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Spatial and seasonal variability of pore water phosphorus concentration in shallow Lake Swarzędzkie, Poland

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Abstract Pore waters play an important role in phosphorus dynamics in aquatic ecosystems. Phosphorus concentrations in pore waters are much higher than above the bottom. This is confirmed by the results of this study concerning the hypereutrophic lake. Pore water was analyzed at 11 sampling stations in the upper layer of bottom sediments. This water was separated by centrifugation and phosphorus level was measured spectrophotometrically with ascorbic acid as a reducer. Total phosphorus concentration in pore waters ranged from 0.5 to 8.1 mgP l^{-1} (mean 3.2 mgP l^{-1}). Mean phosphorus concentration in pore water samples of this lake was the highest in summer and the lowest in winter. High concentrations were observed in samples from the pelagial and low from the macrophyte zone.

Keywords Pore waters · Bottom sediments · Phosphorus · Hypereutrophic lake

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Introduction

Phosphorus deposited in sediments, as both inorganic and organic forms, is dissolved and released to pore waters as a result of biotic and abiotic processes. The soluble reactive phosphorus (SRP) level in pore waters can be even several dozens of times higher than in waters above the bottom. The pore waters of the sediment, which usually contain less than 1% of the sediment's total phosphorus pool, are important for the SRP transport in sediment–water interface (Boström et al. 1982; Ignatieva 1996; Katsev et al. 2006). The observed concentrations of phosphorus in pore waters are the result of P-turnover, namely sorption and mineralization and P-transport (Lewandowski et al. 2005). Diffusion is regarded as the main mechanism transporting SRP from interstitial waters to the water layer above the bottom (Katsev et al. 2006; Kentzer 2001). This process is supported by microcurrents in pore waters and above the bottom, resulting from the activity of benthic organisms (bioturbation), as well as by resuspension of the upper layer of sediment due to wind action or to the bubbling of gases from sediments (Andersen et al. 2006; Qin et al. 2006). Phosphorus concentrations in pore waters and above the sediments are commonly regarded as indices of intensity of its transport across the sediment–water interface (Kentzer 2001; Komatsu et al. 2006). The chemical composition of pore waters depends mainly on the quality of the sediment, its redox potential, as well as the number and activity of the microorganisms. The chemistry of sediments and of interstitial water can be examined to determine the role of bottom sediments in nutrient cycling in the lake (Mayer et al. 1999). Pore water phosphorus investigations are an underestimated ecological tool in studying and describing the trophic status, redox conditions, phosphorus release from sediments, potential precipitation mechanisms on a long-term basis, groundwater inflow areas, as well as lakewater seepage (Enell and Lofgren 1988). Spatial heterogeneity of SRP content in pore waters of the lake sediments is not frequently studied, although it can be very high. It is due to many environmental variables, mainly oxygen conditions, and also wave action, currents, and bioturbation, caused by macroinvertebrate activity (Boers and de Bles 1991; Ignatieva 1996; Lewandowski et al. 2002, 2005, 2007; Spears et al. 2007). Due to these reasons variability of the pore water SRP is highest at the sediment–water interface and diminished with sediment depth (Lewandowski et al. 2002). Seasonal variability of P content in pore waters was also not frequently studied (Kleeberg and Kozerski 1997; Søndergaard 1988, 1990; Wanatabe and Tsunogai 1984).

The main goal of this study was an examination of seasonal and spatial variation of phosphorus concentration in pore waters in Swarzędzkie Lake and by comparing them with P release from the sediments creation a simple tool for the estimation of P internal loading.

Material and methods

The Swarzędzkie Lake (area 93.7 ha, maximum depth 7.2 m, mean depth 2.6 m) is a throughflow water body of glacial origin. It is located in the northwestern part of the town of Swarzędz, at the border of Poznań city (Poland; 52°25′ N, 17°04′ E). The lake is supplied by the Cybina River and the Mielcuch Stream. The latter one is polluted by the part of stormwater run-off and slightly by the sanitary sewage from Swarzędz. For 20 years the lake has been hypereutrophic. Although municipal sewage stopped to be discharged into the lake and its tributaries in 1991, this water body is still heavily polluted due to the long-term influence of the accumulated nutrients and large external loading from the catchment area especially of non-point origin (Kowalczewska-Madura and Gołdyn 2006, 2010). Swarzędzkie Lake is elongated, narrowing from half its length towards the outlet. The wider part is deeper (the deepest site is situated there), while the narrower is only up to 2 m deep. The shallower southwestern part of the lake is covered by floating leaves plants: *Nuphar lutea*, *Nymphaea alba*, and *Hydrocharis morsus-ranae*. Near the

