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Optimal physical design in a new lake for reducing phosphorus pools

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Abstract

After 200 years of reclaiming shallow lakes to expand cultivated land in Europe and North America, recent decades have been marked by the establishment of new lakes, this time to stop the decline of freshwater biodiversity and help reduce nutrient transport from land to sea. However, new lakes risk becoming eutrophic and turbid, because they are established mainly on fertile agricultural soils. Minimizing internal nutrient loading from sediments can be accomplished by relocating nutrient-rich sediment to deep water with low release, rapidly exporting nutrients by washout, or immobilizing soil-nutrients before inundation. We studied sediment relocation in relation to sediment shear stress and phosphorus decline in sediment in new Lake Birke, Denmark (area 128 ha, mean water depth 0.56 m, retention time ca. 193 days). Evaluating core samples and other data on two occasions, 116 and 530 days after establishment, we found that sediment density changed towards harder materials in the middle of the lake, which is characterized by high bottom shear stress, while islands and shores exposed to short fetches from the prevailing winds experienced low bottom shear stress and accumulated softer, nutrient-rich organic material. After 530 days, sediment density had become a highly significant linear function of bottom shear stress (P < 0.001, R² = 0.59). Daily mean sediment P in surface sediment (0–10 cm) decreased by 20.1 mg P m⁻² sediment during the first 116 days and 7.9 mg P m⁻² during the next 414 days. Overall, 69 % of the phosphorus pool in surface sediments was lost and likely washed out over the first 530 days. Managing a lake by keeping initially shallow water and short water retention time, and locating the lake outlet in a wind-exposed area of high particle concentration, may facilitate loss of sediment nutrients and thus promote desired ecological qualities. Moreover, deeper sedimentation areas that are easily accessible to mechanical dredging may be planned to reduce nutrient release of fine, nutrient-rich organic particles.
Introduction

Over the last 200 years, numerous freshwater lakes and open streams have disappeared from the landscape in Europe and North America due to reclamation for farmland (Biggs, Von Fumetti & Kelly-Quinn, 2017; Dahl, 1990, 2011; Verhoeven et al., 2006). This loss has had severe consequences both because freshwater habitats support the life of many species and because freshwater itself removes or retains nutrients and carbon while it moves from terrestrial to marine environments (Strand & Weisner, 2013; Zedler & Kercher, 2005). Furthermore, deterioration of the freshwater linkage from land to the sea has contributed to marine coastal eutrophication and the resulting higher frequency of algal blooms, anoxia and loss of benthic animals and fish (Carstensen et al., 2014; Johnston, 1991; Whigham, Chitterling & Palmer, 1988).

An increasing focus on biodiversity and ecological quality of freshwater and marine habitats has inspired recent initiatives to reestablish former wetlands and lakes. In Denmark alone, approximately 100 lakes (>5 ha) have been created within the last 30 years to support biodiversity both in the lake and downstream, by reducing nutrient loading throughout the catchment (Stage Sø, Sand-Jensen & Baastrup-Spohr, 2020). Biodiversity, nutrient loading and ecological quality are essential management issues, according to the EU Water Frame Directive (European Parliament of the Council, 2000). In this study, we report on the relocation of sediment, with special attention to the reduction of phosphorus in sediment, over about 18 months following the establishment of a shallow lake.
Many new lakes have been created on what had been intensely cultivated fields with high concentrations of nitrogen (N) and phosphorus (P) in the soil. Lake managers understand the importance of reducing internal nutrient loading in new lakes, either through deposition and immobilization of nutrient-rich sediments in deeper water or via outflow of nutrient-rich water to robust downstream recipients (Braskerud, 2002; Welch & Cooke, 2005). In large, reestablished Lake Fil, a restoration strategy combining shallow water, high wind exposure and short water retention time resulted in extensive resuspension of sediment particles and nutrient outflow from the lake to the North Sea (Kragh et al., 2017). The present study evaluated the relocation of sediment and reduction of internal P-loading in reestablished Lake Birke, in northern Jutland, Denmark. Lake Birke is shallow, but it is smaller and not as strongly wind exposed as Lake Fil, and its water retention time is longer. These physical and hydrological conditions may hinder efforts to promote nutrient export and decrease internal nutrient loading. However, we hypothesized that it was still possible that sediment mobilization and washout of nutrient-rich fine particles would be sufficiently effective to reduce sediment nutrient pools in Lake Birke and, thus meet the managers’ and owners’ ecological and biodiversity goals.

