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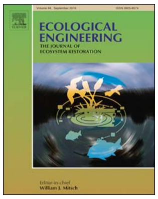

Fast phosphorus loss by sediment resuspension in a re-established shallow lake on former agricultural fields

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ABSTRACT

Lake restoration on fertilized agricultural fields can lead to extensive nutrient release from flooded soils which can maintain a poor ecological quality in the new lake. The period with high sediment release is poorly understood due to few detailed lake restorations studies. We conducted such a study of phosphorus (P) mass balance and sediment dynamics in the large (889 ha) and shallow (avg. 1.03 m) Lake Filsø, Denmark to evaluate when and how fast P was removed from the lake during the first three years after establishment in autumn 2012. The results revealed that P release was high and temporally dynamic due to strong wind and wave exposure, frequent sediment resuspension and a short water retention time (WRT: 20–183 days). To quantify sediment pools across the entire lake, we performed broad-scale sonar measurements of sediment density and established close relationships to organic carbon and P contents. This enabled estimate of the loss of sediment P with high spatial resolution by comparison with the initial homogeneous P content in the soils. The approach was advantageous as P pools were highly heterogeneously distributed depending on water depth and wave exposure. We found that 65 tons P of the initial 163 tons P in the top 9 cm of the sediment had been lost from the lake between October 2012 and September 2015. Detailed measurements of P stream input and output, initiated 7 months after establishment of the lake, showed that sediment release peaked during winter when mean WRT was much shorter (40 days) than during summer (92 days). Phosphorus concentrations in the water were closely related to wind speed which caused resuspension of P-containing sediment particles particularly from shallow areas. The excess stream output relative to stream input from May 2013 to November 2015 was much smaller than the broad-scale estimate from sediment analysis suggesting that extensive P pools had already been lost from the lake during the first winter after lake establishment. We conclude that high wind exposure, shallow water and short water retention time can be a useful combination in future lake restorations on former agricultural land by facilitating fast and profound sediment P loss lowering subsequent internal loading in the following years. Keeping the water level low during the earliest phases could increase P loss by enhancing both sediment resuspension and hydraulic flushing.

1. Introduction

Approximately half of Europe's wetlands have disappeared during the last 200 years due to extensive land reclamation and agricultural expansion (Moreno-Mateos et al., 2012; Zedler and Kercher, 2005). Urban development and water abstraction have been the main reasons for the reduction (Hoffmann and Baattrup-Pedersen, 2007) and especially shallow lakes and ponds have disappeared to an alarming extent in intensively cultivated lowland regions of Europe (Sand-Jensen 2001; Williams et al., 2001). Profound loss of biodiversity and accelerating marine coastal eutrophication have increased the interest in restoring former wetlands and lakes in order to retain or remove nutrients during transport from land to freshwaters and marine waters (Strand and Weisner, 2013; Zedler and Kercher, 2005) and improve aquatic biodiversity (Mitsch et al., 1998). In Denmark, more than 50 large shallow lakes have been re-established during recent decades usually on low-lying agricultural fields that used to be natural shallow lakes before they were drained and reclaimed as agricultural land (Hansen, 2008).

A great concern regarding the ecological quality of re-established lakes is the potential mobilization of phosphorus (P) in the plough layer of former agricultural fields (Pant and Reddy 2003; Steinman and Ogdahl 2011). When inundated, the large P pool accumulated in the soils after many years of fertilization can be released to the water column causing high internal loading and dense phytoplankton blooms. This release can be problematic in agricultural soils which have often surpassed the P binding capacity to minerals such as calcium,

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aluminium and iron due to net accumulation of P over many years (Reynolds and Davies, 2001). Furthermore, in fields receiving large amounts of organic fertilizers most P is bound in organic matter which is susceptible to microbial degradation and release (Laboski and Lamb, 2003). To avoid this unfortunate development, it is essential to understand the mechanisms influencing the nutrient concentrations in the water column through water-born input and output of nutrients and nutrient exchange with the new lake sediments.

Wind and wave-induced mixing in shallow lakes can boost degradation of organic sediment and nutrient release by sediment resuspension in the aerated water column (Søndergaard et al., 2003). Furthermore, release can continue at increased rates when particles settle again on the oxygenated sediment surface (Wetzel, 1983). When water retention time is long, nutrient release from the sediments will prolong the time for the lake to recover until the excess nutrient pool has been either buried permanently in the sediment as immobile P minerals, as recalcitrant organic matter or lost from the lake via the outlet. In contrast, when water retention is short, both suspended particles and released dissolved organic and inorganic nutrients can be rapidly lost from the lake by hydraulic flushing (Marsden 1989).

