Polish J. of Environ. Stud. Vol. 18, No. 4 (2009), 635-643

Original Research

Internal Loading of Phosphorus from Sediments of Swarzędzkie Lake (Western Poland)

K. Kowalczewska-Madura*, R. Gołdyn

Department of Water Protection, Adam Mickiewicz University, Faculty of Biology,
Umultowska 89, 61-614 Poznań, Poland

Received: 1 September 2008
Accepted: 10 March 2009

Abstract

Sediments, being the most important source of phosphorus (P) in the shallow (max. depth 7.2 m), polymictic Swarzędzkie Lake during the summer, were thoroughly studied in laboratory experiments with intact cores sampled at 7 stations in four seasons of the year. Under anaerobic conditions P release rates peaked in the samples from the deepest part of the lake at 26.86 mgP $m^{-2}d^{-1}$. However, the highest rates were determined at one of the littoral sites (near the mouth of a polluted stream) at 59.5 mgP $m^{-2}d^{-1}$. Littoral P release coincided with occasionally low oxygen concentrations (0.2 mgO_2 l^{-1}) above the bottom. On the scale of the whole lake, P release from the littoral zone, where both temperature and oxygen concentration were highly variable, had the strongest influence on the trophic state. It accounted for 63% of the annual internal load but only 55% of total lake area.

Keywords: bottom sediments, hypereutrophic lake, internal loading, phosphorus

Introduction

Lakes receive phosphorus (P) loads not only from external sources (tributaries, surface run-off, precipitation), but also from their bottom sediments. Sediments play an important role in the overall P metabolism of lakes, acting both as a P sink and a source. In most lakes there is a net P deposit in the sediments [1, 2]. The P deposition in bottom sediments and its later release to the overlying water is one of the most important issues in hydrobiological research. P release is believed to play a significant role in the process of eutrophication of water bodies [3]. The P return to circulation in open water is a result of many interrelated processes: biological (e.g. biological immobilization and mobilization), physicochemical (e.g. desorption, dissolution), and physical processes (e.g. diffusion) [4]. P mobilization is affected by a multitude of factors (e.g. mineralization, redox potential, pH, temperature, bacteria activity, dissolved oxygen), and in various lakes different factors can be dominant [5-7]. The intensity and duration of P release may have a significant impact on its concentration in lake water and subsequently on lake water quality [8-10]. Such strongly eutrophicated lakes require the application of restoration measures for their recovery, if they are to regain a balanced ecological status [11, 12].

The Swarzędzkie Lake ecosystem for many years has been subject to strong human impact, namely the direct discharge of urban sewage and the high external nutrient loads which supply the lake through tributaries from non-point sources. Although about 80% of the direct discharge of the sewage load was diverted from the lake in 1991, water quality has not improved markedly. The concentration of phosphorus in summer near the bottom sediments has decreased only slightly in the last decade. Initially it even increased from 1.18 mgP l^{-1} in 1992 to 1.31 mgP l^{-1} in 1997, although it later decreased to 0.87 mgP l^{-1} in 2002.

---

*e-mail: madura@amu.edu.pl

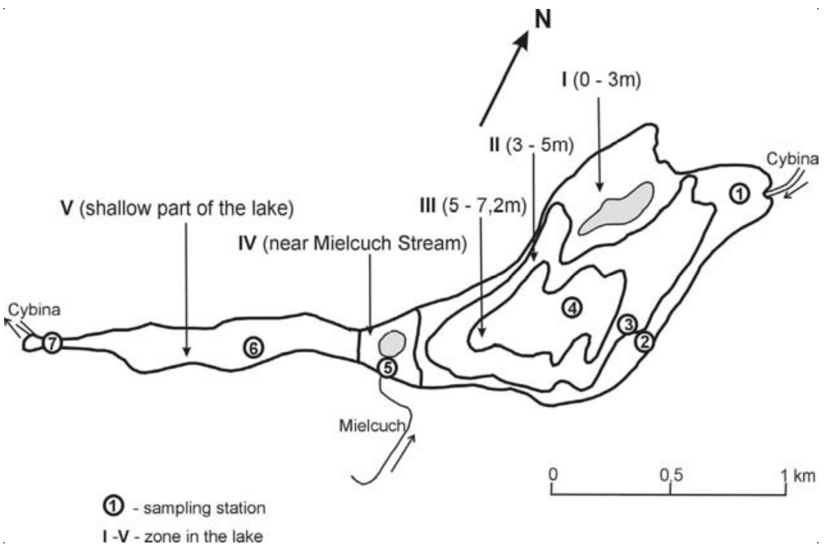

Fig. 1. Location of sampling stations and P release zones (differing in P release rate, depth and character of bottom sediments) on a bathymetric map of Swarzędzkie Lake (after [49], with modification). The numbers in parenthesis indicate depths.

However, despite the fact that P concentration in the surface water layer decreased clearly from 0.9 mgP l^{-1} to 0.3 mgP l^{-1} in 1997, and to 0.2 mgP l^{-1} in 2002 [13], the Cyanobacteria water blooms were still intense [14].

Laboratory experiments were conducted on the bottom sediments of Swarzędzkie Lake for studying the intensity of the P release process. The aims of this study were:

(1) to assess the rate of P release from sediments and its seasonal variation;
(2) to analyze the spatial variation in internal loading, in respect to depth, distance from tributaries, etc.; and
(3) to estimate the P loading from bottom sediments in relation to the total P balance in that lake.