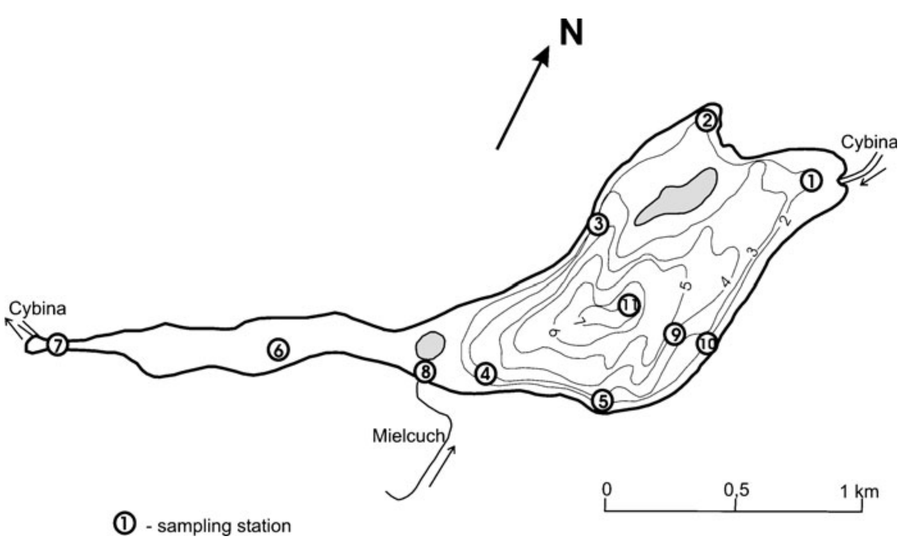


Fig. 1 Location of sediment sampling stations (according to Kowalczewska-Madura and Gołdyn 2005, modified)

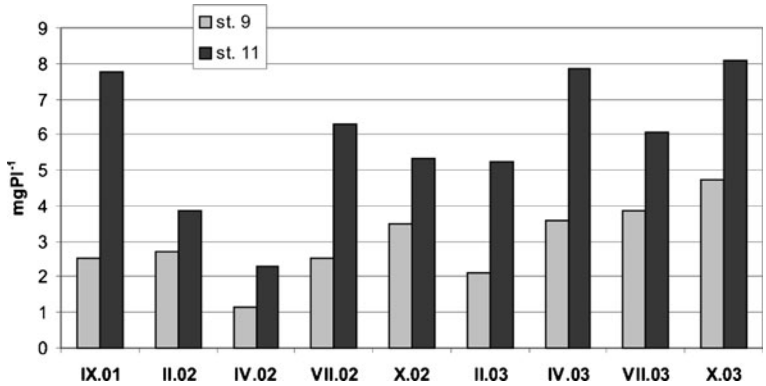


Fig. 2 Total phosphorus concentration in pore waters of bottom sediments at lake depth of 4 m (station 9) and 7 m (station 11)

shore line is a growing belt of emergent vegetation, belonging to the community *Thelypteridi–Phragmitetum* and *Cicuto–Caricetum pseudocyperi*.

Due to the strong algal water blooms (caused mainly by colonial cyanobacteria), the lake cannot be used for recreation. Thermal stratification is incomplete. Only metalimnion is formed in summer in the deeper part of the lake. The oxygen deficits and high concentration of nitrogen and phosphorus compounds in this layer was observed (Kowalczewska-Madura and Gołdyn 2006, 2009; Stefaniak et al. 2007).