Here, we report the study of P-dynamics in the new 889-ha large Lake Filsø which was re-established in 2012 after 60 years of intensive agricultural use during which the original lake had been completely drained and reclaimed (Hansen 2008). Our general objective was to understand and quantify P dynamics in the re-established Lake Filsø. The specific objectives were: 1) to apply a novel approach for determining P pools and release at high spatial resolution to estimate the removal from the time of inundation to three years later, 2) to quantify the temporal development of P mass balances between stream input and output, and 3) to quantify nutrient pools in water and sediments and the influence of wind and resuspension on nutrient removal from the lake.

2. Materials and methods

2.1. Study site

This study was conducted in Lake Filsø (Fig. 1), which is located on sandy soils in South-West Jutland, Denmark only 3 km from the North Sea (55°42′N, 8°14′E). Before 1850, Lake Filsø was the second largest lake in Denmark (2185 ha). It was a shallow, mesotrophic lake supporting extensive populations of submerged macrophyte species of the isoetid growth form that are now threatened by extinction in several European countries because of eutrophication and intensive agricultural land use (Pedersen et al., 2006). Lake Filsø was drained and the area reclaimed for cultivation on several occasions from 1850. From 1952–2011, the land was cultivated intensively by a single farmer growing the same crops in annual cycles involving ploughing and spreading of manure several times a year resulting in a homogenous soil top layer. This development was confirmed by preliminary investigations showing concentrations of 2132 ± 238 mg P m^{-2} cm^{-1} (SD, n = 15) in homogenized plow layer. The lake was re-established in the autumn of 2012 after a summer with wheat crops without the addition of fertilizers to remove a small part of the soil nutrient pool. Furthermore, the stubbles and roots were left in the soil to stabilize it during flooding and reduce immediate sediment resuspension (COWI, 2010) (Fig. 3A).

The new Lake Filsø is 889-ha large divided into a southern and a northern basin (Søndersø and Mellemsø, respectively), which are separated by a 7 m wide dam and interconnected by a 5 m wide canal (Fig. 1). The mean water depth is 1.03 m and maximum depth is 3.5 m. Because of its size, shallowness and location close to the North Sea, the lake is highly exposed to the prevailing winds from the southwest. The water column is well mixed and the shallow sediments are frequently exposed to waves. The catchment area is about 104 km^2, and water is mainly supplied to the southern basin through a large stream inlet, while the water outlet is located in the northern basin (Fig. 1).

2.2. Sampling

Field work started in May 2013, 7 months after re-establishment of Lake Filsø, and continued to November 2015. The initial postponement of field work was due to a delay in logistic support. Wind speed (m s^{-1}) was measured continuously, 2 m above the ground, by a meteorological station (HOBO S-WSB-M003, Onset Computers) placed on the open shore by the lake. Water discharge in and out of the lake was determined daily using the general relationship between water discharge and water depth (Q-H relationship) and daily measurements of water depth recorded by a submerged water level data logger (HOBO U 20-001-04, Onset Computers, Bourne USA) relative to a similar reference logger in air. Water discharge was determined as the product of the mean cross section area of 5 transects located 4 m apart multiplied by the mean water velocity along the 20 m long stretch. Mean velocity was determined as the passage time of 50% of a NaCl-pulse added upstream and measured downstream by a continuously recording conductivity meter (YSI 30, OH, USA). From June 2014 and onwards we recorded water depth and flow velocity with a SonTek-IQ plus Doppler (Xylem, CA, USA). Discharge calculations from the Q-H relation showed a close linear relationship with the SonTek-IQ Doppler measurements (slope = 0.94 ± 0.03, ± 95% C.L., n = 365, $P < 0.00001$) thus confirming the accuracy of measurements derived from the Q-H relationship.

Water samples were collected weekly between May 2013 and November 2015 from the inlet, the outlet and from either both basins or the short canal connecting them. The samples were collected from a water depth of 0.3 m in the mixed water column. Direct atmospheric deposition of phosphorus was estimated to be 0.04 kg P ha^{-1} $year^{-1}$ according to measurements in neighbouring areas (Ellermann, 2013). Phosphorus received from the catchment as hydraulic diffusive input to the lake was based on a revised estimate from Blicher-Mathiesen et al. (2013). This was done by changing the background concentration to correspond with the measured concentrations in the inlet water during periods with no precipitation, acting as a groundwater baseline. Water samples in stream input and stream output were combined with discharge measurements to estimate the daily phosphorus input, output and net sediment release in the lake (output − input). The mass balance is presented as running average over three months due to large fluctuations in weekly concentration and discharge. This procedure ensures a clearer picture of the seasonal variations in of transported P.