Our results allowed the comparison of the rates of P release from well oxygenated sediments in the shallow littoral zone (only sporadically anoxic), with that from the deeper littoral zone (periodically deoxygenated) and from the metalimnion, in the deepest part of the lake (with oxygen completely depleted in summer).

Materials and Methods

Swarzędzkie Lake is a shallow, polymictic, hypereutrophic, flow-through water body of glacial origin, located on the border that lies between the town of Swarzędz and the city of Poznań, in western Poland (52º25'N, 17º04'E). The total area of the lake is 93.7 ha, maximum depth 7.2 m, and mean depth 2.6 m [15]. The lake is elongated, narrowing from half its length toward the outlet. The wider, north-eastern part of the lake is much deeper (up to 7.2 m), while the narrower, south-western part is only up to 2 m deep (Fig. 1). Two tributaries, the Cybina River and the Mielcuch Stream, supply the lake with abundant loads of nutrients, especially in the early spring.

Intact sediment cores for laboratory experiments were taken using a modified Kajak core sampler from 7 stations between September 2001 and October 2003. Samples were collected every 2 or 3 months at station 4 (11 times in total) and at station 3 (10 times). In the littoral zone at stations 1, 5, 6 and 7 (Fig. 1), samples were collected once in every season of 2003. At station 2 samples were taken only twice, in the summer and in the autumn of 2003. 2-3 replicates were collected from each station at each sampling. Intact sediment cores were sampled to transparent and rigid plastic tubes (PMMA - polymethyl methacrylate). Each tube contained ca 15 cm of sediment together with ca 25 cm of the abovelying water. The sampling process did not change the concentration of dissolved oxygen in the water layer because immediately after sampling the tubes were tightly capped with rubber stoppers and transported to the laboratory (Fig. 2).

The cores were incubated in the laboratory, under constant thermal and light conditions, similar to the natural conditions within the lake during the sampling. The mean error of the temperature value in laboratory conditions was 1ºC.

Fig. 2. Tubes with intact sediment cores and overlying water sampled in the lake.

Depending on the oxygenation of water above the sediments within the lake, the cores were incubated in aerobic or anaerobic conditions. To maintain the anaerobic conditions the tubes were tightly capped. In experiments with aerobic conditions the tubes were simply left open to the atmosphere and oxygen concentration was monitored once every day. At a temperature of 20ºC when the oxygen concentration decreased below 4 $mgO_2\ l^{-1}$, additional aeration was started using aquarium air pumps. At low temperatures (6.5-10ºC) the oxygenation was sufficient without aeration, with one exception (at 10ºC and station 3) in which aeration was necessary. At intermediate temperatures (14-17.5ºC) long windless conditions were simulated (without additional aeration). In these conditions the oxygen content decreased slowly, reaching 0.2 $mgO_2\ l^{-1}$. Because of the water bloom and small Secchi depth of the lake (ca 40 cm), generally there was no light near the sediment-water interface. Due to this all experiments were conducted in darkness. Daily fluctuations of dissolved oxygen, pH and redox were not stated, so they were not measured continuously.

During the experiments the concentration of total phosphorus (TP) in water was monitored, initially every day, and later every 3-4 days. Water for analyses was sampled from every tube after slow and sensitive mixing and the same volume (50 ml) of water taken from the lake above the sediments was added to the tubes. This supplementary water was sampled at every station before sediment sampling and stored in a laboratory together with the tubes. The water was not filtered so as to supplement bacterially-mediated processes with new portions of organic carbon. Using the concentration of phosphorus and water volume in the tube the load of phosphorus was calculated. Concentration of phosphorus was also analyzed in the supplementary water, which enabled the calculation of the new phosphorus load in the overlying water within the tubes. The released/sorbed phosphorus in every tube was calculated as a result of the difference in loads during the time between the sampling periods and expressed in $mgP\ m^{-2}d^{-1}$. Each experiment lasted on average about 4 weeks. P analyses were carried out spectrophotometrically with ascorbic acid as a reducer.

Total internal loading for the lake was not calculated as a mean value from data obtained from the 7 stations because of their diversity. Data of each station was given the weight proportional to its input to the total internal loading. This weight was the surface of the zone with similar environmental conditions and expected similar P flux. Five zones differing in rates of P release from bottom sediments were distinguished in the lake, taking into account also its morphometry and the character of its bottom sediments (Fig. 1). Zone I denotes the bottom at the depth of 0-3 m in the northeastern part of the lake, distinguished on the basis of P release from stations 1 and 2. Zone II comprised a depth of 3-5 m, based on data from station 3, while zone III was at a depth of 5-7.2 m, based on station 4. Additionally, zone IV was distinguished at the mouth of the heavily polluted Mielcuch Stream (station 5), and zone V in the shallow southwestern part of the lake (stations 6 and 7). Only the open water area in every zone was taken into account. The annual total internal P loading to the lake was calculated as the sum of product of areal P loading and the area of individual zones.

On the basis of the correlation analysis between temperature and P release, equations were established which were used for the calculation of annual P loading at stations 3 and 4 and areal loading in zones II and III. At other stations the correlation was not significant, so the raw laboratory data were used for calculating annual P loading. We deliberately took into account the results of all experiments, including those conducted at low oxygen concentrations, decreasing as far as 0.2 $mgO_2\ l^{-1}$, since in the shallow littoral zone of this lake periodical deoxygenation of sediments is also observed. First the mean loading data characteristic for each zone and season was calculated (in $mgP\ m^{-2}d^{-1}$), next this data was multiplied by the mean number of days in each season. Annual areal P loading in each zone was the sum of values calculated for every season.