Lakes reestablished on former agricultural fields that had been fertilized over many years may contain large P pools in the plough layer, which can be a cause for great concern for the ecological quality of the future lake (Pant & Reddy, 2003; Steinman & Ogdahl, 2011). When terrestrial soils become inundated, P that is dissolved in the pore-water and loosely adsorbed to particles immediately starts to be released to the lake water. Mobile P bound in organic material is also highly susceptible to microbial degradation and release (Laboski & Lamb, 2003). Maintaining a lower water level over the first 1–2 years than intended in the future has been proposed as a possible restoration strategy for new lakes because shear stress is stronger at shallower depths, and strong shear stress can cause the resuspension of sediment particles (Kragh et al., 2017).
Resuspension of sediment particles at high wind exposure allows for aeration and mixing of the water column and the top layer of the sediment, thus increasing microbial degradation (Wetzel, 1983) and nutrient release (Søndergaard, Jensen & Jeppesen, 2003). Shallow water can ensure rapid loss of phosphorus by hydraulic flushing (Kragh et al., 2017).

Our overall objective was to evaluate the P-dynamics in newly established Lake Birke by examining the mobilization and removal of the sediment P pool, using measurements of wind, water depths, P concentrations in sediments and calculations of bottom shear stress across the lake bottom. The specific objectives were: 1) to apply a wind model to calculate shear stress and sediment relocation of organic material and P, and 2) to quantify temporal development of sediment P from before to 1.5 year after reestablishment of the lake.

2. Methods

The study was conducted on Lake Birke in northern Jutland, Denmark (56°88’N, 10°20’E, Fig. 1). The lake was drained in 1761 for agricultural cultivation and it was reestablished 250 years later, in December 2017 (Hansen, 2011). The reestablished lake surface area is 124.6 ha (2018) and includes three small islands created to support bird populations. Mean water depth was 0.54 m (0.58 m) and maximum depth 1.54 m (1.75 m) in April 2018 (depths in May 2019 in parentheses, Fig. 2). Lake Birke receives much of its water from Lake Tofte, which hosts a cormorant nesting colony and is located next to a major peat bog. Thus, in addition to the 250 years of farming on the lake’s floor, the water that enters the lake contains substantial amounts of nutrients and organic material.

2.1 Water depth, fetch and shear stress

Water depth throughout the lake basin was measured in April 2018 and May 2019 using sonar scans, which were merged into georeferenced images (specification below). A spatial resolution of
1 m was obtained by sailing across the lake in transects no more than 50 m apart. Water retention time (WRT) was calculated as lake water volume divided by the entire year’s inflow of water. WRT was calculated based on data for two periods. Once Lake Birke was reestablished, observations showed that the lake became water-filled over 86 days (1 December 2017 – 1 March 2018), which enabled a calculation of mean daily water input. This daily input was expected to continue until 1 May. During summer months (1 May – 30 September 2018), the lake’s water level dropped below that of the outlet. Water input was low due to extensive evapotranspiration in the catchment. Thus, in the calculations of water retention time, we actually assumed that no water entered the lake during summer. Between 1 October and 5 December 2018, lakes water level changes were measured using pressure sensors (Odyssey depth/temperature logger). This allowed calculations of net water input from the increase of water volume over a period from very low to medium water level, where water output through the outlet was zero and evaporation was low due to low temperatures.