Sediment cores (surface area 21 cm^2) were first sampled in Lake Filsø in late January 2013 in triplicate at five randomly selected sites at 1.5–2.0 m water depth using a Kajak sediment core sampler attached to an acrylic cylinder. Collected sediment cores were kept in an upright position and stored cold (< 5 °C) in the dark prior to analysis. As the sediment until recently was agricultural soil under plough and it has been greatly disturbed during re-establishment of the lake, it was presumably well mixed and homogenous before flooding in terms of P content with sediment depth. Measurements of 6 cores in terrestrial soils located immediately above the lake in May 2015 showed such a homogeneous distribution of P concentrations with soil depth. Since none of our P measurements at 9 cm depth in the sediment were significantly different from the P content in the soils, we decided that the upper 9 cm would make a representative sample of the sediment pool directly involved in nutrient exchange processes with the lake water. Due to the lack of reliable soil analysis before re-establishment of the lake, the constant P concentrations in deeper sediment layers between 5 and 9 cm in cores collected from water depths of 1.5–2.0 m were used to determine the P baseline content in the soil before flooding.

Later in April 2014, 21 sediment cores were sampled for simultaneous measurements of organic C and P content. An additional 46 cores were collected in May 2015, which used to determine the relationship between sediment density and carbon content. These 67 sediment cores

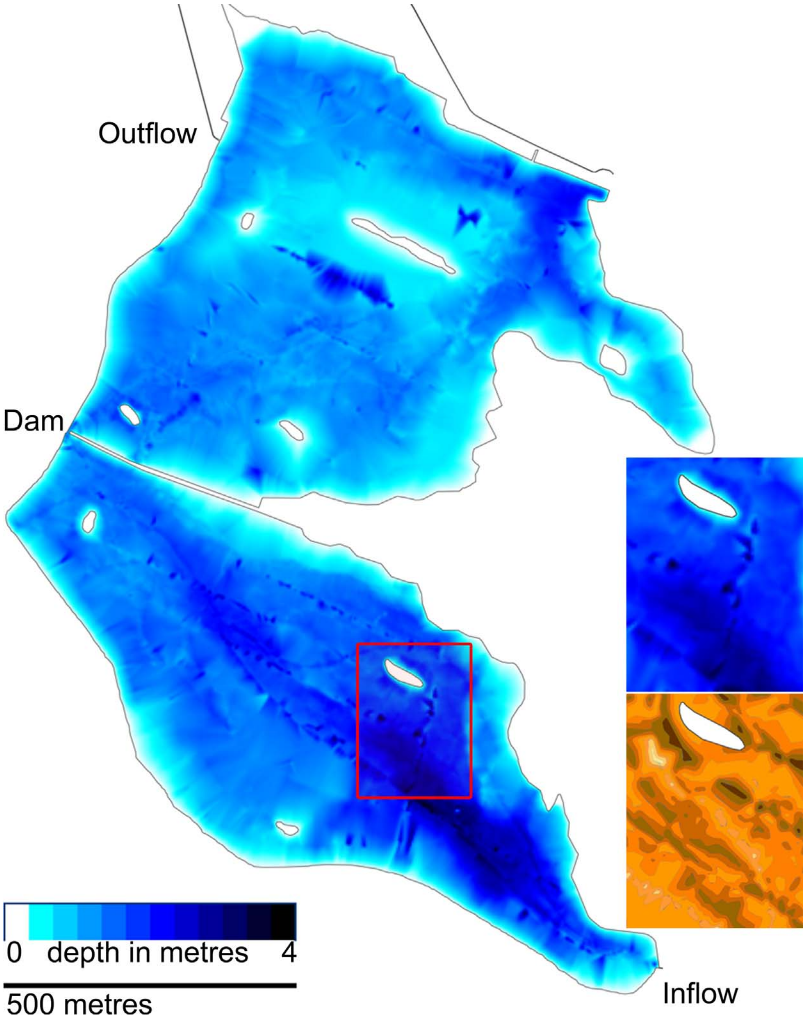

Fig. 1. Bathymetric map of Lake Filsø with a southern and a northern basin separated by a dam. The inflow and outflow are marked as well. The boxes show a close-up of the red-marked section on the bathymetric map (upper box insert) and a close-up of sediment density in the same area (lower box insert) derived from sonar measurements showing high density, minerogenic sediments (light brown) and softer, organic sediments (dark brown).

were collected throughout the lake basin.

2.3. Laboratory measurements

Water samples were kept at −18 °C until analysis. Samples were analysed in triplicate for total phosphorus (TP) as described in Kragh and Søndergaard (2004). Sediment cores were sliced and subdivided into four depth zones (0–1 cm, 1–2 cm, 2–5 cm and 5–9 cm) for analysis. To determine water content, fresh weight was registered immediately after sectioning the cores. Dry weight was determined after 48 h at 105 °C. The dried fractions were homogenized before taking subsamples for further analysis. The sediment was analysed for TP, NH_4Cl-extractable P (NH_4Cl-P), NaOH-extractable P (NaOH-P), HCl-extractable P (HCl-P) and residual P (Res-P) according to the sequential technique described by Hieltjes and Lijklema (1980). NH_4Cl extracts include the dissolved and loosely adsorbed P fraction, while NaOH extracts include the fraction of P adsorbed to surfaces of Fe, Al or Mn oxides-hydroxides and possibly clay particles. HCl extracts P bound to Ca and Mg. Residual P (Res-P) was measured on combusted samples boiled in 1 M HCl. The residual fraction mainly consists of organic bound P. All fractions were analysed for *ortho*-P. TP was measured by combustion and acidification of the subsamples immediately after drying, with no intermediate steps like the ones in the sequential technique. Organic C in the sediment was measured according to