Results

The bottom sediments of Swarzędzkie Lake are characterized by a considerable variation in structure, texture and composition. The sediment types can be classified as algal gyttja (station 4), as sapropel gyttja (station 5) as rough detrital gyttja (shallow zone) and as sandy sediments (station 2).

Experiments in Anaerobic Conditions

The incubation of cores in anaerobic conditions showed that the rate of P release markedly increased with temperature. For samples from depths of 7 m (station 4) and 4 m (station 3), P release ranged from 6.94 to 26.86 $mgP\ m^{-2}d^{-1}$ (Table 1). The highest values were observed at 20ºC at both stations, and decreased with decreasing temperature. Variation in P release within stations was usually greater at higher temperature than at a lower one. However, P release from the bottom at a depth of 7 m was always greater than at 4 m (Table 1).

For stations 1, 5, 6 and 7, the laboratory experiments in anaerobic conditions were conducted only once because oxygen depletion in sediments at those stations was rare. Further experiments were conducted only in aerobic conditions. The rate of P release was lower there than at greater depths (stations 3 and 4), and ranged from 2.77 to 6.06 $mgP\ m^{-2}d^{-1}$ (Table 1). At station 2 no experiment was conducted in anaerobic conditions, since samples from that station were collected only twice (due to technical difficulties).

Experiments in Aerobic Conditions

Aerobic conditions were simulated in two ways, depending on the observed conditions in the lake. The water over the sediment in the cores during incubation was either aerated artificially or the cores were left open to enable diffusion of

Table 1. P release rate (mean±SD, mgP m^{-2} d^{-1}) from bottom sediments of Swarzędzkie Lake at individual sampling stations in anaerobic conditions, n = number of replicates.

Station (depth)	Temperature			
	20ºC	17.5ºC	10ºC	2ºC
4 (7 m)	26.86±10.2 1)	22.82±8.5 3)	13.54±2.1 1)	8.38±2.1 1)
3 (4 m)	19.19±2.3 1)	11.9±4.9 2)	-	6.94±2.7 1)
1 (1 m)	-	-	-	3.34±1.0 1)
5 (0.5 m)	-	-	-	3.98±0.6 1)
6 (1 m)	-	-	-	6.06±4.6 1)
7 (1 m)	-	-	-	2.77±2.6 1)

1) – n (number of replicates) = 3,
2) – n = 6,
3) – n = 12.

Table 2. P release (mean±SD, mgP m^{-2} d^{-1}) from bottom sediments of Swarzędzkie Lake at individual sampling stations in aerobic conditions (# marks the tubes with artificial aeration, * marks the experiments during which oxygen concentration decreased to 0.2 mgO_2 l^{-1}).

Station (depth)	Temperature				
	20ºC	17.5ºC	14ºC	10ºC	6.5ºC
4 (7 m)	-	*19.94±5.2 2)	*15.7±5.9 2)	-	7.8±2.1 3)
3 (4 m)	-	*15.49±1.7 2)	*14.6±2.8 1)	#-1.42±0.2 1)	8.7±4.0 3)
2 (1.5 m)	#1.47±1.6 1)	-	-	6.9±3.53 1)	-
1 (1 m)	#13.3±0.7 2)	*22.27±0.8 2)	-	-	13.1±2.6 2)
5 (0.5 m)	#59.5±40.8 2)	*19.27±7.3 2)	-	-	38.1±7.6 2)
6 (1 m)	#-2.4±4.2 1)	*15.25±2.9 2)	-	-	9.01±2.7 2)
7 (1 m)	#4.44±4.5 2)	*11.19±2.7 2)	-	-	6.7±2.2 2)

1) – n (number of replicates) = 2,
2) – n = 3,
3) – n = 6.

oxygen from the air (Table 2). Oxygen concentration in the water above the sediment at the end of the experiments varied from 7 to 16 mgO_2 l^{-1} in the case of artificial aeration, and from 0.2 to 8 mgO_2 l^{-1} in the case of diffusion. The incubation temperature simulated the natural conditions in the lake in the given season. In samples from station 4 (at 7 m), P release decreased together with temperature from 19.9 mgP $m^{-2}d^{-1}$ at 17.5ºC to 7.8 mgP $m^{-2}d^{-1}$ at 6.5ºC. A similar trend was observed for samples from station 3 (at 4 m), but the difference was smaller (Table 2). An exception was an experiment during which P was not released, but sediments acted as a sink for P (by 1.42 mgP $m^{-2}d^{-1}$). This was observed under conditions of artificial aeration at 10ºC (Table 2).

At shallower sites, the pattern of P release was slightly different. At station 2 its release was much more intensive at 10ºC (6.9 mgP $m^{-2}d^{-1}$) than at 20ºC (1.47 mgP $m^{-2}d^{-1}$). At station 1 in summer, the mean P release was 13.3 mgP $m^{-2}d^{-1}$. At slightly lower temperatures (17.5ºC) and lower oxygen concentrations, P release was nearly twice as high (Table 2). At 6.5ºC it decreased to 13.1 mgP $m^{-2}d^{-1}$. A similar increase in P release at low oxygen concentration and lower temperature (17.5ºC), was also observed at stations 6 and 7, located in the shallow southwestern part of the lake (Table 2). However, at station 5 (near the mouth of the polluted Mielcuch Stream), P release was higher than at other stations. In summer it reached on average 59.5 mgP $m^{-2}d^{-1}$. Presumably such a high rate of P release was maintained for most of the summer period because the temperature of the sediments was high due to the small depth (0.5 m). At 17.5ºC, P release declined to 19.27 mgP $m^{-2}d^{-1}$, but at 6.5ºC it increased again, reaching 38.1 mgP $m^{-2}d^{-1}$ (Table 2).