Concentrations of total phosphorus (TP) and soluble reactive phosphorus (SRP) in pore waters in bottom sediments of Swarzędzkie Lake were measured from September 2001 till October 2003. Samples of the upper layer (10 cm thick) of bottom sediments were collected with Kajak tube sampler, 7 cm in diameter. Despite the sediment layer is very deep in this lake, we have taken into account only 10 cm layer, as it is the most representative for the evaluation of phosphorus internal loading (i.e., Ignatieva 1996). Eleven sampling stations were located both in the deeper northeastern part and in the shallow southwestern part of the lake (Fig. 1). Water depth was about 1 m at stations 1 and 2, 6–8, and 10; 2 m at station 4; and 3 m at stations 3 and 5. These stations were situated within the littoral zone of the lake. Within the deeper zone, which was in contact with metalimnetic water, station 9 was situated at a depth of 4 m and station 11 at 7 m. More stations in the shallow, marginal zone of the lake were, due to expected larger variability in this part of the lake, connected with the influence of external factors, such as inflow and outflow of Cybina River, inflow of Mielcuch Stream, vicinity of different plant communities etc. Sediment samples were taken nine times from stations 9 and 11 and five times from stations 1–8 and 10. Once (in September 2002) the same sampler was used to collect samples of the vertical profile of the sediment at the deepest site. The samples were divided into four layers: 0–5, 5–10, 10–20, and 20–30 cm.

Pore waters were separated by centrifugation for 1 h at 3,000 revolutions per minute in closed containers to prevent the samples oxidation. In the supernatant, SRP level was immediately measured with the molybdenum blue method with ascorbic acid, and TP with the same method, after sample thermal mineralization (Elbanowska et al. 1999).

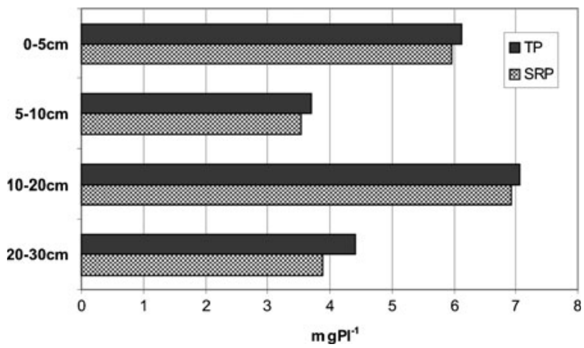
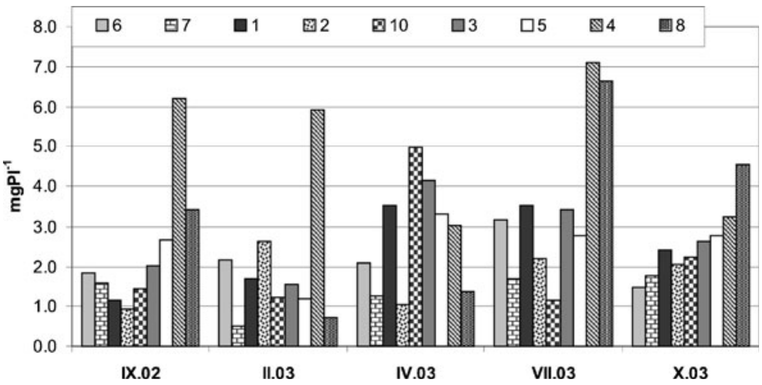


Fig. 3 SRP and TP concentration in pore waters in depth profile of bottom sediments at the deepest site in September 2002 (mean from duplicate analysis)

Fig. 4 Seasonal changes in TP concentration in pore waters of bottom sediments at shallow stations in Swarzędzkie Lake



Statistical calculations were made with STATISTICA version 8.0 software.

Results

At the deepest site (station 11), SRP concentration was high, as it reached up to 7.7 mgP l^{-1}, while TP up to 8.1 mgP l^{-1} (October 2003). In the shallower part of this zone (station 9), lower values were recorded: up to 4.5 and 4.7 mgP l^{-1}, respectively (Fig. 2).

The analysis of phosphorus in pore waters in depth profile of lake sediments at the deepest site showed that concentrations of both SRP and TP were high at the sediment surface (0–5 cm) and at the depth of 10–20 cm (Fig. 3).

At the shallow stations 1–3, 5, and 10, located in the broader, northeastern part of the lake (littoral zone), concentrations of phosphorus in pore waters were usually similar and in most cases did not exceed 5.0 mgP l^{-1} (Fig. 4). The maximum value was recorded there in spring 2003 (up to 4.4 mgP l^{-1} of SRP and 4.9 mgP l^{-1} of TP), whereas the lowest in early autumn 2002 (0.8 and 0.9 mgP l^{-1}, respectively; Figs. 4 and 5).