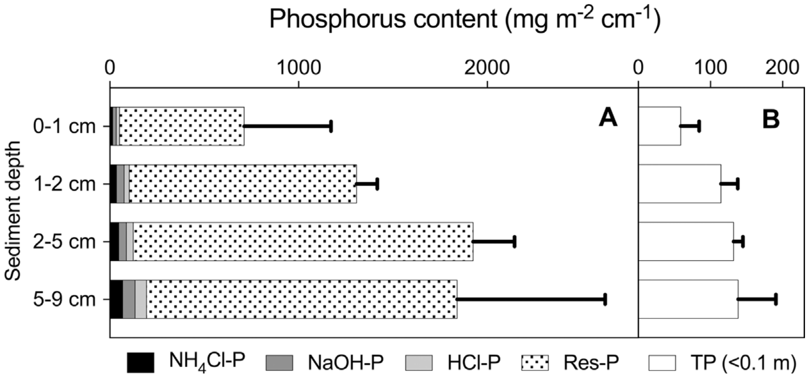

Fig. 2. Distribution of P content in 1 cm thick sediment layers from four depth strata in the upper sediment from Lake Filsø. Panel A illustrates the different fractions of P found in sediment sampled in the deeper parts of the lake (1.5–2.0 m, n = 15). Panel B shows TP content in shallow waters (< 0.1 m, n = 6). All data are presented as mean mg P m^{-2} cm^{-1} ± SEM.

Fig. 3. Sediments in shallow water were highly organic shortly after flooding (spring 2013 left), whereas the P-rich organic matter had been lost and the sediments become sandy 3 year later (right). Photos Theis Kragh.

Søndergaard and Middelboe (1993).

2.4. Sediment density

Sampling in Lake Filsø started 7 months after its re-establishment resulting in a gap in the P mass balance of the lake. This situation, together with the large size and heterogeneity of the lake, called for a novel approach to determine the P pools in the sediment. Therefore, a relationship was established between sediment density and P content. Sediment density was determined by image analysis of recorded sonar scans that were merged into georeferenced images. Data were collected from mid-June to September in 2015 using a Lowrance HDS-12 Gen3 equipped with Lowrance Hybrid Dual Imaging (HDI) Skimmer Transducer operating at 200 KHz and a StructureScan HD transducer (Navico, Egersund, Norway). Lake mapping was done in such a way that the maximum interpolation between data paths was 50 m and data points were recorded in one meter intervals. Computer files were assembled to images in Reefmaster 1.8 with the Bottom composition module (Reefmaster, Birdham, UK). Peak SV was used as it measures the strength of the sonar signal that is reflected from the sediment surface and this signal is highly correlated to sediment density. Images were analysed for sediment areas of different densities with ImageJ (imagej.nih.gov/ij). The calculated coverage of different sediment densities was converted to sediment contents of P and organic C in 46 sediment cores that covered the entire range of sediment densities.

2.5. Statistics

Differences in TP sediment concentrations between sites were analysed by *t*-test for matched pairs. Comparison of TP content in different depth fractions in the sediment as well as differences in relative depth distribution of P in NH_4Cl-P, NaOH-P, HCl-P and Res-P were analysed by one-way ANOVA. Homogeneity of variance was tested by an *F*-test. Tukey test was used as post-hoc test when ANOVA revealed significant differences between means. Statistical analyses were performed with GraphPad Prism 6.

3. Results

3.1. Sediment composition

Phosphorus content in cores retrieved from deep water (1.5–2.0 m) increased significantly with sediment depth from 760 mg P m^{-2} cm^{-1} in the surface to about 2040 mg P m^{-2} cm^{-1} in the 2–9 cm fraction (one-way ANOVA, $P < 0.05$; Fig. 2A). By assuming that the concentration in the 5–9 cm depth interval in sediment cores from deep water (2034 mg P m^{-2} cm^{-1}, $n = 15$) represented the initial content in the upper 9 cm of sediment in the entire lake we estimated a baseline pool of 163 tons P in the soil before flooding. The P content in the deep sediment used for the calculation corresponded well to the mean P content in March 2015 in the surrounding fields (2078 ± 590 mg P m^{-2} cm^{-1}, $n = 6$) as well as samples taken in 2011 before flooding in the homogenized plow layer (2132 ± 238 mg P m^{-2} cm^{-1}, SD, $n = 15$).