Internal Loading

Statistical analysis shows that there is a significant (P<0.01) linear correlation between the rate of P release

Table 3. Linear correlations between the rate of P release (W, mgP m^{-2} d^{-1}) from bottom sediments and water temperature (T, ºC) above the bottom in Swarzędzkie Lake.

Station	Conditions	r	P	Regression equation
3	anaerobic	0.688	0.0022	W=3.6140+0.4681·T
	aerobic	0.737	0.0097	W=4.4227+0.6718·T
4	anaerobic	0.781	0.0000	W=2.3977+1.2588·T
	aerobic	0.809	0.0014	W=0.8307+1.0984·T

from bottom sediments and water temperature above the bottom, both in anaerobic and aerobic conditions, for stations 3 and 4 (Table 3). However, in aerobic conditions the rate of P release was also influenced by variable oxygen conditions, to some extent. At the other stations the correlation of P release and temperature was not significant.

In the case of the deepest site (station 4), located in zone III, the highest calculated rates of P release were recorded in summer and autumn (maximum 22.16 mgP $m^{-2}d^{-1}$ in August 2000), while the lowest in winter and early spring (minimum 5.59 mgP $m^{-2}d^{-1}$ in March 2002) (Fig. 3). At station 3 (zone II), the pattern of seasonal variation in P release was very similar. The highest calculated value was 16.78 mgP $m^{-2}d^{-1}$ in July 2000, and the lowest was 5.44 mgP $m^{-2}d^{-1}$ in January 2002 (Fig. 3).

At stations 6 and 7, located in the shallow part of the lake (zone V), P release was the most intensive in autumn (13.22 mgP $m^{-2}d^{-1}$) and the lowest in winter (3.43 mgP $m^{-2}d^{-1}$) (Fig. 4). At station 5, located near the mouth of the Mielcuch Stream (zone IV), P release was very intensive, reaching up to 59.53 mgP $m^{-2}d^{-1}$ in summer. Station 1, located near the mouth of the Cybina River, was characterized by P release ranging from 3.34 mgP $m^{-2}d^{-1}$ in winter to 22.27 mgP $m^{-2}d^{-1}$ in autumn (Fig. 4).

The comparison of internal P loading in the four seasons of the year showed that its values were usually the highest in summer or autumn and the lowest in winter (Fig. 4).

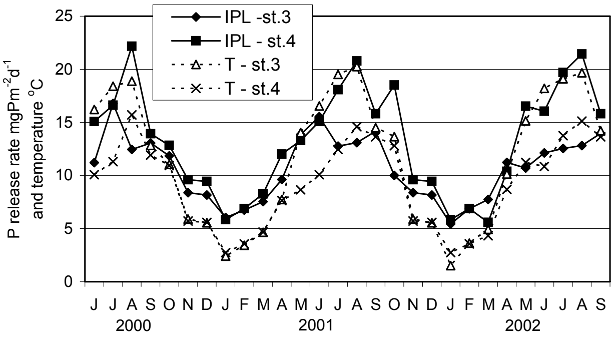

Fig. 3. Seasonal changes of internal P loading (IPL) from bottom sediments in Swarzędzkie Lake at stations 3 (zone II) and 4 (zone III), calculated for individual months (on the basis of equations from Table 3), presented versus temperature above the bottom (T – values measured within the lake).

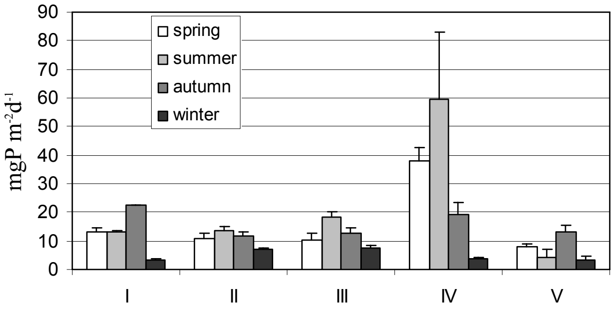

Fig. 4. Comparison of internal P loading in five zones of Swarzędzkie Lake (mean seasonal values and standard errors).

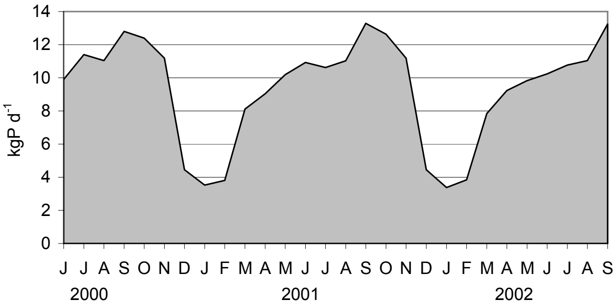

Fig. 5. Internal P loading from bottom sediments in Swarzędzkie Lake in the period 2000-02.

