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Phosphorus forms in urban and agricultural runoff: Implications for management of Danish Lake Nordborg

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Abstract


The catchment of eutrophic Lake Nordborg, Denmark, consists of 25% urban areas with separate sewer systems and 63% agricultural areas with clayey soil and grain crops. Diffuse runoff is the only external phosphorus (P) source (∼550 kg/yr), but the lake suffers from high internal loading (∼1300 kg/yr). In-lake aluminum treatment is suggested if external P-loading can be brought down by ∼30% to an annual average inlet concentration of <0.100 mg/L. We examined the share and bioavailability of particulate P (PP) in 14 tributaries during a winter season to evaluate if the reduction in bioavailable P-load can be obtained by construction of precipitation/retention ponds in major inlets. One-third of the P-load occurred as PP, independent of catchment type. For urban runoff, 62% of PP was surface adsorbed P, iron-bound P, and extractable organic P, all of which may be considered bioavailable. The corresponding value for agricultural tributaries was 76%. For both types of catchments more than 70% of total P (PP and dissolved P) was bioavailable, but total concentrations were much higher (0.174 ± 0.032 mg/L) in agricultural runoff than in urban runoff (0.082 ± 0.019 mg/L). Measurements of PP settling velocity revealed that ∼30% settled slower than 1 cm/h whereas ∼50% settled faster than 1 m/h. Therefore, water retention time in precipitation ponds to Lake Nordborg should exceed 8 h to reach the target reduction in P-load. Focus should be on the agricultural catchment that contributes 140 kg to PP load, rather than the urban catchment that only contributes 48 kg.

Key words: drain water, internal loading, particulate phosphorus, runoff, sequential extraction, stormwater, urban runoff

Similar to many other lakes in developed watersheds, Lake Nordborg, Denmark, has remained in a eutrophic state even 16 years after diversion of domestic sewage. The main reason for this condition is internal phosphorus (P) loading during summer. Two management actions being considered for Lake Nordborg are contingent upon reducing both external and internal P loading. (1) Internal P loading may be reduced by aluminum treatment provided that external P loading can be reduced to a level where a good ecological water quality can be obtained. (2) Because Danish streams often carry >50% of the P load as particulate P (PP; e.g., Jensen et al. 2006), a significant reduction in the external P-loading to Lake Nordborg can possibly be obtained by establishing precipitation ponds in the major inlets to the lake (e.g., Hvítved-Jacobsen et al. 1994). External loading to Lake Nordborg derives primarily from runoff (28% from urban watershed and 53% from agricultural; County of Southern Jutland 2003).

To accomplish these management actions, we evaluated internal and external P loading based on mass balance and lake survey data from 2002. For evaluating internal loading we measured sediment P release at three stations and quantified the pool of potential available P in the sediment (e.g., Reitzel et al. 2005). To evaluate external P loading we examined concentration and composition of PP in the inlets to Lake Nordborg to evaluate if a 30% reduction in the annual average inlet P concentration from 0.149 mg/L to ∼0.1 mg/L could be reached. This would guarantee an in-lake P concentration <0.100 mg/L according to general loading-retention models such as Vollenweider (1976). Experiences from Danish lakes suggest that annual average in-lake P concentrations below 0.100 mg/L are required for long-term improvements in lake water clarity (Jeppesen et al. 1999).
Meanwhile, the amount of available PP from the watershed is largely unknown. The overall aim of this study was to examine bioavailability of PP from urban and agricultural runoff as well as the share of the total load carried as PP for the two types of land-use. The results may be generally useful for the management of lakes with similar clayey soils in their catchment basins and/or separate sewer systems. Reports on P forms and bioavailability in urban runoff from separate sewer systems are rare, but Cowen and Lee (1976) found that bioavailability of PP varied between 10 and 45% (average 30%) by use of chemical extractions and algal bioassays for 13 separate sewer systems in Madison, Wisconsin. The potential bioavailability of PP originating from other types of catchments has been studied more frequently using both algal tests (Ekholm 1998) and sequential chemical extraction with increasingly stronger chemicals (Pacini and Gächter 1999, Jensen et al. 2006). A widely used method for sequential extraction was suggested by Psenner et al. (1984) and slightly modified by Jensen and Thamdrup (1993) and Paludan and Jensen (1995). Using this method we examined the share and composition of PP four times during the wet season (covering 70% of the annual runoff) and covered all the gauged (80% of total) part of the watershed to Lake Nordborg. We distinguished between runoff from urban and agricultural watersheds by sampling 14 sites in tributaries to the major inlets.

