDP (22–108 µg l^{-1}). Total iron (TFe, i.e. PFe + DFe) also varied (370–2201 µg l^{-1}), resulting in a TFe:TP ratio of 6–12. The six different catchment types were proven to influence the inlet concentrations (Table III). The highest concentrations came from nutrient-enriched catchments and were 200–500% higher than those from the second highest catchment type. Exceptions were 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 four to six ponds. The latter is problematic for the Kruskal–Wallis analysis as groups of less than five 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^+, particulate nitrogen (PN), TP, PP and TFe (Table III). For all eight 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 dependently 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 and 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 and 1–3 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

Table III. Median inlet concentrations for all 66 ponds and the six catchment types.

Parameter	Unit	All $n=66$	Nutrient-enriched $n=4$	Industrial $n=17$	Mixed $n=6$	Urban $n=15$	Rural $n=19$	Developing $n=5$
SS	mg l^{-1}	7.9	*57.8*^{a,b}	12.9^{c}	16.0	5.9^{a,c}	6.8	4.0^{b}
LOI	mg l^{-1}	5.0	*34.8*^{a,b}	9.8^{c}	9.3	4.6^{a,c}	3.5	2.0^{b}
DOC	mg l^{-1}	3.8	4.3	4.3	3.3	3.6	4.0	*4.8*
TN	µg l^{-1}	1240	*2533*	1247	1577	1210	1233	629
NO_3^-	µg l^{-1}	750	754	440	926	*1116*	885	395
NO_2^-	µg l^{-1}	8	*44*^{a,b}	10^{c}	12	6^{a,d}	9^{b,d}	4^{c}
NH_4^+	µg l^{-1}	89	*639*^{a,b,c,d}	113^{a,e}	98	71^{b,e}	95^{c,f}	52^{d,f}
PN	µg l^{-1}	220	*785*^{a}	325^{b}	350^{c}	16^{a,b,c}	194	19
TP	µg l^{-1}	60	*372*^{a,b}	107^{c}	121	41^{a,c}	62	32^{b}
TDP	µg l^{-1}	28	*108*	34	33	22	32	27
DIP	µg l^{-1}	25	*103*	31	28	21	31	21
PP	µg l^{-1}	37	*173*^{a,b}	86^{c}	87	24^{a,c}	42	25^{b}
TFe	µg l^{-1}	456	*2201*^{a}	660	677	370^{a}	443	381
DFe	µg l^{-1}	111	125	117	93	36	*170*	131
PFe	µg l^{-1}	287	*372*	349	369	216	286	217

SS, suspended solids; LOI, loss of ignition; DOC, dissolved organic carbon; TN, total nitrogen; NO3-, nitrate; NO2-, nitrite; NH4+, ammonium; PN, particulate nitrogen; TP, total phosphorus; TDP, total dissolved phosphorus; DIP, dissolved inorganic phosphorus; PP, particulate phosphorus; TFe, total iron; DFe, dissolved iron; PFe, particulate iron.
Note that particulate and dissolved fractions of the same parameter do not add up to total concentration of the same parameter because of median values.
The highest concentration of each parameter is italicized.
Parameters with bold are indicating that at least two of the catchment types are significantly different, specified with superscript letters.

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%, after which 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}. 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 ($p < 0.05$) 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 ($p < 0.001$).

Measurements of pH, oxygen and colour 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 colour 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 ($p < 0.001$), and both of them correlated positively with PP and PFe ($p < 0.001$). Positive correlations also existed between PP, PFe and PN ($p < 0.01$). Concerning the dissolved fractions, there were significant positive correlations between DIP, DFe and fractions of N ($p < 0.05$). DOC correlated negatively with SS and LOI, and positively with TN, PN, DFe and colour ($p < 0.05$). Colour showed similar trends by correlating positively with different fractions of Fe and N ($p < 0.02$).

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 any trends. As seen in Table III, 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, because it was impossible to calculate the retention. In addition, ponds without flow measurements were left out, because flow was required to find the retention. This left 39 ponds for analysing retention (Table IV). None of the retentions differed significantly between pond types, probably due to the very low number of ponds in three of the four pond types (27 out of 39 ponds were wet ponds). Different retention trends between pond types were though seen (Table IV, Figure 5). Wet ponds with filters were generally