The impact of shear stress on the sediment surface throughout the lake basin was calculated from the combination of wind speed, fetch and water depth. The Danish Meteorological Institute provided data on wind direction and wind speed, calculated from three wind station in the municipality in which Lake Birke is located. The wind stations are located 13, 20 and 30 km away so we regard the mean values as representative of the wind field across Lake Birke, as the flat topography and open area pose limited obstruction of the wind. Wind data cover daily values for the entire period from reestablishment of the lake on 6 December 2017 to the last sampling 31 May 2019. As daily wind input, we used the highest gust wind speed measured 2 m above ground level. Fetch is the distance that the wind for a given direction can travel over water, while shear stress (Newton m⁻²) is the drag force impacted on the lake bed by the fluid motion (Rohweder et al.,
Fetch was calculated for every 10 compass degrees, using a restricted shore protection manual calculation method (Rohweder et al., 2012). To account for the sheltering effect of shallow depths, water depths of less than 20 cm were regarded as land by the model, thus resetting the fetch calculations. Fetch, wind data and water depth were used to calculate each day’s bottom shear stress, including identifying variations across the lake bottom with a grid containing 1x1 m cells. Shear stress was calculated using the formulas (1 and 2) (Rohweder et al., 2012).

\[ \tau = \frac{\rho f u_m^2}{2} \]  

Where \( \tau \) is shear stress at the sediment (Newton m\(^{-2}\)), \( \rho \) is density of the water, which was set at a constant value of 998.2 kg m\(^{-3}\). \( f \) is the friction factor, which was set at the default value of 0.032, while \( u_m \) was the maximum orbital wave velocity at the bottom (m s\(^{-1}\), formula 2).

\[ u_m = \pi \frac{H_{m0}}{(T_P \sinh(2\pi \frac{d_f}{L}))} \]  

Here \( H_{m0} \) is the significant wave height (m), \( T_P \) is the spectral peak wave period (s), which is calculated using fetch and wind speed (for more information, see Rohweder et al. (2012)), \( d_f \) is the water depth (m) and \( L \) is the wave length (m). Shear stress was calculated for each day and mean shear stress was calculated for each sampling period (December 2017 – April 2018 and April 2018 – May 2019). Analyses were done in ArcGIS toolbox Waves 2012 (Rohweder et al., 2012).

### 2.2 Sediment density

Sediment density was measured by recording sonar scans that were merged into georeferenced images, as described in Kragh et al. (2017). Continuous sonar scans were measured with a Lowrance HDS-12 Gen3 equipped with a Lowrance Hybrid Dual Imaging (HDI) Skimmer Transducer. Data were recorded at the same time as sediment sampling in April 2018 and May 2019. Lake isobaths and density maps were calculated using Reefmaster 1.8 (Reefmaster Software
Limited, 2015), with the bottom composition module having a maximum interpolation between data
paths set at 50 m, while data points were recorded as one-meter intervals.

2.3 Sediment composition

Sediment cores were collected using a Kajak sediment core sampler (surface area 21 cm²) attached
to an acrylic cylinder. Each sediment core was divided into three sediment depth intervals of 0–2
cm, 2–5 cm and 5–10 cm, which were kept frozen at -18°C until laboratory analysis. Samples were
collected on three occasions: November 2017 (before lake reestablishment), April 2018 and May
2019. Samples collected prior to reestablishment were characterized by three substrate groups:
plough, grass and sand layer. Plough and sand layers were only divided into two depth intervals of
0–5 and 5–10 cm, as the top 5 cm was thought to be homogenous. A total of 15 sediment core
samples were collected in 2017 and 2018; 11 samples were collected in 2019. The cores were taken
at the same locations defined within 0.5 m using a GPS (Biobase, 2013).

Sediment samples from different depth intervals were homogenized. Subsamples were
used to determine organic matter content by combustion at 550 °C in a combustion furnace
(Søndergaard & Middelboe, 1993). Total phosphorus was measured after combustion of samples,
dissolving the minerals in 1 M HCl in an oven for 2 hours at 120 °C and spectrophotometric
measurements of dissolved ortho-phosphate (Hieltjes & Lijklema, 1980).

2.4 Integrated lake sediment phosphorus

Integrated phosphorus in soils and sediment was calculated in 2017, 2018 and 2019. An orthophoto
(Kortforsyningen) from 2017, taken before the soils were flooded, was used to divide the areas of
the upcoming lake into three substrate groups (i.e. plough, grass and sand layer) of measured carbon
and phosphorus content. In April 2018 and May 2019, the sediment density mapped across the lake
bottom was divided into four density types (i.e., softest, soft, hard and hardest) based on the quartiles of the relative bottom density. Values were interpolated to the edge of the lake using an inverse-distance-weighted interpolation. From the sediment cores, we determined the average phosphorus content for each of the depth intervals in the density types. This enabled us to calculate the entire P pool for each depth interval across the lake, and subsequently the P pool contained in the upper 10 cm of the sediment throughout the lake. All maps and data calculations were made in R (R Core Team, 2018) using the tidyverse package (Wickham H., 2019). After we began to work with rasters, four packages were used: raster (Hijmans, 2019), rgdal (Bivand R., 2019), sf (Pebesma, 2018) and sp (Pebesma Ej, 2005).