**Study site**

Lake Nordborg (55 ha, mean depth 5 m, watershed area 11.8 km²; Fig. 1) is located on the island Als in the southern part of Denmark. The town Nordborg on the south side of the lake covers 25% of the catchment, and agriculture with grain crops makes up 63%. The soil type is clayey sand. The remaining watershed consists of roads, forests and uncultivated areas without drainage systems. Annual water balance and nutrient mass balance have been measured four times since 1988. The four major inlets, representing 60% of the catchment area, have been measured annually 12–15 times in 1988, 14 times in 1992, 20–22 times in 1994 and 26 times in 2002. Loading from the ungaged catchments was estimated with data from similar gauged catchments. The mass balances showed a generally declining trend in external P load from 1665 kg in 1988 to 528 kg in 2002 (Table 1). Retention of P varied from 421 kg in 1988 to −35 kg in 2002 (Table 1; County of Southern Jutland 2003).

Water retention time in 2002 was 0.82 yr (inflow 3.8 million m³, outflow 3.4 million m³). During summer 2002 P accumulation in the water column amounted to 1200 kg (County of Southern Jutland 2003), but sediment P release during summer may have been even higher because it was

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**Table 1.-Annual TP mass balance and precipitation for 4 years in Lake Nordborg. Discharge and P flux in the inlets was measured monthly in the gauged (80% of total) watershed and measured daily in the outlet. Precipitation is measured 200 m away from the lake shore (County of Southern Jutland 2003 and unpublished data).**

<table>
<thead>
<tr>
<th>Year</th>
<th>Inlet (kg P)</th>
<th>Retention (kg P)</th>
<th>Precipitation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1988</td>
<td>1665</td>
<td>421</td>
<td>715</td>
</tr>
<tr>
<td>1992</td>
<td>498</td>
<td>−280</td>
<td>730</td>
</tr>
<tr>
<td>1994</td>
<td>1202</td>
<td>175</td>
<td>878</td>
</tr>
<tr>
<td>2002</td>
<td>528</td>
<td>−35</td>
<td>911</td>
</tr>
</tbody>
</table>

---

![Figure 1.-Lake Nordborg showing the 14 sampling stations.](image-url)
Discharge was measured with an Ott Klein vígil propeller instrument. Water samples were collected in polypropylene carboys and stored at 5°C until next morning. All samples were collected during or just after a rain event.