Mean content of SRP and TP was ca. 40% lower at stations 6 and 7, located in the shallow

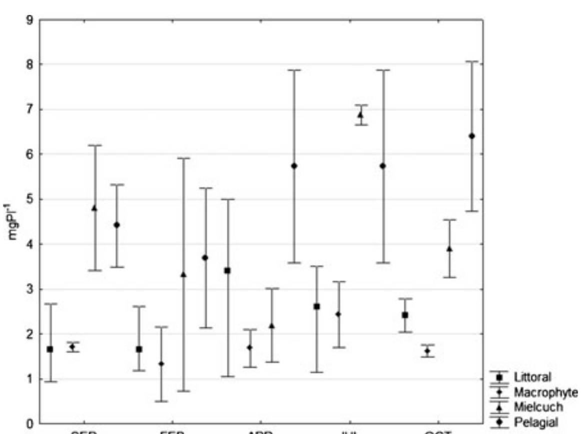


Fig. 5 Mean, maximum, and minimum concentrations of TP in pore waters of bottom sediments at individual zone in Swarzędzkie Lake (littoral—stations 1–3, 5, and 10; macrophyte—stations 6 and 7; Mielcuch—stations 4 and 8; pelagial—stations 9 and 11)

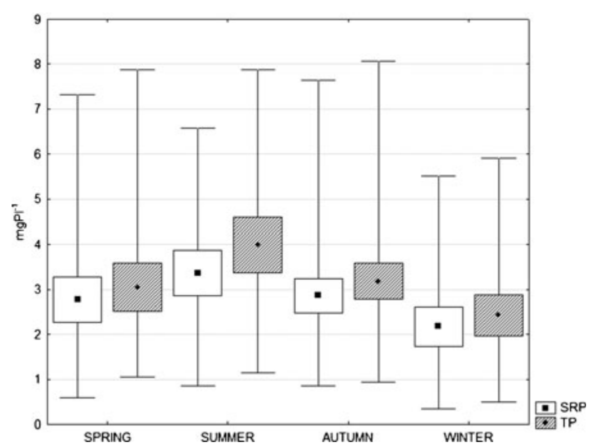


Fig. 6 Seasonal variation in SRP and TP concentration in pore waters of bottom sediments (analyzed jointly for all stations)

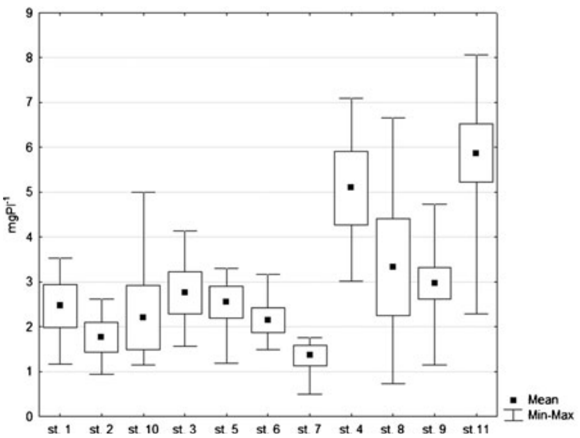


Fig. 7 Mean concentrations of TP in pore waters of bottom sediments at individual stations in Swarzędzkie Lake

southwestern part of the lake (macrophyte zone), than at stations 1–3, 5, and 10 mentioned above. The concentrations were the highest in summer, up to 2.6 mgP l^{-1} of SRP and up to 3.2 mgP l^{-1} of TP; and the lowest in colder months, 0.4 and 0.5 mgP l^{-1}, respectively (Figs. 4 and 5).

Phosphorus content in pore water at stations 4 and 8, located near the former and present mouth of the Mielcuch Stream (Mielcuch zone), were ca. 45% higher than at the other shallow stations. Maximum values observed in summer 2003 exceeded 6.5 mgP l^{-1} of SRP and 7.1 mgP l^{-1} of TP (Figs. 4 and 5).

The analysis of seasonal variation in TP concentration of pore waters in bottom sediments showed that the mean concentrations of both SRP and TP for all stations were the highest in summer (July 2003). The lowest values were observed in winter (Fig. 6).