Water samples from the lake were taken approximately weekly over a 5-month period, from 2 April to 22 August 2018. TP concentrations were determined by the method described in Kragh and Søndergaard (2004).

2.5 Statistics
Temporal changes in TP content in the 2018 and 2019 sediment depth intervals were tested using a paired t-test. Furthermore, to test for differences at various depths and over time, the change in TP content between 2018 and 2019 was tested using a one-way ANOVA, with sample depth being the independent variable and ∆TP (TP\textsubscript{2018}-TP\textsubscript{2019}) being the dependent variable. All tests were made for TP content expressed as g P m\(^{-2}\) per cm of sediment depth.

Prior to modelling, mean shear stress was log-transformed to obtain a normal distribution. To determine the effect of shear stress on sediment mobilization, a linear regression model was used. Shear stress was used as the independent variable and bottom density was used as the dependent variable. All tests were done in R (R Core Team, 2018), using the base-package for the t-test and linear model and the car-package (Fox & Weisberg, 2019) for the one-way ANOVA.
3. Results

3.1 Sediment density and shear stress

Lake Birke’s sediment is susceptible to wind exposure due to the substantial lake surface area (125 ha) and, in particular, its shallow mean depth (0.54–0.58 m, Fig. 2.). This causes relatively strong shear stress on sediment surfaces and induces particle resuspension and P mobilization.

From the creation of the lake in December 2017 until May 2018, a mean daily volume of 8,059 m$^3$ of water entered the lake each day, while from October to December 2018 the mean daily input was 1,891 m$^3$. No surface water entered the lake during the summer months (May–September). Thus, nutrient flushing only took place during the winter months (October–April). Water retention time, calculated summing the water input for the entire year, averaged 193 days.

Sediment shear stress displayed high values in the middle of the lake, while the islands and the shores offered shelter against the wind and caused lower bottom shear stress (Fig. 3). This was particularly the case for the western shore, which had short fetches in the prevailing SW–NW wind directions. Maps describing sediment density in April 2018 and May 2019 show spatial changes as a result of mobilization and relocation of sediment particles (Fig. 4). Sediment density changed towards harder and denser materials (sand) in the middle of the lake, while the N to N-E and S-W areas of the lake experienced the accumulation of softer organic material. This pattern was consistent with the spatial distribution of sediment shear stress.

Linear regression indicates a significant relationship between bottom shear stress and sediment density. In the period December 2017–April 2018 the relationship was: Density = 4.97 log (Shear stress) + 185 (df = 771101, P < 0.001, adjusted-R$^2$ = 0.12). In the period April 2018–May 2019 it was: Density = 9.35 log (Shear stress) + 195 (df = 891446, P < 0.001, adjusted-R$^2$ = 0.59).
Thus, shear stress accounted for a higher proportion of the variation in sediment density across the lake bottom in the second period, compared with the first period.

### 3.2 Sediment composition

Phosphorus content in the sediment was lowest at all depths in 2019, compared to earlier (Fig. 5). Changes in P content from 2018 to 2019 showed the same pattern with sediment depth (one-way ANOVA, $P = 0.66$), suggesting a uniform P loss with depth.

### 3.3 Lake phosphorus pool

Lake P in the surface sediment (0–10 cm) decreased markedly over time. The first 116-day period in 2017–2018 showed the highest monthly P decrease, while the monthly decrease was lower in the second, 414-day period in 2018–2019 (Table 2).

Between 2018 and 2019, the sediment developed toward higher density types. The decline of coverage of the softest and most P-rich type, from 59% to 35% was most pronounced (Table 1). The hard density type almost doubled in areal cover; the hardest sediment density type increased more than four-fold in cover.