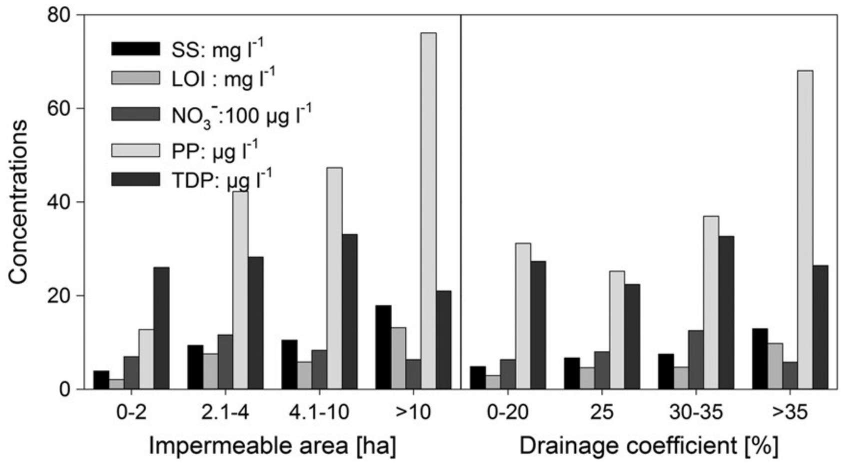

Figure 3. Median runoff concentrations for five parameters [suspended solids (SS), loss of ignition (LOI), nitrate (NO_3^-), particulate phosphorus (PP) and total dissolved phosphorus (TDP)] divided into intervals of impermeable area (ha, left) and drainage coefficient (%, right). Notice the different units for each parameter given in the legend box.

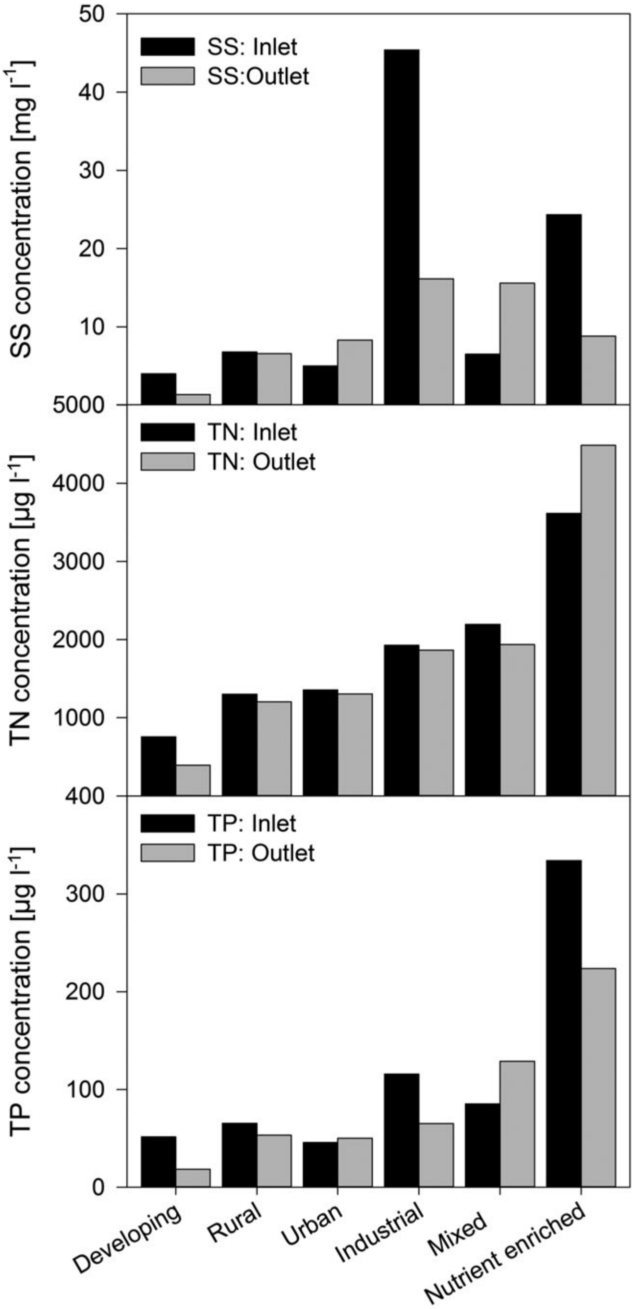

Figure 4. Median inlet and outlet concentrations of suspended solids (SS), total nitrogen (TN) and total phosphorus (TP) for the six catchment types. For inlet, $n = 66$, and for outlet, $n = 64$ ponds. Direct subtraction of data to produce retention is not possible because of median values.

Table IV. Median retentions (%) for 39 ponds and four pond types.