Water samples were filtered on two pre-washed and pre-dried Whatman GF/C filters. Filters were pre-washed to avoid filter weight loss due to wash out of glass fibers during filtration. Filtered water was analyzed for dissolved inorganic P (DIP) and total dissolved P (TDP) by the molybdenum-blue method before and after wet oxidation with persulfate (Koroleff 1983). One of the filters was used for dry weight (105°C, 24 h), loss on ignition (450°C, 4 h), and PP. Particulate P was measured by boiling the combusted filter in 1 M HCl (1 h) then measuring DIP in the extract (Andersen 1976). The other filter was used for the sequential chemical extraction of P according to Jensen and Thamdrup (1993) with the modification that DI water is used in rinses instead of 0.5 M NaCl. In this protocol, loosely adsorbed P is extracted first with H2O. Second, iron-bound P is extracted by a reducing bicarbonate-dithionite solution, and P bound to aluminum, humic P, and organically bound P of different forms is liberated by a NaOH extraction (see also Jensen et al. 2005, Reitzel et al. 2006). Next, calcium-bound P is dissolved by a cold HCl extraction and, finally, the sediment residue is combusted and extracted in hot HCl to liberate the remaining refractory organic P. Jensen and Thamdrup (1993) was modified to use 10 ml extractant in each step/wash instead of 25 ml. There seems to be some consensus that inorganic P \( P(iP) \) from the first two extraction steps and extractable organic P from the first three steps provide a measure of P forms that are potentially mobile (or potentially bioavailable) under the conditions that prevail in eutrophic lakes (Hupfer et al. 1995, Rydin 2000, Reitzel et al. 2005). Thus, bioavailable PP is calculated from these pools, and bioavailable TP is calculated as the sum of DIP and bioavailable PP.

Settling velocities for particles were determined for 5 of the stations in January 2005: Stations 2, 3, 8, 12 and 13 (Table 2; Fig. 1). Settling velocity for PP was determined for the same stations except for Gammel Dam (8). The settling velocity was determined by use of an Owen Tube (Owen and Eng 1976), where the water sample is put into a vertical tube (about 1 m height) and subsamples are taken from the bottom of the tube at gradually increasing time intervals. By analyzing dry weight and P concentration in the particles in the subsamples, the settling velocity of particles and PP can be calculated (Owen and Eng 1976). Because the particle sizes in the inlets are generally small, it was necessary to concentrate the samples before starting the settling velocity measurement. Thus, the water samples were allowed to precipitate for 24 h in advance, and 70–80% of the original volume was decanted and analyzed in the same way as the subsamples from the Owen Tube. The 24-h samples of

counteracted by sedimentation. Thus, the internal P load was at least 2–3 times higher than external load (Table 1), and observed summer mean P concentration in lake water was 0.350 mg/L. Very little P (35 kg) was washed out of the lake on an annual basis in 2002 and, consequently, no improvement in lake water quality could be expected for future years without actively reducing both internal and external P loading.

### Materials and methods

We sampled 14 sites in the tributaries where 70% of the annual runoff occurs during the winter period 2004–2005. The stations were chosen to represent specific types of land-use: 8 were situated in agricultural systems and the other 6 were in systems with urban runoff (Table 2). Samples were analyzed for dissolved (inorganic and organic) and particulate P, and filtered particles were analyzed by use of a sequential extraction procedure. On one occasion the settling velocity of particles from five selected inlets was determined to provide local information for an eventual dimensioning of sedimentation ponds. All 14 stations were sampled four times (Oct, Nov, Jan, and Mar), always on the same days. Discharge was measured with an Ott Klein vígil propeller

![Table 2.-Name, catchment type, situation of the station and catchment area for the 14 sampling stations.](image)

<table>
<thead>
<tr>
<th>No.</th>
<th>Name</th>
<th>Catchment</th>
<th>Situation</th>
<th>Area (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Lavensby</td>
<td>Agriculture</td>
<td>Inlet</td>
<td>119</td>
</tr>
<tr>
<td>2</td>
<td>Bommarks Bæk</td>
<td>Agriculture</td>
<td>Inlet</td>
<td>166</td>
</tr>
<tr>
<td>3</td>
<td>Kildespring (73.8%)</td>
<td>Agriculture</td>
<td>Inlet</td>
<td>118</td>
</tr>
<tr>
<td>4</td>
<td>Drain pipe</td>
<td>Agriculture</td>
<td>Inlet</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>Inlet north (93.8%)</td>
<td>Agriculture</td>
<td>Inlet</td>
<td>32</td>
</tr>
<tr>
<td>6</td>
<td>Gammel Dam basin Urban runoff</td>
<td>Urban runoff</td>
<td>Upstream</td>
<td>7.4</td>
</tr>
<tr>
<td>7</td>
<td>Gammel Dam ditch Agriculture</td>
<td>Urban runoff</td>
<td>Upstream</td>
<td>54</td>
</tr>
<tr>
<td>8</td>
<td>Gammel Dam outlet Agriculture (66.7%)</td>
<td>Inlet</td>
<td>81</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Basin inlet Urban runoff</td>
<td>Upstream</td>
<td>27.9</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Basin outlet Urban runoff</td>
<td>Upstream</td>
<td>27.9</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Golf course Urban-runoff</td>
<td>Upstream</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Fægteborg Bæk Agriculture (81.4%)</td>
<td>Inlet</td>
<td>375</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Pipe 1 Urban runoff</td>
<td>Inlet</td>
<td>0.98</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Pipe 2 Urban runoff</td>
<td>Inlet</td>
<td>2.4</td>
<td></td>
</tr>
</tbody>
</table>