The greatest contribution to the annual internal load of P to the lake is provided by the shallow zone (0-3 m in depth) in the northeastern part of the lake (1432.9 kgP a^{-1}), and the smallest by the narrow zone near the mouth of the Mielcuch Stream (242.9 kgP a^{-1}) (Table 4).

The calculated values of P release from individual zones in consecutive months show a clear seasonal variation in the internal loading of the whole lake. The highest values were observed in summer and early autumn, and lower in the colder seasons. The maximum value calculated for the total open water area of the lake was 13.29 kgP d^{-1}, recorded in September 2001, while the minimum was 3.52 kgP d^{-1}, in January 2001 (Fig. 5).

Mean daily internal loading of the lake reached 8.65 kgP d^{-1}, which can be expressed per unit area of lake surface as 10.89 mgP $m^{-2}d^{-1}$, and per unit volume of lake water as 4.32 mgP $m^{-3}d^{-1}$.

Discussion

Many authors have stated that there is a distinct relationship between thermal conditions and the rate of P release from bottom sediments [e.g. 16-18]. The results of this study confirm this relationship but only in reference to the deeper sites of the lake. It is noteworthy that standard deviation was generally higher at higher temperatures. This attests to variation in the internal loading of the lake among sediment samples collected from the same station, analyzed

Table 4. Mean annual internal P load in five zones of Swarzędzkie Lake in 2000-02.

Zone	Annual areal loading of phosphorus	Zone area		Annual internal phosphorus load in that zone	
	(mgP m^{-2} a^{-1})	(m^2)	(%)	(kgP a^{-1})	(%)
I (0-3 m)	4,765.1	300,700	37.9	1,432.9	45.4
II (3-5 m)	3,059.9	236,060	29.7	722.3	22.9
III (5-7.2 m)	3,780.9	118,720	14.9	448.9	14.2
IV (near Mielcuch Stream)	11,076.7	21,930	2.8	242.9	7.7
V (SW part, 0-2 m)	2,649.0	116,590	14.7	308.8	9.8
Total		794,000		3,155.8	

in parallel as replicates. Our observations of cores during the experiments suggest that as temperature increased, the amount of gases produced also increased in the sediments as a result of microbiological processes. Intensification of these processes with temperature was also responsible for increasing P concentration in pore waters in summer and early autumn [19], which contributed to the higher P release rates at higher temperature. The bubbles of gas released from bottom sediments to the overlying water are probably responsible for the transport of P from pore water to open water, as the process of direct diffusion between those media is very slow [20]. The intensity of P transport probably depends not only on the amount of released gases but also on the size of the bubbles, which are responsible for the resuspension of sediment in the water. In extreme cases, portions of sediments were uplifted by the bubbles and floated on the water surface. This was also observed by Kentzer [21] in Lake Gościąż, where the release of gases from sediments was one of the factors modifying the exchange of P between water and sediment under conditions of good oxygenation of the water layer above the sediment. Consequently, in our calculations of P release from a given station, we took into account all the results of the laboratory experiments, since in natural conditions this process is highly variable at the sediment surface.

Another important factor affecting the intensity of processes taking place at the sediment-water interface is the oxygen concentration of the surface layer of the sediment and of the overlying water. This determines the direction and rate of P flow, i.e. its sorption or release. It is a well known fact that often in anaerobic conditions the rate of P release to open water is several times higher than in aerobic conditions [22, 23]. Such high differences are not confirmed by our results, as P release at station 4 under anaerobic conditions was only slightly higher than in aerobic conditions (Table 3). At station 3, an inverse trend was even observed as P release was more intensive there in aerobic conditions. This was probably due to the transport of P from pore water to the water above the sediments, since it is dependent on the difference in P concentration between these two phases. As a result of the periodic mixing of water at station 3 under the influence of wind, a very steep gradient of P concentration was noted between the pore water and the water layer above the sediments, so the gradient facilitated the process of diffusion. This was confirmed by the P concentration analyzed in the water layer above the sediments, which in summer was 0.09-0.179 mgP l^{-1} at station 3, whereas 0.434-1.213 mgP l^{-1} at station 4. Due to more intensive P release at station 3, the concentrations of P in pore water at this station were lower than at station 4 (2.524-3.852 mgP l^{-1} and 5.326-6.280 mgP l^{-1} respectively) [19]. Similar mechanisms were observed by Kentzer [21] in Lake Gościąż, where in aerated conditions P release was more intensive than in anaerobic conditions, which leads to the decrease of P content in the bottom sediments. Such conditions were simulated during this study, when artificial aeration of the water above the sediment caused its mixing, so that P concentration at the sediment-water interface decreased. Presumably in this zone of the lake, such intensive P release is limited only to short periods associated with strong winds.

In Swarzędzkie Lake the changes in the rate of P release depending on temperature and oxygen concentration in sediments from deeper parts of the metalimnion (zones II and III) were quite predictable. The values of internal loading of P in those zones could be quite precisely estimated on the basis of regression equations. In the littoral zone, however, the changes were less predictable. In spite of the good oxygenation of epilimnetic water, short-term deoxygenation of bottom sediments was sometimes observed in the surface layer of sediments and in the overlying water, especially if water temperature was high and there was no wind. This was confirmed by laboratory experiments with unplugged cores, where oxygen concentration above the sediment sometimes decreased to 0.2 mgO$_2$ l^{-1}. Under such conditions, the rate of P release was many times higher than during continuous aeration of the water above the sediment. This was connected with the decrease of redox potential and iron reduction, which caused the release of iron-bound P [10, 23]. In summer these pulses of P release were more frequent than in cold seasons, as higher temperature stimulated oxygen depletion during calm weather.