A comparison of values recorded at individual stations indicates that both SRP and TP levels were high most frequently at station 11, i.e., at the deepest site (7 m). In some periods, high concentrations were recorded also at stations 4 and 8, due to the discharge of polluted waters of the Mielcuch Stream. Increased levels occurred at station 9 (at the depth of 4 m), while lower levels at the shallower stations located in the littoral zone. The lowest concentrations were observed at station 7, near the outflow of the lake. Similar low values were obtained at station 2 (Fig. 7). Both of these stations were situated in similar environmental conditions, in the shallow bays close to helophyte belt (*Typha angustifolia* and *Typha latifolia*).

Mean TP concentration (± standard deviation) in pore waters for all stations in Swarzędzkie Lake in the whole study period was 3.2 ± 1.9 mgP l^{-1}, while mean SRP level was 2.8 ± 1.8 mgP l^{-1} ($n = 63$). The recorded values ranged from 0.5 to 8.1 mgP l^{-1} for TP and from 0.4 to 7.7 mgP l^{-1} for SRP.

Analyzing spatial variability of phosphorus concentration in the interstitial water of bottom sediments of the lake, highest values were observed in the lake's pelagial (stations 9 and 11) (5.2 mgP l^{-1}), somewhat lower in the mouth of the Mielcuch Stream (station 4 and 8; 4.2 mgP l^{-1}) and the lowest in the elongated and shallow part of the water body overgrown with macrophyte (stations 6 and 7; 1.8 mgP l^{-1}). In the littoral of deeper part of the lake, values were somewhat higher than in macrophyte zone (2.3 mgP l^{-1}; Fig. 8).

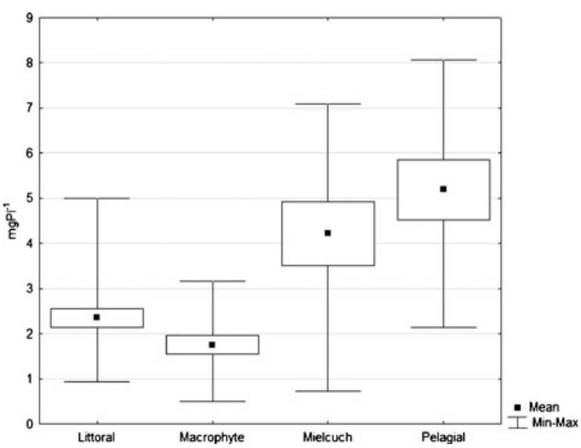


Fig. 8 Mean concentration of TP in pore water in several zones in Swarzędzkie Lake

Discussion

Sediments with their pore waters serve as a specific buffer mechanism postponing the change in trophic conditions in the lake if external sources of phosphorus are modified (Boers and de Bles

1991; Kentzer 2001; Schindler et al. 1976). Pore waters contain the phosphorus originated from organic matter decomposition of bottom sediments, which accumulates there at high concentrations. According to literature, SRP concentrations reach up to 7–10 mgP l^{-1} in eutrophic waters (especially in hypereutrophic lakes). Kentzer (2001) reported that SRP level in pore waters in Lake Gościąż (Poland) varied from 0.2 to 10.5 mgP l^{-1}. In hypertrophic lakes Wobel, Juno, and Rzeckie (Poland), SRP concentration in pore waters was similar to that in Swarzędzkie Lake (Poland), as it ranged from 5.3 to 7.2 mgP l^{-1} (Wiśniewski and Planter 1987).

Phosphorus content in pore waters in the deepest part of the lake, where sediments are not penetrated by macroinvertebrates, should increased gradually with depth (Lewandowski et al. 2005, 2007). Depth profile recorded in Swarzędzkie Lake show larger heterogeneity, which may indicate variability in the trophic state of the lake during the last decades. The significantly higher concentration stated in the layer 10–20 cm, than in the adjacent layers, probably results from the high organic matter content of the sediments deposited in the period of intensive discharge of untreated sewage in the 1980s (Kowalczewska-Madura 2004).