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decanted water were later included in the settling velocity calculations.

Undisturbed sediment cores (i.d. 5.2 cm) were sampled in February by a gravity corer on three stations in the lake (maximum depth 9 m, a station at 6.5 m depth, and a shallow sedimentation area with 4.5 m water depth). The stations represented approximately 15 ha of bottom each and thereby 45 of the 57 ha lake area. Three cores from each site were sliced in 1-cm layers, and layers from each depth were pooled before analyses of total P and sediment P pools using same procedures as for PP in tributaries, except that the two first extraction steps were carried out in an N₂-filled glove bag to avoid oxidation of reduced iron compounds that could cause an over-estimation of iron-bound P. Five cores from each site were incubated with 15 cm of oxic bottom water over the sediment surface and continuously stirred to measure sediment P release. Release rates were measured first at 5 C, then at 15 C and finally at 20 C. Measurements were conducted over 2–4 days, with 2 days for acclimatization at each new temperature. The overlying water was replaced with new bottom water between each measurement. Release rates were calculated as the mean for the five cores. Variability (standard deviation) was 30–50% of mean values. Gross P release for a summer period was estimated by using the observed temperature dependency for P release and the development in lake water temperature observed in 2002.

Statistical analyses

Two-factor ANOVA was used to evaluate differences in time of sampling and differences between catchment types; α was chosen as 0.05. For each catchment type, samples from the same date are represented as mean values with standard error of means (SEM). Where results were calculated in mg/L the data were log-transformed before statistical analyses to fulfill the requirement of normal distribution. Results from station “Pipe 2” from October were excluded from the statistical analyses due to abnormal sample conditions compared with the other stations. The water sample at Pipe 2 from October was collected from the first rainwater coming to the station after the beginning of a rainstorm; therefore, the sample contained very high amounts of P due to first flush effect at this station. First flush effect at the station was proved by sampling intensively during a whole rain event (unpublished data). The other stations were sampled later during the rain event or just after the rain event; these stations have a continuous water flow between rain events and therefore first flush effects were not observed.

Results

The concentration of TP was significantly higher (p < 0.0001) in the inlets coming from agricultural areas (0.174 ± 0.032 mg/L) than in the inlets with urban runoff (0.082 ± 0.019 mg/L) (Fig. 2). Similarly, the concentration of particulate P (PP) was higher in agricultural drainage water (0.063 ± 0.015 mg P/L) than in urban runoff (0.030 ± 0.013 mg P/L; p < 0.01). There were no significant differences with respect to the time of year the stations where sampled (p = 0.49 for TP and p = 0.30 for PP; Fig. 2). The contribution of PP to TP was not significantly different between the two catchment types (p = 0.40) or between sampling times