The biggest P loading due to the above-mentioned mechanism was observed from the extensive shallow zone I (stations 1 and 2; 0-3 m in depth), where temperature and

Table 5. P release from bottom sediments of diverse water bodies, presented in the literature.

Lake, reservoir or river	Conditions or season	P release ($mgP\ m^{-2}d^{-1}$)	References
Zegrzyński and Sulejowski (Poland)	summer	22.5	[34]
Kujno, Gant and Spychowskie (Poland)	year	0.4-18.0	[35]
Majcz, Głębokie, Jorzec, Inulec (Poland)	anaerobic	0.5-21.1	[36, 37]
	aerobic	0.0-1.34	
Piburger See (Austria)	4ºC, anaerobic	0.271	[18]
	4ºC, aerobic	0.57	
Agmon (Israel)	20ºC, anaerobic	6.0	[38]
Biwa (Japan)		14.0	[39]
Scharmützelsee (Germany)		2.64	[40]
Søbygaard (Denmark)	low oxygen	145.0	[41]
Grosser Müggelsee (Germany)		25.0-100.0	[42, 43]
Warnow River (Germany)	anaerobic	175.2-236.6	[44]
Mai Po Marshes (Hong Kong)	anaerobic	31.8	[45]
	aerobic	9.4	
Beaver Reservoir (USA)	anaerobic	0.31	[46]
	aerobic	0.09	
Sławskie (Poland)	aerobic	3.7-10.2	[47]
Rusałka (Poland)	anaerobic	29.84	[48]
	aerobic	2.31	
Swarzędzkie	anaerobic	2.77-26.86	this study
	aerobic	-2.4-59.5	

oxygen concentration were highly variable. It accounted for 45.4% of total internal P loading to the lake, although it accounted for only 38% of total lake area (Table 4). The deeper zones II and III (3.0-7.2 m), where oxygen depletion was more frequent and of longer duration than in the shallow zone, contributed jointly to only about 37% of the annual internal P load to the lake, although they accounted for 45% of the total lake area. These results confirm earlier observations made by many researchers [5, 24-27] that P release can also be intensive under good oxygen conditions, not only in anaerobic ones. In shallow lakes, rapidly changing conditions in sediments and overlying water are observed because of alternate temporary thermal stratification and mixing due to wind and wave action. This can give rise to a phosphate gradient across the sediment-water interface, which enhances P release [28-31]. As stated by Andersen and Ring [32], shallow lakes usually have extensive littoral areas, so the littoral sediment plays an important role there in P cycling, especially if low O_2 concentrations occur at the sediment-water interface. James and Barko [33] estimated that littoral sediments provided 26% of the internal loading to the pelagic zone during the summer. Our estimations are much greater, as littoral sediments (zones I, IV and V) provided about 63% of the annual internal P loading to the lake.

The high rates of P release at station 5 (near the mouth of the Mielcuch Stream) were probably due to the high concentrations of this element in sediments resulting from the pollution of the stream with organic matter and other pollutants.

The literature data presented in Table 5 attest to a high variability of internal P loading, and indicate the individual character of each studied lake. The same applies to Swarzędzkie Lake, where the rate of P release varied widely both in time and space, especially in the littoral zone. Seen against the background of other results, the data obtained in Swarzędzkie Lake are relatively high (Table 5), which was expected as this is a hypereutrophic lake. The highest values stated in the River Warnow in Germany were 4 times greater, as this river was strongly polluted with municipal sewage [44]. It was characteristic that within Swarzędzkie Lake the highest values were also stated near the mouth of Mielcuch Stream, polluted with municipal sewage. The lowest P fluxes have been noted in oligo-mesotrophic lakes –

Piburger See and Beaver Reservoir [18, 46]. In eutrophic lakes [34-37, 48], P release was similar to that stated in Swarzędzkie Lake at non-polluted stations.

Conclusions

The study of benthic P release showed that in the deepest part (zone III) of Swarzędzkie Lake it was more intensive in anaerobic than in aerobic conditions. One of the highest rates of P release was observed at the deepest site in summer (over 25.0 mgP $m^{-2}d^{-1}$). At two stations located in the deeper part of the metalimnion (stations 3 and 4), the rate of P release depended on temperature and increased with increasing water depth. At shallow stations within the littoral zone under well aerated conditions, P was released slowly or was even deposited, irrespective of temperature. Periodical deoxygenation of sediments at shallow stations, followed by water mixing due to strong wind action, resulted in increased rates of P release. In contrast, aeration at the heavily polluted station 5 resulted in intensive P release from the sediments. On the scale of the whole lake, the process of benthic P release played a more important role in the shallower parts, in the littoral zone (0-3 m in depth); it accounted for 63% of the annual internal load. The deeper zones of the bottom (3-7.2m) with oxygen depleted in summer, accounted for 45% of the lake area but for only 37% of the annual internal load. The process of P release from bottom sediments was intensive not only in summer but also in autumn, whereas in other seasons it was less intensive.

Acknowledgements

Our study was supported by the Polish Committee for Scientific Research (grant No. 3PO4FO1724).