Total sediment P in lake sediment was calculated for each sampling time. For 2018 and-2019, density maps of four types were used (Fig. 6), while in 2017 the lake area was split into substrate groups (37 % plough-layer, 60 % grass-layer and 3 % sand-layer) based on orthophotos. Total P in lake sediment was highest in 2017 before the lake was reestablished, and it decreased markedly upon inundation (Table 2). The upper 10 cm of the sediment released an average of 0.75 ton P month$^{-1}$ over the first 116 days after the shift from land to lake conditions, while the release was 0.3 ton month$^{-1}$ over the following 414 days (Table 2). The mean daily loss was 20.1 mg P m$^{-2}$
(sediment) over the first period and 7.9 mg P m\(^{-2}\) (sediment) over the second period. Overall, 69% of the total P pool was lost over full 530-day observation period.

Total P concentrations in the water ranged from 1.1 to 3.04 mg P L\(^{-1}\) during the summer months of 2018. TP in the water column averaged 878 mg P m\(^{-2}\) from April to August and peaked (1359 mg P m\(^{-2}\)) in late June.

4. Discussion

It is essential to search for the optimal morphometric and hydrological design in order to ensure the best future environmental and biological qualities of newly established lakes. These qualities have become a political priority at the highest level in Europe (European Parliament of the Council, 1992, 2009). A main concern for the quality of new lakes established on former farmland is the risk of ongoing release of high quantities of nutrients into the water column, which can cause sustained poor ecological conditions (Ardón et al., 2010; Pant & Reddy, 2003). Thus, our discussion focuses on two questions. First and most importantly: Can rapid depletion of sediment P pools be ensured with use of suitable morphometry and physical lake design? Second: Can interventions beforehand prevent or reduce P release from the sediment after a lake has been reestablished?

4.1 Morphometry and physical design

Using sonar equipment and simple wind models, we constructed significant matching relationships between shear stress and sediment density at high spatial resolution across the sediment of Lake Birke. The results showed intensive particle mobilization in exposed areas of high shear stress and sedimentation in sheltered areas of low shear stress. This was due mainly to the alternation of wave-exposed sediments with deeper, wave-protected areas at the leeward side of the main shore and behind the constructed bird islands. Using the WAVE-model, we constructed maps of daily shear
stress across the lake bottom. Shallow areas and areas characterized by long fetch in the main wind
direction were subjected to high bottom shear stress and consequent resuspension of fine particles;
this resulted in the development of sediment composed of coarser mineral particles (e.g., sand and
gravel) of low nutrient content. Fine particles were relocated to deeper and sheltered sites, unless
they passed through the lake outlet.

By using the WAVE-model, which only accounts for fetch, depth and wind at one
point at a time, some of the accuracy of the model is lost. Any obstacles surrounding that single
point, be it macrophytes, underwater slopes or rocks, would interrupt the water flow and cause the
model to overestimate the shear stress. Furthermore, macrophyte beds within the lake could
decrease water flow, thereby causing lower shear stress at the sediment, as well as, causing
accumulation of organic material. In the summer of 2018, macrophyte coverage was examined in
the lake and showed very low values (2.4 %, data not shown), which is likely due to the lake water
being highly colored in dissolved organic material. In lakes with high morphological heterogeneity
and macrophyte beds the use of a 3D model would reduce any discrepancy between shear stress and
sediment density and composition. However, in the case of Lake Birke, the advanced 3D models
were not needed due to the low water depth, low macrophyte coverage and only few obstacles due
to the history of the lake as a former cultivated field.

Kragh et al. (2017) proposed keeping water levels low during the earliest phases of
lake establishment, in order to increase bottom shear stress, stimulate loss of sediment nutrients and,
subsequently, generate lower internal nutrient loading. Combining information on wind speed,
direction and fetch with bathymetry and water level, prior to establishing a new lake, makes it
possible to predict bottom shear stress and the likelihood of particle resuspension. It is even
possible to predetermine bathymetry to some extent by working the soils, thus enhancing nutrient
loss and relocation of particles to deeper parts with less turbulence and stronger nutrient retention in the sediment.