Figure 2.-TP and PP in mg/L for agricultural and urban run-off. Average and SEM are calculated for the two catchment types and the four sampling times.
Particulate P made up 39.1 ± 7.8% of TP in inlets from agriculture and 33.8 ± 10.0% in urban runoff. The sequential extraction procedure for PP revealed that the first three fractions (bioavailable P) made up the biggest share in samples from both types of catchments (Table 3). Particles from agricultural drainage always had higher percentages of bioavailable P (75.6 ± 2.9%) than particles from urban runoff (61.9 ± 7.0%; p < 0.001). Bioavailable PP constituted approximately of 15% loosely adsorbed P, ~55% iron-bound P and ~30% extractable organic P. In contrast, the three last fractions (aluminum-bound P, calcium-bound P and refractory organic P) were higher for urban runoff than for agricultural areas. The share of TP that may be considered bioavailable was not significantly different for the two catchment types (p = 0.16), with an average value of 77.0 ± 3.3% for agricultural catchments and 72.2 ± 6.0% for urban runoff. The bioavailable TP fraction did not appear to be significantly different over time (p = 0.06), while bioavailability of PP was significantly higher in November than in March for both catchment types (p < 0.05; Fig. 4). Other differences were not significant.

Combining the results above with the measured water flow allow for a rough calculation of the areal runoff per hour for each separate catchment. The agricultural catchments had a higher P leaching (3.8–32.3 g P/km²·h) for three out of four occasions than the catchments draining urban runoff (8.2–21.2 g P/km²·h; Table 4) but the difference is not significant (p = 0.21). The P leaching in March was significantly higher for both catchments than in the three other months (p < 0.01).

In the settling velocity measurements (Fig. 5) only one of the stations (Pipe 1) represented urban runoff. The remaining four represented mainly agricultural catchments, and in
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Figure 4.- Bioavailable fractions (in %) of TP and PP. Average and SEM are calculated for the two catchment types and the four sampling times.

“Fægteborg,” an urban catchment, about two-thirds of the water passed through a small precipitation pond upstream. There were no significant differences between settling velocities of particles at the five stations (Fig. 5) although it seems that particles from Fægteborg settled slower than particles from the other stations at velocities < 1 m/h. In general, 38–57% of the particles from the five stations settled more slowly than 1 m/h. The settling velocities for PP were less similar for the four investigated stations (Fig. 5). Particulate P from Fægteborg settled slower than PP from the three other stations, whereas PP in urban runoff from Pipe 1 settled a little faster than PP from the three stations with agricultural catchments. The percentage of PP that settled with a slower rate than 1 m/h for the four stations was in the same range as for the particles (47–73%). A large proportion (>28%) of both particles and PP settled out with slow rates of <1 cm/h.

Table 4.- Average amount of TP in g/km²·h and SEM shown for agricultural and urban runoff at each sampling time. Stations “basin in” and “basin out” were excluded because it was not possible to measure the flow at these stations.

<table>
<thead>
<tr>
<th></th>
<th>October g P/ km²·h</th>
<th>November g P/ km²·h</th>
<th>January g P/ km²·h</th>
<th>March g P/ km²·h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture</td>
<td>3.84 ± 1.60</td>
<td>5.57 ± 2.10</td>
<td>11.45 ± 3.28</td>
<td>32.28 ± 9.34</td>
</tr>
<tr>
<td>Urban runoff</td>
<td>8.24 ± 8.09</td>
<td>1.32 ± 0.63</td>
<td>1.44 ± 0.70</td>
<td>21.20 ± 11.19</td>
</tr>
</tbody>
</table>

Sediment P-release rates from three stations in the lake varied between 3 mg P/(m²·day) at 5°C and 50 mg P/(m²·day) at 20°C. The temperature dependency expressed as Q¹₀ (Jensen and Andersen 1992) was 2–3 for the temperature interval 5–15°C, and 4–7 for the interval 5–20°C, indicating an enhanced release of iron-bound P at temperatures above 15°C, even from an aerobic sediment surface (Jensen and Andersen 1992). Calculated for the summer period (May–Sep) the 45 ha of sediment would release 1340 kg P, which agrees with the observed hypolimnetic accumulation of 1200 kg P in summer 2002, considering that sedimentation may have carried some P back to the sediment.