References

1. GOLTERMAN H. L. The role of ironhydroxyde-phosphate-sulphide system in the phosphate exchange between sediments and overlying water. Hydrobiologia **297**, 43, **1995**.
2. BOSTRÖM B., ANDERSEN J.M., FLEISCHER S., JANSSON M. Exchange of phosphorus across the sediment – water interface. Hydrobiologia **170**, 229, **1998**.
3. GAO L., ZHOU J.M., YANG H., CHEN J. Phosphorus fractions in sediment profiles and their potential contributions to eutrophication in Dianchi Lake. Environ. Geol. **48**, 835, **2005**.
4. MITRASZEWSKI P., UCHMAŃSKI J. A numerical model of phosphorus exchange between the sediments and the near-bottom water in a lake. Ekol. Pol. **36** (3-4), 317, **1988**.
5. BOSTRÖM B., JANSSON M., FORSBERG C. Phosphorus release from lake sediments. Arch. Hydrobiol. Beih. Ergebn. Limnol. **18**, 5, **1982**.
6. JIANG X., JIN X., YAO Y., LI L., WU F. Effects of biological activity, light, temperature and oxygen on phosphorus release processes at the sediment and water interface of Taihu Lake, China. Water Research **42**, 2251, **2008**.
7. PERRONE U., FACCHINELLI A., SACCHI E. Phosphorus dynamics in a small eutrophic Italian lake. Water Air Soil Pollut. **189**, 335, **2008**.
8. JEPPESEN E., KRISTENSEN P., JENSEN J.P., SONDERGAARD M., MORTENSEN E., LAURIDSEN T. Recovery resilience following a reduction in external phosphorus loading of shallow, eutrophic Danish lakes: duration, regulating factors and methods for overcoming resilience. Mem. Ist. Ital. Idrobiol. **48**, 127, **1991**.
9. GONSIORCZYK T., CASPER P., KOSCHEL R. Variations of phosphorus release from sediments in stratified lakes. Water, Air, Soil Pollut. **99**, 427, **1997**.
10. SØNDERGAARD M., JENSEN J.P., JEPPENSEN E. Internal phosphorus loading in shallow Danish lakes. Hydrobiologia **408/409**, 145, **1999**.
11. DUNALSKA J. Influence of limited water flow in a pipeline on the nutrients budget in a lake restored by hypolimnetic withdrawal method. Polish Journal of Environmental Studies **11**, 631, **2002**.
12. GAWROŃSKA H., BRZOZOWSKA R., GROCHOWSKA J., LOSSOW K. Possibilities to reduce internal loading to lake water by artificial aeration. Polish Journal of Environmental Studies **12**, 171, **2003**.
13. KOWALCZEWSKA-MADURA K., GOŁDYN R. Antrophogenic changes in water quality in the Swarzędzkie lake (West Poland). Limnol. Rev. **6**, 147, **2006**.
14. STEFANIAK K., GOŁDYN R., KOWALCZEWSKA-MADURA K. Changes of summer phytoplankton communities in Lake Swarzędzkie in the 2000-2003 period. Oceanological and Hydrobiological Studies **XXXVI**, (1), 77, **2007**.
15. SZYPER H., GOŁDYN R., ROMANOWICZ W. Lake Swarzędzkie and its influence upon the water quality of the river Cybina, Poznańskie Towarzystwo Przyjaciół Nauk, Prace Komisji Biologicznej **74**, 7, **1994**.
16. KELDERMAN P. Sediment – water exchange in Lake Grevelingen under different environmental conditions. Neth. J. Sea Res. **18**, 286, **1984**.
17. FORSBERG C. Importance of sediments in understanding nutrient cyclings in lakes. Hydrobiologia **176/177**, 263, **1989**.
18. PSENNER R. Phosphorus release patterns from sediments of a meromictic mesotrophic lake (Piburger See, Austria). Verh. Internat. Verein. Limnol. **22**, 219, **1984**.
19. KOWALCZEWSKA-MADURA K. Influence of changes of nutrient loading on structure and functioning of ecosystem of the Swarzędzkie Lake. PhD thesis, Adam Mickiewicz University, Poznań, Poland, **2005** [In Polish].
20. GOLOSOV S.D., IGNATIEVA N. Hydrothermodynamic features of mass exchange across the sediment-water interface in shallow lakes. Hydrobiologia **408/409**, 153, **1999**.
21. KENTZER A. Phosphorus and its biologically accessible fractions in bottom sediments of lakes of diverse trophic state, University Press, Toruń, **2001** [In Polish].
22. WIŚNIEWSKI R.J., PLANTER M. Phosphate exchange between sediments and the near-bottom water in relationship to oxygen conditions in a lake used for intensive trout cage culture. Ekol. Pol. **35**, 219, **1987**.
23. ISHIKAWA M., NISHIMURA H. Mathematical model of phosphate release rate from sediments considering the effect of dissolved oxygen in overlying water. Water Res. **23**, 351, **1989**.
24. DRAKE J.C., HEANEY S.I. Occurrence of phosphorus and its potential remobilization in the littoral sediments of a productive English lake. Freshwater Biol., **17**, 513, **1987**.