Phosphorus in surface sediment decreased rapidly in Lake Birke after inundation, and continued to decrease throughout the following 18-month study period. Probably, part of the P in organic matter was mineralized, was released into the water column, and finally lost through the outflow, although a substantial pool of P within the water column was retained. Likewise, P-rich organic and mineral particles were likely resuspended in the water column and washed out. In order to decrease the internal P-loading, P export from the lake is important. Outflow serves as an effective sink, as the export of both dissolved and particle-bound P reduces internal P-loading in new lakes on former cropland (Kragh et al., 2017). The outflow could be particularly effective in the export of re-suspended sediment, if it is located where maximum particle concentration will occur; in the direction of the prevailing wind.

In new lakes with long water retention, it is also possible to plan beforehand where sheltered areas with deeper water should be located and where particle sedimentation is possible and wanted. For example, deeper areas located close to the leeward shore could be easily accessible to dredging or pumping equipment thus removing the organic nutrient-rich sediment as it accumulates over time.

4.2 Sediment mobilization and phosphorus loss

Sediment mobilization in Lake Birke was traced through use of sonar scans of sediment density. The spatial changes of sediment density over time comprise a linear relationship between measured sediment density and calculated bottom shear stress. Bottom shear stress explained little of the variance ($R^2 = 0.12$) in the sediment density map in April 2018, but more than half of the variance ($R^2 = 0.59$) in May 2019, when changes in sediment density had had the time to develop as a result
of variable shear stress across the bottom of the new lake. The development suggests that mobilization of sediment surface particles across the entire lake started before April 2018, while relocation of fine particles from exposed sites to sheltered sites had continued until May 2019. Subsequently, sediment resuspension has become less prominent, though it was still observed after May 2019 during heavy storms. Frequent resuspension of sediment into the water column during the early periods of the lake’s existence is known to cause aeration, increased mineralization and nutrient release from sediment particles (Søndergaard, Jensen & Jeppesen, 2003; Wetzel, 1983). Those nutrients can either be dispositioned or flushed out of the lake, resulting in the lake being dominated by harder, less organic and P-poorer sediment as time progresses.

Phosphorus in the upper 10 cm of the sediment decreased by almost 30 % during the first four months of Lake Birke’s existence. The decrease was essentially the same at all depth intervals (0–2 cm, 2–5 cm and 5–10 cm), suggesting that bottom shear stress affected all sediment layers equally. The greater decrease in sediment P during the first four months compared to the next ten months could be due to gradual depletion of the nutrient-rich fine particles, including the labile P pool, leaving behind the heavier particles and the more refractory P pools. Furthermore, the decrease in the earliest period could be attributed to an immediate nutrient release, upon inundation, of dissolved or loosely adsorbed P in the soil (Bostic & White, 2007; De Vicente et al., 2010; Gilbert, Guerrero & De Vicente, 2014; Kerr et al., 2010; Watts, 2000).

The large P amounts were probably released from the sediment due to the depletion of inorganic, organic-bound and Fe-bound P, while Al- and Ca-bound P is expected to be more refractory or firmly bound. Likewise, fast initial release of dissolved inorganic P was observed in sediment cores from the new Lake Rønnebæk, Denmark, also established on former agricultural soil (Jensen, 2020). Over a 210-day laboratory incubation of sediment cores, 85 % of P release happened within the first 60 days (Jensen, 2020), which was consistent with very high CO₂ and
CH$_4$ production observed in the field at the same time (Martinsen, Davidson & Sand-Jensen, 2019). These features reflect intense initial organic degradation. The same development has probably taken place in Lake Birke. Newly inundated sediment probably contained high amounts of inorganic and organic-bound P in the former agricultural soils, which are prone to direct release and decomposition. Once inundated, this sediment is expected to rapidly turn anoxic below the sediment surface, causing reduction of precipitated Fe(III) to dissolved Fe(II) and, thus release of Fe-bound P (Hupfer & Lewandowski, 2008).