The depth distribution in the sediment cores reflects a profound P loss from the uppermost 2 cm of the sediment (Fig. 2A). This is also reflected in decreasing water content with sediment depth from 74% in 0–1 cm, 59% in 1–2 cm, 49% in 2–5 cm to 43% in the 5–9 cm fraction and in the bulk density which gradually increased with sediment depth from 0.26, 0.52, 0.70–0.74 g dry mass cm^{-3} in the same depths. The sediment samples in the shallow areas showed markedly lower P content, reflecting a higher P loss than in deep waters (Fig. 2B).

Sediment cores and visual inspections showed high heterogeneity in P content across the new lake (Figs. 2 and 3), which makes it unreliable to estimate the contemporary P pool from relatively few sediment samples at a particular depth. The heterogeneity motivated us to map sediment P content by sonar measurements with a high spatial resolution across the lake to estimate the contemporary P pool and, thus, the removal of P in the period from filling of the lake utilizing the estimated baseline before flooding.

3.2. Sediment analyses by sonar

Sonar measurements of sediment density across the entire lake were related to organic C and P content in 46 sediment core samples. Fractionation by different chemical solvents quantified the total and specific P pools with sediment depth (Fig. 2A). The relative distribution among the different P pools was independent of sediment depth (one-way ANOVA, $P > 0.05$). NH_4Cl extractable P represented 2.5%, NaOH extractable P 3.1%, HCl extractable P 2.5% and Res-P 91.9% of the total P pool. The main fraction, Res-P, represents organic bound P. Because most P (91.9%) was bound in organic matter there was a highly significant linear relationship between TP (g P m^{-2}) and organic C (%) ($TP = 0.147$ Org. $C + 0.04$; $P < 0.0001$; $R^2 = 0.89$; $n = 46$). Sediment density derived from sonar measurements was described by relative values between 0 (lowest density) and 1 (highest density) with a resolution of 0.05. The linear relationship between sediment organic C (%) and sediment density was highly significant and predictable as well (Org. $C = 21.93$ Density $+ 21.58$; $P < 0.0001$; $R^2 = 0.98$; $n = 46$).

These highly significant relations enabled estimation of the direct linear relationship between sediment P content (g P m^{-2}) and sediment density (Sed-$P = 3.17$ Density $+ 3.17$; $P < 0.0001$; $R^2 = 0.93$; $n = 46$) (Fig. 4). This latter relationship enabled calculation of the areal P content from extensive sonar measurements of sediment density throughout the entire lake. The estimated P content in the upper 9 cm of sediment was 98 tons (September 2015). The difference between the

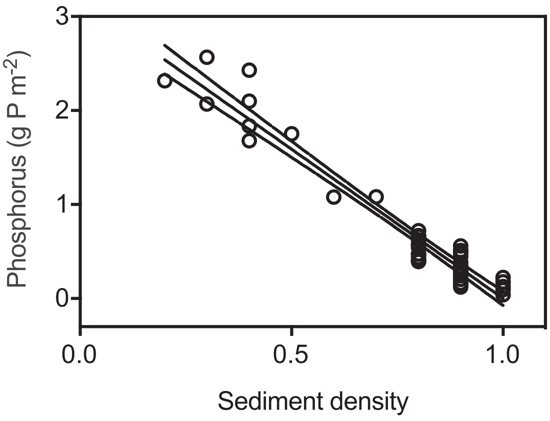

Fig. 4. Linear relationship between phosphorus content (g P m^{-2}) in sediment depths of 0–9 cm and sonar measurements of sediment density (Density, relative units 0–1, P cont. = − 3.17 Density + 3.17; $P < 0.0001$; $R^2 = 0.93$, n = 46).

initial sediment pool, estimated from the deep fraction in the sediment cores, and the pool 3 years later suggested removal of 65 tons P, or 40% of the initial P pool.

A higher P removal of 75.8 tons P was estimated when core samples at 1.5–2 m water depth was extrapolated to depth intervals of 1–3.5 m (9.6 tons P) and samples in shallow areas (< 0.1 m) were extrapolated to depth intervals of 0–1 m (66.2 tons P).

3.3. Hydrology and P balance

Running average of the P mass balance from May 2013 to November 2015 showed pronounced temporal differences in input, output and sediment P net release (Fig. 5). Input of P was markedly higher during winter than summer with winter peaks of 20 kg P day^{-1} during the first year and 30 kg P day^{-1} the following year. Likewise, output of P was markedly higher during winter than summer with winter peaks exceeding 30 kg day^{-1} while summer maximum output was 3-fold lower. The high winter outputs are supported by markedly lower water retention time (minimum 20 days) than in summer (maximum 183 days). Sediment net release, estimated as the difference between input and output, was also much higher in winter than summer. Sediment net release was higher in the second winter after flooding (maximum 18 kg day^{-1}) than in the third winter (maximum 8.5 kg day^{-1}). While, no mass balance measurement was available for the first winter. Annual input of phosphorus was estimated at 8.95 tons P during the 870 days monitored by weekly measurements. Only 85 kg P derived from atmospheric deposition and 27 kg from hydraulic diffusive input. Annual P export in the outlet was 13.8 tons P and exceeded input by 4.85 tons P as a result of net sediment release. This net loss from the lake was much lower than loss rates estimated by mapping of the sediment content. Presumably because sampling in areas with visually extensive loss where omitted the initial sampling period from autumn 2012 to May 2013.