25. UCHMAŃSKI J., SZELIGIEWICZ W., LOGA M. Modeling of physical, chemical and biological processes in Polish lakes and reservoirs. Comparative Reservoir Limnology and Water Quality Management, pp 99-118, **1993**.
26. KLEEBERG A., DUDEL G.E. Changes in extent of phosphorus release in a shallow lake (Lake Grosser Müggelsee; Germany, Berlin) due to climatic factors and load. Mar. Geol. **139**, 61, **1997**.
27. JIANG X., JIN X., YAO Y., LI L., WU F. Effects of oxygen on the release and distribution of phosphorus in the sediments under the light condition. Environmental Pollution **141**, 482, **2006**.
28. PETERS R.H., CATTANEO A. The effects of turbulence on phosphorus supply in a shallow bay of Lake Memphremagog. Verh. Internat. Verein. Limnol. **22**, 185, **1984**.
29. FOWLER B., DRAKE J.C., HEMENWAY D., HEANEY S.I. An inexpensive water circulation system for studies of chemical exchange using intact sediments cores. Freshwater Biol. **17**, 509, **1987**.
30. MARSDEN M.W. Lake restoration by reducting external phosphorus loading: the influence of sediment phosphorus release. Freshwater Biol. **21**, 139, **1989**.
31. BEHRENDT H., NIXDORF B., PAGENKOPF W.G. Phenomenological description of polymixis and influence on oxygen budget and phosphorus release in Lake Müggelsee. Int. Rev. Ges. Hydrobiol. **78**, 411, **1993**.
32. ANDERSEN F.Ø., RING P. Comparison of phosphorus release from littoral and profundal sediments in a shallow, eutrophic lake. Hydrobiologia **408/409**, 175, **1999**.
33. JAMES W.F., BARKO J.W. Littoral-pelagic phosphorus dynamics during nighttime convective circulation. Limnol. Oceanogr. **36**, 949, **1991**.
34. WIŚNIEWSKI R.J. Role of internal loading in eutrophication process of man-made reservoirs in: Biological processes in protection and restoration of lowland reservoirs (Eds: M. Zalewski), Biblioteka Monitoringu Środowiska, Łódź, pp 61-70, **1995** [In Polish].
35. WIŚNIEWSKI R.J., RZEPECKI M. Bottom sediments of the river-lake and lake-river transition zones in the Krutynia fluvio-lacustrine system (Mazurian Lakeland); the role in the phosphorus cycling. In: The functioning of river-lake system in a lakeland landscape: river Krutynia (Mazurian Lakeland, Poland) (Eds: A. Hillbricht-Ilkowska, R.J. Wiśniewski). Zeszyty Naukowe Komitetu „Człowiek i Środowisko" **13**, 313, **1996** [In Polish].
36. PLANTER M., WIŚNIEWSKI R.J. Factors affecting nutrient budged in lakes of the river Jorka watershed (Masurian Lakeland, Poland). IX. The exchange of phosphorus between sediments and water. Ekol. Pol. **33**, 329, **1985**.
37. WIŚNIEWSKI R.J., PLANTER M. Exchange of phosphorus across sediment-water interface (with special attention to the influence of biotic factors) in several lakes of different trophic status. Verh. Internat. Verein. Limnol. **22**, 3345, **1985**.
38. HAMBRIGHT K.D., ECKERT W. Sediment – water phosphorus dynamics in newly created Lake Agmon (Agmon-Hula wetlands). Israel. Verh. Internat. Verein. Limnol. **27**, 4001, **2001**.
39. MURPHY T., LAWSON A., KUMAGAI M., NALEWAJKO CZ. Release of phosphorus from sediments in Lake Biwa. Limnology **2**, 119, **2001**.
40. KLEEBERG A. Interactions between benthic phosphorus release and sulfur cycling in Lake Scharműtzelsee (Germany). Water, Air, Soil Pollut. **99**, 391, **1997**.
41. SØNDERGAARD M., JENSEN J.P., JEPPENSEN E. Retention and internal loading of phosphorus in shallow, eutrophic lakes. The Scientific World, **1**, 427, **2001**.
42. KLEEBERG A., KOZERSKI H.P. Phosphorus release in Lake Groβer Műggelsee and its implications for lake restoration. Hydrobiologia **342/343**, 9, **1997**.
43. KOZERSKI H.P., KLEEBERG A. The sediments and benthic-pelagic exchange in the shallow Lake Müggelsee (Berlin, Germany). Internat. Rev. Hydrobiol. **83** (1), 77, **1998**.
44. KLEEBERG A., SCHLUNGBAUM G. In situ phosphorus release experiments in the Warnow River (Mecklenburg, northern Germany). Hydrobiologia **253**, 263, **1993**.
45. LAI D., LAM K. Phosphorus retention and release by sediments in the eutrophic Mai Po Marshes, Hong Kong. Marine Pollution Bulletin **57**, 349, **2008**.
46. SEN S., HAGGARD B.E., CHAUBEY I., BRYE K.R., COSTELLO T.A., MATLOCK M.D. Sediment phosphorus release at Beaver Reservoir Northwest Arkansas, USA, 2002-2003: A preliminary investigation. Water Air Soil Pollut **179**, 67, **2007**.
47. KOWALCZEWSKA-MADURA K., ŻAK J., GRZEŚKOWIAK A. Bottom sediments of Sławskie Lake. Wiadomości Meteorologii Hydrologii Gospodarki Wodnej **II** (3-4), 21, **2008** [In Polish].
48. GOŁDYN R., KOWALCZEWSKA-MADURA K., DONDAJEWSKA R. Phosphorus release from the bottom sediments of Rusałka Lake (Poznań, Poland). Oceanological and Hydrobiological Studies (in press).
49. KOWALCZEWSKA-MADURA K., GOŁDYN R. Phosphorus content of bottom sediments in Swarzedzkie Lake. Verh. Internat. Verein. Limnol. **29**, 1063, **2005**.