Analyses of sediment total P and sediment P pools revealed that both surface sediment and sediment down to 10 cm sediment depth had lower total P concentrations than the particles in the inlets (Table 3), and that sediment particles, especially when buried above 10 cm depth, were relatively depleted in loosely adsorbed P and iron-bound P forms, which are considered mobile. Instead the sediment particles were relatively enriched in calcium-bound P, a form that is considered immobile and subjected to permanent burial. Extractable organic P contributed the same share in the lake sediment as in the inlet particles, although concentrations were lower. Relative to the loosely adsorbed and the iron-bound P, the extractable organic fraction appears more persistent in the sediment. From bulk density and the concentrations of loosely adsorbed P, iron-bound P and extractable organic P, the potential mobile P pool at 0–10 cm...
depth was estimated to be 7.2, 8.2 and 7.4 g/m² at the three stations, respectively. For the 45-ha lake bottom the potential mobile P pool amounted to 3400 kg.

**Discussion**

Provided that measures such as aluminum treatment (Cooke *et al.* 2005, Reitzel *et al.* 2005) are taken against internal loading in Lake Nordborg, any reduction in external P loading would likely further improve water clarity (Jeppesen *et al.* 1999). The target inlet P concentration of 0.100 mg/L could, theoretically, be met by removing all PP (~35% of total P) from the inlets. Our study of particulate P-forms revealed that this would remove 25–30% of the bioavailable P (dissolved and particle-bound). Particulate P is more subject to retention in the lake (by sedimentation) than dissolved P during winter flushing; therefore, removal of particles in the inlets may be even more important for lake water clarity than can be predicted from the percentage reduction in P load because the retained PP may be subject to further P release from the sediment in the summer period. Thus, precipitation/retention ponds (e.g., Hvitved-Jacobsen *et al.* 1994) in Lake Nordborg tributaries could be a useful restoration tool and, given the somewhat typical nature of the agricultural and urbanized surroundings, this recommendation for reducing diffuse P loading may apply to many lakes in developed watersheds.

Comparison of particles from the inlets with lake sediment clearly revealed that loosely adsorbed P and iron-bound P was lost to the water before or shortly after settling, and that further losses occurred with burial as seen in sediment from 10 cm depth. This observation supports our interpretation of bioavailable versus nonavailable P forms.

High proportions of bioavailable P in PP as observed in Lake Nordborg tributaries were also reported by Pacini and Gächter (1999; 25–70%) and by Jensen *et al.* (2006; 49–86%) for streams draining agricultural soils. These studies also used sequential extraction. Further, the proportion of PP to total P is in the same range (25–50%) as other studies (Johansen 1985, Reinhardt *et al.* 2005). The proportion was independent of catchment type and time of year, but more PP was bioavailable in the drainage water from agricultural soils (75.6%) compared to urban runoff (61.9%). Ellison and Brett (2006) also reported high bioavailability of PP in urban streams during base flow (73%), while it declined to 19% during rain storms. Considering that we sampled at base flow after or during a moderate rain, these numbers are comparable to ours. In contrast, Cowen and Lee (1976) reported a bioavailability estimate of 30% for urban runoff in Madison, Wisconsin.

Although the total P concentrations reported for urban runoff from separate sewer systems vary widely between and within different locations (Browman *et al.* 1979, Ellis 1986, 1989, Makepeace *et al.* 1995), the values are generally well above 0.1 mg/L. Danish reference values are in the range of 0.1–1.0 mg/L (Johansen 1985, Kjølholt *et al.* 1997, Danish Environmental Protection Agency 2006) but are only based on extensive studies with one or two study sites. Ellis (1986) and (1989) found an average concentration of 0.34 mg/L for European sites with a range of 0.02–4.3 mg/L. A similar P concentration (0.36 mg/L) was found in urban runoff from Cincinnati, Ohio, USA (cited in Cowen and Lee
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1976). In comparison, our average value for total P concentration (0.082 ± 0.019 mg/L) seems low. It may be that higher values in other (and older) studies are due to seepage or overflow from domestic sewer systems and/or larger quantities of mineral particles that can have a lower share of bioavailable P, such as found by Cowen and Lee (1976).