### 4.3 Pretreatment of soils

Pre-treatment of agricultural soils before inundation has been shown in long-term laboratory measurements to be an effective and cheap way to eliminate the initial P release into the water column and, in some cases, even cause P uptake from the water column into the sediment (Jensen, 2020). Thus, pre-treatment of sediment by sand-capping and depth ploughing can bury nutrient-rich organic material deeper into the sediment making it inaccessible to direct release to the water column (Jensen, unpublished results). This appears to lower internal P-loading and may increase water clarity and facilitate development of submerged macrophytes (Jensen, 2020). Macrophytes are particularly important in shallow lake ecosystems, as they may obtain a high areal cover and improve environment quality (Jeppesen et al., 1998; Madsen & Sand-Jensen, 1991). Moreover, macrophytes play an important role as habitat and refuge for zooplankton, invertebrate and fish (Jeppesen et al., 1998; Madsen & Sand-Jensen, 1991). By contrast, trapping the rich organic sediment in deep sediment strata could reduce bacterial production and lower macroinvertebrate abundance for bird populations in shallow water. On balance, pre-treatment could be a useful tool when P concentrations in the soils and water retention time are high, Moreover, the treatment could be essential in order to reduce P transport to susceptible downstream recipients. In lakes with low
water retention time and robust downstream recipients, the pre-treatment effect might be negligible as most of the P will quickly be flushed away without any treatment and no major downstream damage (Kragh et al., 2017).

4.4 Biodiversity

The creation of new lakes will have complex influences on biodiversity. Reduction of internal release of dissolved P by relocation of sediment and washout will reduce phytoplankton shading thus and risk of bottom anoxia, thereby, stimulating biodiversity of submerged macrophytes and deep-living macroinvertebrates and fish.

New shallow lakes on agricultural soils are characterized by high species diversity and abundance of birds (Møller, Sand-Jensen & Baastrup-Spohr, 2019). Waders and other invertebrate-eating birds show an especially swift increase in the first and second year of a new lake’s existence and, thereafter, a decrease over the next 10–20 years (Hapner et al., 2011; Møller, Sand-Jensen & Baastrup-Spohr, 2019), most likely due to depletion of macroinvertebrate resources in sediment and increasing competition from developing benthic fish populations (Vander Zanden & Vadeboncoeur, 2002). Macroinvertebrates initially feast on dense bacteria populations in the soils and they provide a rich food source for birds.

Lake Birke was exceptionally rich in bird life during the first year of its existence. Mean species richness varied between 11 and 57 across seasons and bird numbers ranged from about 6,000 in winter and spring to about 13,500 in autumn (Danish Ornithological Association). These numbers correspond to very high densities of about 48–108 individuals per ha of lake surface. In terms of numbers, invertebrate eaters, herbivorous and omnivorous birds were almost equally common (each 23–32 %), whereas carnivorous birds (mainly fish eaters) were less common (14 %). Migrating waders were particularly abundant in autumn (September –November), when
their mean density reached 50 individuals per ha. In comparison, a complex of four natural, old Danish lakes (Maribo lakes, 45–957 ha), known for high bird richness, had approximately 10-fold lower bird densities (Sand-Jensen, 2001). Densities of breeding individuals during summer in the four Maribo lakes were 0.8–3.0 per ha of lake surface, whereas the mean value of recorded maximum densities during autumn–winter over several years was 4.0 (Sand-Jensen, 2001, p. 196-197).

Islands created on Lake Birke were intended to function as refuges from predators, mainly fox, and to stimulate bird diversity (Naturstyrelsen, 2013). In the creation of these islands, however, soil was dragged from nearby areas creating a trench around the islands with steep depth gradients from the islands into the water, thus increasing shear stress on the steeply sloping sediment surface. Over time, the high shear stress will generate erosion, gradual depletion of organic matter and likely fewer benthic macroinvertebrates and waders over time. Furthermore, the steep sediment slope will narrow the zone where waders can forage. The deep trench accumulates organic material that had been resuspended and carried from other parts of the lake basin. Although this material may serve as food for bacteria that in turn are exploited by invertebrates, it is by and large unavailable to waders and other invertebrate-eating birds. A low sediment slope around the islands would be more suitable to foraging bird populations but would require taking soil to construct the islands on parts of the lake that are more conducive to a sedimentation basin.