3.4. Wind speed and resuspension

Lake Filsø is located in a very windy region close to the North Sea. Because of the large size and shallow depth, surface sediments are highly susceptible to resuspension. Average wind speed during the two hours with highest wind speeds in the 48 h prior to P sampling showed a strong positive relationship with TP content in the water column (Fig. 6). Phosphorus concentrations in the water column increased with wind speed up to 8 m s^{-1} and remained high and constant above this threshold irrespective of wind direction. The greater number of days during winter with average wind speeds above 8 m s^{-1} over two hours (Fig. 5A) contributed to greater sediment P loss from the lake during

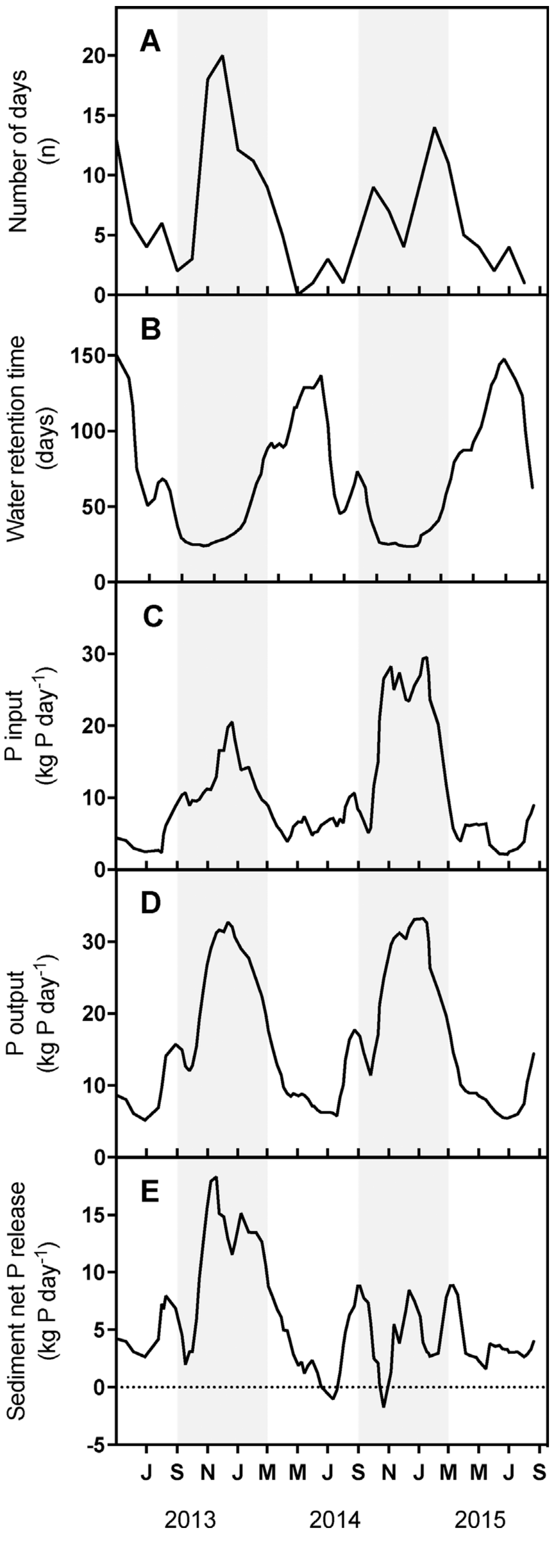

Fig. 5. (A) Number of days (n) per month with an average wind speed above 8 m s^{-1} over more than two hours, (B) Water retention time, (C) daily P flux into the lake, (D) daily P flux out of the lake and (E) the net P release from the lake sediment. Data derived from measurements of wind speed every 10 min and weekly measurements of P concentrations in the period from May 2013 to Nov 2015. Water retention time and P dynamics are presented as running average over three months (B to E). Gray bars mark the winter months from September to March.