Seasonal changes of phosphorus concentration in pore waters were investigated by i.e. Kleeberg and Kozerski (1997) and Søndergaard (1988, 1990). All of them observed increasing phosphorus content during summer and decreasing trend in the autumn/winter period which is in accordance to the seasonal variation stated in Swarzędzkie Lake. Wanatabe and Tsunogai (1984) observed much higher values soon after the spring peak of phytoplankton growth and also in summer during intensive phytoplankton growth. It was probably connected with higher content of readily degradable organic matter in bottom sediments. In Swarzędzkie Lake, the highest values were generally observed in summer, but in some cases also in spring and autumn. In this lake phytoplankton growth was very intensive continuously from May till September, so the highest content of fresh organic matter in bottom sediments was stated usually just after this period, i.e., in early autumn (Kowalczewska-Madura 2004; Stefaniak et al. 2007). On the other hand, increased content of organic matter in autumn was due to macrophytes decay, especially at the shallow stations. High phosphorus release from bottom sediments was observed in the deeper part of the lake, especially in summer and autumn, when the passage of P to pore water occurred due to mineralization processes and metal compounds reduction (Kowalczewska-Madura and Gołdyn 2009). High P concentrations in interstitial water were observed also near the mouth of Mielcuch Stream, which brings high loading of nutrients into the lake (Kowalczewska-Madura 2003). Very high values of P release from bottom sediments were also observed at this station (Kowalczewska-Madura and Gołdyn 2009). Stations 6 and 7 are situated closely to the macrophyte belt, therefore they display high content of organic matter in bottom sediments, but this organic matter is harder degradable than phytoplankton originated one at deeper stations. This is the reason of low content of P in pore waters at most shallow stations and also lower phosphorus release from these stations, despite high content of organic matter. This is confirmed by statistical analysis, which indicated significant correlation between pore water content and P release ($r = 0.529$, $p = 0.001$, $n = 35$, PR = 5.442+2.493 PPW; where: PR—phosphorus release, PPW—phosphorus in pore water). When comparing the data of P concentration in pore waters with the data of organic matter content published by Kowalczewska-Madura (2004) and P content in bottom sediments of Swarzędzkie Lake (Kowalczewska-Madura and Gołdyn 2005), no significant statistical correlations were stated.

Conclusions

Spatial variation of phosphorus content in pore waters was high. The highest SRP and TP contents were in the deep sites, in the range of meta and hypolimnion. High concentrations of P in pore waters were also near the outlet of polluted Mielcuch Stream. Opposite low data were characteristic for shallow littoral sediments at stations situated close to helophyte belt. These shallow sites proved the highest organic matter content; however, because of its hard microbial decomposition, it has no influence on pore water phosphorus content. This is very important issue for restoration measures designed for shallow lakes. Seasonal changes of phosphorus content in pore waters were modest. Much higher values appeared in summer (sometimes also in spring and autumn), lower in winter. Significant correlation of P content in pore waters and P release from bottom sediments is described by the simple model. It can be used as a tool for calculating the internal P loading of the lake.

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References

Andersen, F. Ø., Jørgensen, M., & Jensen, H. S. (2006). The influence of Chironomus plumosus larvae on nutrient fluxes and phosphorus fractions in aluminum treated lake sediment. *Water, Air, and Soil Pollution, 6*, 465–474.

Boers, P. C. M., & de Bles, F. (1991). Ion concentration in interstitial water as indicators for phosphorus release processes and reactions. *Water Research, 25*, 591–598.

Boström, B., Jansson, M., & Forsberg, C. (1982). Phosphorus release from lake sediments. *Archiv für Hydrobiologie–Beiheft Ergebnisse der Limnologie, 18*, 5–59.

Elbanowska, H., Siepak, J., & Zerbe, J. (1999). *Physico-chemical analyses of waters*. Warsaw: PWN Public, (in Polish).

Enell, M., & Lofgren, S. (1988). Phosphorus in interstitial water: Methods and dynamics. *Hydrobiologia, 170*, 103–132.

Ignatieva, N. V. (1996). Distribution and release of sedimentary phosphorus in Lake Ladoga. *Hydrobiologia, 322*, 129–136.

Katsev, S., Tsandev, I., L'Heureux, I., & Rancourt, D. G. (2006). Factors controlling long-term phosphorus efflux from lake sediments: Exploratory reactive-transport modeling. *Chemical Geology, 234*, 127–147.

Kentzer, A. (2001). *Phosphorus and its biologically accessible fractions in bottom sediments of lakes of diverse trophic state*. Toruń: University Press, (in Polish).

Kleeberg, A., & Kozerski, H.-P. (1997). Phosphorus release in Lake Großer Müggelsee and its implications for lake restoration. *Hydrobiologia, 242/243*, 9–26.

Komatsu, E., Fukushima, T., & Shiraishi, H. (2006). Modeling of P-dynamics and algal growth in a stratified reservoir—Mechanisms of P-cycle in water and interaction between overlying water and sediment. *Ecological Modeling, 197*, 331–349.