While the two catchments were similar with respect to the proportion of bioavailable P to total P, the concentration of both components was twice as high in agricultural runoff compared to urban runoff. Part of the explanation for this is differences in runoff volume that will normally be larger in urban watersheds because of higher imperviousness than in agricultural watersheds; however, the comparison of area runoff from the catchments also indicated that area P loss was generally higher from the agricultural catchments. To evaluate how representative our four sampling events were for a whole runoff season and thus, to evaluate the certainty in the above conclusion, we extrapolated the four measurements of P flux to a whole year and calculated an annual P load of 568 kg. This value is comparable with the 528 kg in 2002 where the annual load estimate was based on 26 measurements; however, precipitation was a little higher in 2002 than in 2004 and 2005, and therefore our area P loss values may be slightly overestimated. The autumn value for agricultural catchments is comparable to the average Danish value of ~5.6 g/km²·h (Kronvang et al. 2001), but the spring values, when most of the runoff occurs, are higher than the Danish average value. The corresponding annual average value for catchments with unfertilized forest or natural areas is 0.93 g/km²·h (Kronvang et al. 2001).

Our measurement of settling velocities for PP did not allow a detailed discrimination between the two types of catchment because we only had one representative for the urban watersheds (Pipe 1). The tendency was, however, that PP settled faster in this sample even if the settling velocity for particles (dry material) was in between those measured for agricultural catchments. We found that for all catchments, 30% of PP settled with a rate that was slower than 1 cm/h, and that 53% of PP settled faster than 1 m/h. While we had too little material to analyze for bioavailable P, iron-bound P is known to be associated with the finest fractions, and Stone and English (1993) showed that river sediment <63 µm is enriched in bioavailable phosphorus forms. Bioavailable PP is therefore likely to stay in suspension for longer time than PP as a whole. The removal of PP in runoff depends on settling velocity, retention time and pond depth, independent of catchment type. For example, a pond depth of 1.5 m and a retention time of 8 h will remove 29.4–68.3% of PP as calculated from our settling velocities. Higher removal in the detention ponds could be obtained with longer water retention times, or alternatively, with precipitation by chemicals such as iron- and aluminum salts (e.g., Pilgrim and Brezonik 2005). This could also reduce the large fraction of the dissolved, bioavailable P. With such a technique, Pilgrim and Brezonik (2005) showed an average annual TP removal of 61–84%.

For Lake Nordborg, we conclude that, given a slightly higher bioavailability and 2-fold higher concentration of PP in agricultural runoff than in urban runoff, emphasis should be placed on removing particles from agricultural catchments. A complete removal of particles in agricultural runoff would lower the annual P load by 140 kg, equivalent to 25% of the total external load, while only 48 kg (8% of total external load) could be removed with particles from the urban runoff. In general, our study elucidates the possible benefits of a more detailed examination of the P forms carried to a lake with diffuse runoff. In our case, substantial improvement in lake water quality can be expected if the particulate fraction, rich in bioavailable P, is removed, and if internal P loading is combated at the same time. For Lake Nordborg, which has an alkalinity of 3–4 mmol/L, we suggest a total of 29,850 kg Al should be added as poly-aluminum chloride or alum. This amount will provide a molar Al:P binding ratio of 10 relative to the potential mobile P pool of 3400 kg in the upper 10 cm of the sediment. The binding ratio of 10:1 is recommended as a minimum by de Vicente et al. (2008).

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