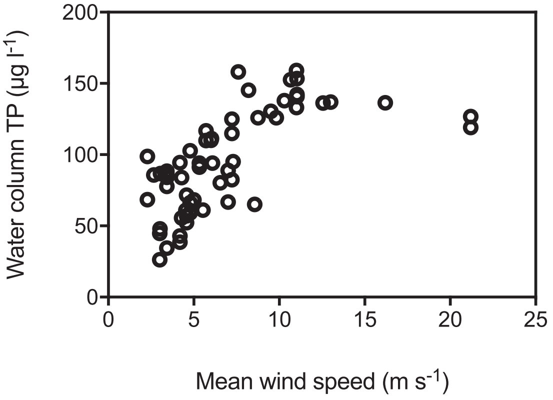

Fig. 6. Relationship between total phosphorus (TP µg l^{-1}) and highest average wind speeds (m s^{-1}) over two hours during the 48 h prior to sampling.

this period. The high sediment P loss during winter was enhanced by low WRT (Fig. 5B).

4. Discussion

We used a combination of broad-scale electronic determination of sediment density and standard chemical measurements of sediment P content to demonstrate fast and extensive loss of sediment P from the former fertilized agricultural fields of the re-established Lake Filsø. The profound P loss was driven by extensive and frequent sediment resuspension in the wind-exposed shallow lake. Below, we discuss these findings and the implications for the future water quality and the possibility of increasing P loss from new lakes even further.

4.1. Sonar and mass balance based P estimates

Using sonar equipment, we were able to construct a detailed map of sediment density across the 889-ha large Lake Filsø. Furthermore, the linear relationship between density, organic C and P content (Fig. 4) enabled precise estimates of P pools in the sediment. This technique yielded an estimated sediment loss of 65 tons P during the 35 months since flooding. In comparison, estimates from a total of 21 sediment cores showed a loss of a similar magnitude, 75.8 tons in the period. The sonar estimated removal of 65 tons P was 13-fold higher than the estimate of 4.9 tons P determined during 29 months of mass balance measurements of stream input and output, not including the loss during the first 7 months after the lake was re-established and water sampling commenced. The deficit between the mass balance and sonar estimated P release suggests that 60 tons may have been removed during the initial 7 months. These findings illustrate the need to initiate measurements of P input and output at the onset of flooding to obtain reliable estimates of fast, initial loss processes.

Since P concentrations in the lake water are highly dependent on wind speeds causing resuspension and losses are also dependant hydraulic flushing, it is logistically difficult to obtain sufficiently frequent sampling for accurate mass balance calculations. Thus, it is more sensible and reliable to perform representative sampling of sediment P pools across the entire lake in order to evaluate P dynamics during the first years after re-establishment of shallow lakes provided losses are substantial.

Estimates of the P concentration in the first winter, before regular weekly water sampling started, suggested a profound loss of 60 tons P during the first 7 months. Assuming a water retention time of 40 days (i.e. the mean value for the next two winters), the mean P concentration in the outlet must have been 930 µg P l^{-1} in order to remove the 60 tons P from the lake. Concentration measurements after May 2013 showed peaks of 250 µg P l^{-1} or almost 4-fold lower than the supposed P concentration during the initial 7 months. This difference is reasonable, considering that the largest sediment pools in shallow water already had been washed out from the lake according to visual and photographic observations (Fig. 3). Moreover, flooding of the lake took place in two steps with the southern basin being flooded already in early-July 2012 and the northern basin being flooded in October 2012, thereby adding an extra 100 days to the 7 months during which the sediment in the southern basin could release P.

A substantial initial sediment release of P to the water column in response to flooding of former agricultural soils is not unprecedented (Ardón et al., 2010; Pant and Reddy, 2003). The initial release includes loss from a redox sensitive P fraction under anoxia induced by flooding and loss of the labile dissolved organic and inorganic P from the top soils. Pant and Reddy (2003) showed that this initial release declined after the first couple of hydraulic retention periods, after which other conditions determined the nutrient flux. Applying the same water retention time of 40 days as above, suggests that at least 4 replacements of the water volume with substantial P loss could have taken place during the initial 7 months. The removal of sediment bound P is particularly extensive in shallow areas where 95% of the initial P pool had been removed.

4.2. Sediment resuspension

Removal of P by resuspension and diffusive loss to the overlying water is reflected by the depth distribution of P in sediments from deeper parts of Lake Filsø (Fig. 2A). Here, the uppermost 2 cm of surface sediments were strongly depleted in P compared with deeper layers. In contrast, P concentrations are higher in surface than deeper sediments in natural lakes (Rydin 2000; Søndergaard et al., 1996). Decreasing P content with sediment depth normally reflects past sedimentation that has undergone many years of decomposition and release events, whereas the surface layers contain P-rich organic matter that have recently settled from the overlying water (Rydin 2000). The 2–9 cm sediment layer from deeper waters of Lake Filsø were apparently largely unaffected by P losses, thus, representing a baseline P content similar to that in the soils immediately above the lake surface. This explanation is also supported by the high mass density of the sediments at 2–9 cm depth which are markedly different from organically rich lake sediments which usually contain about 90% water (Jensen et al., 1992; Rydin 2000; Søndergaard et al., 1992). Sediment cores from shallow water ($<$ 0.1 m Fig. 2B) on the other hand, showed markedly lower P concentrations (50–150 mg P m^{-2} cm^{-1}) supporting the explanation that sediment resuspension and wave exposure induced a stronger P depletion that even affected deeper sediment during winter.