Parameter	All $n = 39$	Wet $n = 27$	Wet with filter $n = 4$	Ditch $n = 4$	Groove with storage $n = 4$
SS	6.1	11.1	*79.2*	−83.1	0.3
LOI	8.3	21.3	*62.4*	−88.8	0.7
DOC	8.0	9.7	−2.5	*15.2*	−2.7
TN	7.2	9.5	*57.6*	5.0	−0.4
NO_3-	8.9	12.7	*78.5*	5.0	0.3
NO_2-	0.2	0.2	*24.2*	19.4	−14.7
NH_4^+	−12.1	−21.5	−7.7	−10.4	*−1.1*
PN	0.9	*23.5*	22.1	6.5	−10.4
TP	3.9	3.8	*54.7*	−55.6	4.7
PP	3.0	21.6	*37.2*	−84.4	−0.6
TDP	4.1	−2.3	*47.9*	−4.4	7.7
DIP	12.2	15.2	*51.4*	6.0	−9.7
TFe	−0.8	−0.2	−4.0	−46.4	*2.8*
DFe	15.4	*15.9*	0.0	−3.1	14.5
PFe	−0.9	−0.9	*32.4*	−75.6	0.6

SS, suspended solids; LOI, loss of ignition; DOC, dissolved organic carbon; TN, total nitrogen; NO3-, nitrate; NO2-, nitrite; NH4+, ammonium; PN, particulate nitrogen; TP, total phosphorus; PP, particulate phosphorus; TDP, total dissolved phosphorus; DIP, dissolved inorganic phosphorus; TFe, total iron; DFe, dissolved iron; PFe, particulate iron.
The highest retention for each parameter is italicized.

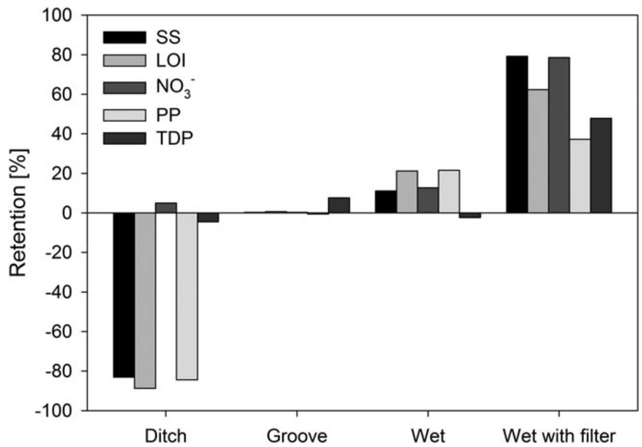

Figure 5. Median retentions in the ponds for five parameters [suspended solids (SS), loss of ignition (LOI), nitrate (NO_3^-), particulate phosphorus (PP) and total dissolved phosphorus (TDP)] divided into pond type.

best at retaining SS, LOI, TP, PP, TDP, DIP, NO_3^- and NO_2^-. On the other hand, this pond type seemed to be less efficient regarding DOC, NH_4^+ 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 NO_2^-. It seemed that grooves with storage did neither retain nor release the measured parameters. Generally, none of the pond types seemed able to retain NH_4^+ and TFe (the latter mostly due to poor PFe retention).

Apart from pond types, the pond age proved to affect the retention ($p < 0.05$). Age since construction correlated negatively with retention of SS, TP and TDP. Age since renovation correlated negatively with SS, TP, LOI and PP (Figure 6C), but it also correlated positively with NH_4^+, indicating that NH_4^+ was the only parameter that was retained better in old ponds. Pond geometry also affected