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Figure 1. Left: Orthophoto of Denmark (Courtesy of Kortforsyningen.dk) with the location of Lake Birke (red dot). Right: Map of Europe showing Denmark in red.
Figure 2. Lake depth in 2018 (left) and 2019 (right). White areas in the middle indicate islands. The same 2018 outline was used for calculations of phosphorus content in surface sediments in the lake in both 2018 and 2019.

Figure 3. Average bottom shear stress over the second period from April 2018 to May 2019. White areas within the lake indicate either islands, or areas which were regarded as land (depth < 0.2m).
Figure 4. Lake sediment density in 2018 (left) and 2019 (right). Lighter colors indicate harder substrate, darker colors indicate softer substrate. Areas which are white indicate either islands or places which could not be sampled due to low depths. The shown outline for 2018 was used in both maps.

Figure 5. Mean phosphorus content (x, mg P per square meter per cm in different sediment depths layers (y) in 2017 before lake establishment and in 2018 and 2019 after lake establishment. Error bars are standard error of the mean. In 2017 the sand layer was only sampled in depth intervals of 0-5 and 5-10 cm, the 0-5cm interval was plotted for both the 0-2 and 2-5cm interval assuming sediment homogeneity from 0 to 5 cm. Phosphorus content declined significantly in all sediment depths from 2018 to 2019 (paired t-test: 0–2 cm: t(10) = 5.4, P = 0.0003; 2–5 cm: t(10) = 4.4, P = 0.001; 5–10 cm: t(6) = 3.9, P = 0.008).
Figure 6. Sediment density interpolated to the entire lake and divided into 4 categories in 2018 (left) and 2019 (right). White areas are islands. 2018 outline of lake margin was used for both 2018 and 2019.

Table 1. Average phosphorus content (g P m⁻² cm⁻¹ sediment) for each of the four quartiles of sediment density in 2018 and 2019. The relative density was used to divide the lake sediment into four groups.

<table>
<thead>
<tr>
<th>Sediment density group</th>
<th>Relative density</th>
<th>Year</th>
<th>Coverage (%)</th>
<th>0–2 cm</th>
<th>2–5 cm</th>
<th>5–10 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Softest</td>
<td>&lt;0.57</td>
<td>2018</td>
<td>59</td>
<td>0.614</td>
<td>0.670</td>
<td>0.645</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2019</td>
<td>35</td>
<td>0.599</td>
<td>0.600</td>
<td>0.534</td>
</tr>
<tr>
<td>Soft</td>
<td>0.58–0.69</td>
<td>2018</td>
<td>23</td>
<td>0.522</td>
<td>0.550</td>
<td>0.672</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2019</td>
<td>20</td>
<td>0.359</td>
<td>0.362</td>
<td>0.339</td>
</tr>
<tr>
<td>Hard</td>
<td>0.7–0.83</td>
<td>2018</td>
<td>13</td>
<td>0.253</td>
<td>0.343</td>
<td>0.279</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2019</td>
<td>24</td>
<td>0.303</td>
<td>0.276</td>
<td>0.225</td>
</tr>
<tr>
<td>Hardest</td>
<td>&gt;0.84</td>
<td>2018</td>
<td>5</td>
<td>0.225</td>
<td>0.353</td>
<td>0.310</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2019</td>
<td>21</td>
<td>0.229</td>
<td>0.254</td>
<td>0.254</td>
</tr>
</tbody>
</table>
Table 2. Total amount of P in sediment depths integrated over the entire area before (2017) and after (2018 and 2019) reestablishment of the lake. The rate of P release per month has been calculated for the two periods between samplings.

<table>
<thead>
<tr>
<th>Year</th>
<th>Days</th>
<th>0–2 cm</th>
<th>2–5 cm</th>
<th>5–10 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>ton P</td>
<td>ton P md(^{-1})</td>
<td>ton P</td>
</tr>
<tr>
<td>2017</td>
<td>116</td>
<td>2.12</td>
<td>0.17</td>
<td>0.19</td>
</tr>
<tr>
<td>2018</td>
<td>414</td>
<td>1.46</td>
<td>2.33</td>
<td>3.79</td>
</tr>
<tr>
<td>2019</td>
<td></td>
<td>0.63</td>
<td>1.17</td>
<td>1.68</td>
</tr>
</tbody>
</table>