Phosphorus release and transport are particularly high during winter due to frequent sediment resuspension combined with low water retention time. Frequent sediment resuspension in Lake Filsø is related to high wind speed, long fetch and shallow water (Fig. 6) as also documented in other studies (Wetzel, 1983). Wind speeds as low as 3 m s^{-1} cause resuspension, while resuspension increases steeply with higher wind speed and saturates above 8 m s^{-1}. It is noteworthy that wind speeds at Lake Filsø above 3 m s^{-1} are very common and even wind speeds above 8 m s^{-1} are present on average 10 days a month during winter and 3 days a month during summer. Combining wind speed with an average water retention time of only 40 days during winter results in a swift removal from the lake of any material susceptible to resuspension.

The P mass balance showed annual and seasonal patterns opposite to those normally observed in natural lakes experiencing relatively constant annual external P inputs (Søndergaard et al., 2002; Wetzel 1983). Annual P output exceeded input in Lake Filsø and the excess output was much higher during winter than summer. In contrast, annual P input is usually higher than annual P output in natural lakes of constant external P loading because P is being incorporated in new sediments (Søndergaard et al., 1992). Moreover, P is usually retained in the well-oxygenated sediments during winter, whereas enhanced mineralization during summer often results in anoxia and the release of Fe-bound P. This may lead to an overall P loss from the lake during that period usually incorporated in phytoplankton (Wetzel, 1983).

4.3. Obtaining true P pool estimates

Simultaneous P exchange experiments in the laboratory with sediment cores retrieved from Lake Filsø showed that the sediment had a binding potential of 3.6 tons P year^{-1} under oxic conditions (Petersen 2014). However, P exchange measurements in the laboratory do not account for the physical conditions in the field, where surface sediments are frequently re-suspended in the water column. Furthermore, the organic matter undergoes faster degradation with unrestricted oxygen supply than when layered in the sediments under oxygen and diffusion limitation below the sediment surface. This comparison shows that P exchange experiments in the laboratory under static water flow, without re-suspension and mixing of the sediment, can generate misleading results compared with those under dynamic conditions in the field. Weekly estimates of P input and output from measurements of water discharge and P concentrations in inlets and outlets may not offer the correct picture of P dynamics either. Here, the frequency of determination is insufficient relative to the temporal variability of input and output which are subject to rapid day-to-day variations due to erratic wind and rain events.

The weekly measurements of P concentrations in the lake showed a high heterogeneity among sampling sites although the lake was regarded as being fully mixed. This heterogeneity was reflected by up to 3-fold differences between samples taken only minutes apart from the outlet and the northern lake basin delivering water to the outlet. This result supports the notion that particle-bound P is moved by the wind, making it difficult to get representative measurements for a longer period and wider area. Heterogeneity among sites is also a challenge when temporal changes in sediment P pools are used to estimate P losses from the lake. The mechanical stress induced by waves removes organic matter and keeps it in suspension until flushing from the lake or re-settlement in sheltered, often deeper parts of the lake (Blais and Kalff, 1995). The complications introduced by temporal and spatial heterogeneity by use of traditional methods are strong arguments for using the sonar based estimation method described here because it can account for high heterogeneity of sediment P content and is unaffected by seasonal variabilities of resuspension and flushing.

4.4. Future application

The knowledge obtained in this study can be used in future restorations of wetlands and lakes. We showed that fast removal of P was facilitated by sediment re-suspension and rapid hydraulic flushing. A combination of sonar based estimates and physiochemical analysis of sediment cores showed that most P was removed close to the shore and in shallow wind exposed areas. Reducing the water level could, therefore, be a powerful tool to increase wave-induced shear and loss of sediment P in new lakes. Water level could be kept low for 1–2 year to flush out nutrients from the deeper parts of the lake before filling to the desired depth if the recipient waters can tolerate the increased P loading. When recipient waters are unable to cope with increased nutrient input then the initial flush of P could be used for irrigation of nearby fields or released during winter if receiving systems have a short water retention time. Focus on fast removal of nutrients and organic matter and a shift to minerogenic sediments also generate a suitable environment for plant growth (Baastrup-Spohr et al., 2016).

4.5. Conclusion

1) The results from monitoring the large, shallow Lake Filsø in the first years after the re-establishment revealed a highly dynamic system characterized by frequent resuspension of sediment, high hydraulic flushing and profound loss of sediment P.
2) A novel approach combining measurements of sediment density by sonar and close relationships of sediment density to contents of organic matter and P made it possible to determine the spatial distribution of P and calculate a high P loss during the first three years of the lake.
3) Sonar based P estimates and later mass balance measurements revealed that the first winter was particularly important for the P removal.

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