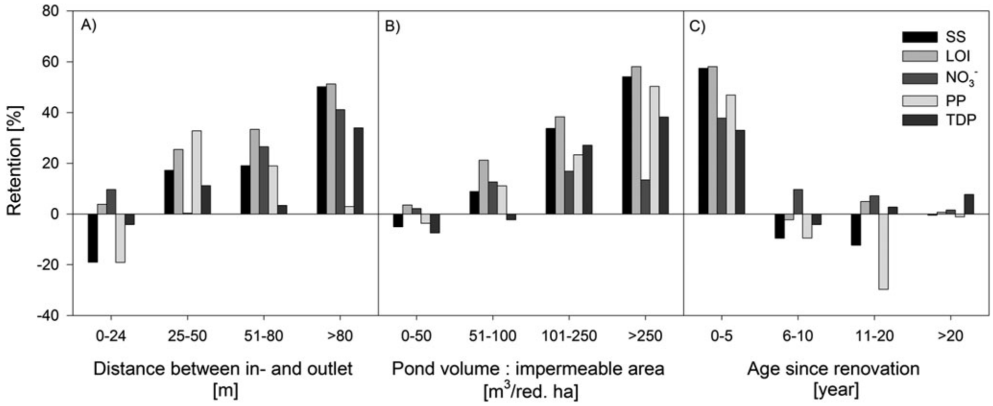

Figure 6. Median retentions in the ponds for five parameters [suspended solids (SS), loss of ignition (LOI), nitrate (NO_3^-), particulate phosphorus (PP) and total dissolved phosphorus (TDP)] divided into (A) distance between inlet and outlet (m), (B) ratio between pond volume (m^3) and impermeable area (red.ha) and (C) age since renovation (year).

the retention ($p < 0.05$), especially volume, because 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). 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 positive relation; the higher the distance or ratio, the better the retention of SS, LOI, NO_3^-, PP and TDP. The number of years since renovation gave the opposite trend, indicating that younger ponds have higher retention. Pond retention was generally efficient (>30%) for the first 5 years for newly constructed or renovated ponds, whereupon the retention drops significantly to <10% for all five parameters.

DISCUSSION

Runoff related to rainfall history

Significant linear regressions between precipitation history and measured inflow were found. The conversion from millimetre to cubic metre, 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, because a shorter distance is equivalent to a smaller uncertainty in precipitation history. The regressions are though significantly ($p < 0.001$) independent of the distance, which may be because the furthermost pond was only approximately 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 I). Because most of the ponds are situated in small cities (21 900 inhabitants in Aabenraa) compared with European countries, there may be a third correlation trend for larger cities.

Besides differences in travelling distance, the impermeable areas differed regarding size/shape, material and age. This might explain the irregular behaviour of the determination coefficients in Figure 2A. The determination coefficients varied a lot with precipitation up to 24 h before sampling, indicating that the catchment was 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 1 day before) and nutrients (the day of sampling plus 2 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 had high retentions, the outlet concentrations tended to depend on the inlet concentration and thereby indirectly on catchment type. For some parameters like TN, a high inlet concentration equals a corresponding high outlet concentration, whereas the concentrations varied more for other parameters like SS. More advanced treatment might therefore be required to ensure low outlet concentrations from ponds in industrial or nutrient-enriched catchments compared with developing catchments.

The measured concentrations are in accordance with extensive literature reviews on stormwater runoff (e.g. Makepeace *et al*., 1995; Gobel *et al*., 2007), although 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 is 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 with 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).

Suspended solids are a simple and useful indicator for PP, PFe and PN through strong correlations between these parameters. TN and TP can also be useful indicators, because they correlate with particulate and dissolved fractions of nutrients, Fe and organic matter. This is in accordance with Ingvertsen *et al*. (2011), who suggested eight 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. Because 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 that 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. As this study was performed outside the growth season, we did not see any correlation between plant cover and retention (Oberts and 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 because they contribute with higher concentrations into, but also out of, the ponds compared with 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 $>250\,m^3\,red.ha^{-1}$, which is in accordance with, e.g. Hvitved-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% NO_3^-, >40% PP and >50% TDP.

ACKNOWLEDGEMENTS

Thanks to Arwos (owner of the ponds), for fruitful cooperation and for providing background data and information. We thank lab technicians at the University of Southern Denmark for the 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

Andersen JM. 1976. Ignition method for determination of total phosphorus in lake sediments. *Water Research* **10**(4): 329–331. DOI:10.1016/0043-1354(76)90175-5.

Barbosa AE, Hvitved-Jacobsen T. 2001. Infiltration pond design for highway runoff treatment in semiarid climates. *Journal of Environmental Engineering-Asce* **127**(11): 1014–1022. DOI:10.1061/(asce)0733-9372(2001)127:11(1014).

Birch GF, Fazeli MS, Niatthai C. 2005. Efficiency of an infiltration basin in removing contaminants from urban stormwater. *Environmental Monitoring and Assessment* **101**(1-3): 23–38.

Egemose S, Jensen HS. 2009. Phosphorous forms in urban and agricultural runoff: implications for management of Danish Lake Nordborg. *Lake and Reservoir Management* **25**: 410–418.

Egemose S, de Vicente I, Reitzel K, Flindt MR, Andersen FO, Lauridsen TL, Søndergaard M, Jeppesen E, Jensen HS. 2011. Changed cycling of P, N, Si, and DOC in Danish Lake Nordborg after aluminum treatment. *Canadian Journal of Fisheries and Aquatic Sciences* **68**(5): 842–856. DOI:10.1139/f2011-016..