Kowalczewska-Madura, K. (2003). Mass balance calculations of nitrogen and phosphorus for Swarzędzkie Lake. *Limnological Review, 3*, 113–118.

Kowalczewska-Madura, K. (2004). Organic matter in bottom sediments of the Swarzędzkie Lake. In A. T. Jankowski & M. Rzetała (Eds.), *Lakes and artificial reservoirs—functioning, revitalization and protection* (pp. 125–131). Sosnowiec: Silesian University, (in Polish).

Kowalczewska-Madura, K., & Gołdyn, R. (2005). Phosphorus content of bottom sediments in the Swarzędzkie Lake. *Verhandlungen Internationale Vereinigung für Theoretische und Angewandte Limnologie, 29*, 1063–1068.

Kowalczewska-Madura, K., & Gołdyn, R. (2006). Anthropogenic changes in water quality in the Swarzędzkie Lake (West Poland). *Limnological Review, 6*, 147–154.

Kowalczewska-Madura, K., & Gołdyn, R. (2009). Internal loading of phosphorus from sediments of Swarzędzkie Lake (Western Poland). *Polish Journal of Environmental Studies, 18*(4), 635–643.

Kowalczewska-Madura, K., & Gołdyn, R. (2010). Models of phosphorus turn-over in a hypertrophic lake: The Lake Swarzędzkie case study. *Oceanological and Hydrobiological Studies, XXXIX*(3), 21–33.

Lewandowski, J., Rüter, K., & Hupfer, M. (2002). Two-dimensional small-scale variability of pore water phosphate in freshwater lakes: Results from a novel dialysis sampler. *Environmental Science & Technology, 36*, 2039–2047.

Lewandowski, J., Schadach, M., & Hupfer, M. (2005). Impact of macrozoobenthos on two-dimensional small-scale heterogeneity of pore water phosphorus concentrations: In-situ study in Lake Arendsee (Germany). *Hydrobiologia, 549*, 43–55.

Lewandowski, J., Laskov, C., & Hupfer, M. (2007). The relationship between *Chironomus plumosus* burrows and the spatial distribution of pore-water phosphate, iron and ammonium in lake sediments. *Freshwater Biology, 52*, 331–343.

Mayer, T., Ptacek, C., & Zanini, L. (1999). Sediments as a source of nutrients to hypereutrophic marshes of Point Pelee, Ontario, Canada. *Water Research, 33*(6), 1460–1470.

Qin, B., Zhu, G., Zhang, L., Luo, L., Gao, G., & Gu, B. (2006). Estimation of internal nutrient release in large shallow Lake Taihu, China. *Science in China Series D: Earth Sciences, 49*(1), 38–50.

Schindler, D. W., Newburgh, R. W., Beaty, K. G., & Campbell, P. (1976). Natural water and chemical budgets for a small Precambrian lake basin in central Canada. *Journal of the Fisheries Research Board of Canada, 33*, 2526–2543.

Søndergaard, M. (1988). Seasonal variations in the loosely sorbed phosphorus fraction of the sediment of a shallow and hypertrophic lake. *Environmental Geology and Water Sciences, 11*, 115–121.

Søndergaard, M. (1990). Pore water dynamics in the sediment of a shallow and hypertrophic lake. *Hydrobiologia, 192*(2–3), 247–258.

Spears, B. M., Carvalho, L., Perkins, R., Kirika, A., & Paterson, D. M. (2007). Sediment phosphorus cycling in large shallow lake: Spatio-temporal variation in phosphorus pools and release. *Hydrobiologia, 584*, 37–48.

Stefaniak, K., Gołdyn, R., & Kowalczewska-Madura, K. (2007). Changes of summer phytoplankton communities in Lake Swarzędzkie in the 2000–2003 period. *Oceanological and Hydrobiological Studies, XXXVI*(Suppl. 1), 77–85.

Wanatabe, Y., & Tsunogai, S. (1984). Adsorption–desorption control of phosphate in anoxic sediment of a coastal sea, Funka Bay, Japan. *Marine Chemistry, 15*, 71–83.

Wiśniewski, R. J., & Planter, M. (1987). Phosphate exchange between sediments and the near-bottom water in relationship to oxygen conditions in a lake used for intensive trout cage culture. *Ekologia Polska, 35*, 219–236.