Egemose S, Sønderup MJ, Grudinina A, Hansen AS, Flindt MR. 2015. Heavy metal composition in stormwater and retention in ponds dependent on pond age, design and catchment type. *Environmental Technology* **36**(8): 959–969. DOI:10.1080/09593330.2014.970584.

Ellis JB, Hvitved-Jacobsen T. 1996. Urban drainage impacts on receiving waters. *Journal of Hydraulic Research* **34**(6): 771–783.

Gibbs MM. 1979. Simple method for the rapid-determination of iron in natural-waters. *Water Research* **13**(3): 295–297.

Gobel P, Dierkes C, Coldewey WC. 2007. Storm water runoff concentration matrix for urban areas. *Journal of Contaminant Hydrology* **91**(1-2): 26–42. DOI:10.1016/j.jconhyd.2006.08.008.

Hongve D, Akesson G. 1996. Spectrophotometric determination of water colour in Hazen units. *Water Research* **30**(11): 2771–2775. DOI:10.1016/s0043-1354(96)00163-7.

Hossain MA, Alam M, Yonge DR, Dutta P. 2005. Efficiency and flow regime of a highway stormwater detention pond in Washington, USA. *Water, Air, and Soil Pollution* **164**(1-4): 79–89. DOI:10.1007/s11270-005-2250-1.

Hvitved-Jacobsen T, Vollertsen J, Nielsen AH. 2010. *Urban and Highway Stormwater Pollution: Concepts and Engineering*. CRC Press/Taylor and Francis Group: New York.

Ingvertsen ST, Jensen MB, Magid J. 2011. A minimum data set of water quality parameters to assess and compare treatment efficiency of stormwater facilities. *Journal of Environmental Quality* **40**(5): 1488–1502. DOI:10.2134/jeq2010.0420.

Koob T, Barber ME, Hathhorn WE. 1999. Hydrologic design considerations of constructed wetlands for urban stormwater runoff. *Journal of the American Water Resources Association* **35**(2): 323–331. DOI:10.1111/j.1752-1688.1999.tb03593.x.

Koroleff F. 1983. Determination of phosphorus. In *Method of Seawater Analyses*, Grasshof K, Erhardt M, Kremling K (eds), 2nd edn. Weinheim, Germany: Verlag Chemie; 125–139.

Makepeace DK, Smith DW, Stanley SJ. 1995. Urban stormwater quality – summary of contaminant data. *Critical Reviews in Environmental Science and Technology* **25**(2): 93–139.

Mallin MA, Ensign SH, Wheeler TL, Mayes DB. 2002. Pollutant removal efficacy of three wet detention ponds. *Journal of Environmental Quality* **31**(2): 654–660.

Muthukrishnan S, Selvakumar A. 2006. Evaluation of retention pond and constructed wetland BMPs for treating particulate-bound heavy metals in urban stormwater runoff. Paper presented at the World Environmental and Water Resource Congress Omaha, Nebraska, United States.

Oberts GL, Osgood RA. 1991. Water-quality effectiveness of a detention wetland treatment system and its effect on an urban lake. *Environmental Management* **15**(1): 131–138. DOI:10.1007/bf02393844.

Persson J. 2000. The hydraulic performance of ponds of various layouts. *Urban Water* **2**(3): 243–250. DOI:10.1016/S1462-0758(00)00059-5.

Shamsudin S, Dan'azumi S, Aris A, Yusop Z. 2014. Optimum combination of pond volume and outlet capacity of a stormwater detention pond using particle swarm optimization. *Urban Water Journal* **11**(2): 127–136. DOI:10.1080/1573062x.2013.768680.

Stone M, English MC. 1993. Geochemical composition, phosphorus speciation and mass-transport of fine-grained sediment in 2 Lake Erie tributaries. *Hydrobiologia* **253**(1-3): 17–29. DOI:10.1007/bf00050719.

Sønderup MJ, Egemose S, Hoffmann CC, Reitzel K, Flindt MR. 2014. Modeling phosphorus removal in wet ponds with filter zones containing sand or crushed concrete. *Ecological Engineering* **66**: 52–62. DOI:10.1016/j.ecoleng.2013.06.003.

Su TM, Yang SC, Shih SS, Lee HY. 2009. Optimal design for hydraulic efficiency performance of free-water-surface constructed wetlands. *Ecological Engineering* **35**(8): 1200–1207. DOI:10.1016/j.ecoleng.2009.03.024.

