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BALANCE AND CIRCULATION OF NUTRIENTS IN A SHALLOW COASTAL LAKE GARDNO (NORTH POLAND)

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BILANS I KRĄŻENIE SUBSTANCJI BIOGENICZNYCH W PŁYTKIM, PRZYBRZEŻNYM JEZIORZE GARDNO (POLSKA PÓŁNOCNA)

W 2002 roku w jeziorze Gardno badano krążenie substancji biogenicznych w profilu pionowym i horyzontalnym oraz oszacowano bilans tych składników. Eutroficzne jezioro Gardno leży w strefie przybrzeżnej Bałtyku i charakteryzuje się dużą powierzchnią oraz niewielką głębokością (średnio 1,6 m). Stwierdzono, że w ciągu roku do jeziora dostaje się 1516 Mg azotu ogólnego i 155 Mg fosforu ogólnego. Z tego 67% azotu i 87% fosforu wypływa z niego poprzez odpływ, a reszta pozostaje w jeziorze. Z pozostającego w jeziorze azotu 45% uwalnia się poprzez proces denitryfikacji, a 53% ulega sedymentacji. Największy wpływ na krążenie związków tych dwóch pierwiastków ma mieszanie się wody wywołane silnymi wiatrami. Przemieszczające się masy wody porywają wierzchnią warstwę osadów dennych i mieszają się z nią. Powoduje to zwiększenie resuspensji i sedymentacji, maskując podobne procesy wynikające z zewnętrznego ładunku substancji biogenicznych oraz procesów i produktów autochtonicznych, które co do wielkości są o jeden, dwa rzędy mniejsze.

Summary

In 2002 the circulation of nutrients and their balance was studied in a large, shallow, eutrophic Lake Gardno. It was determined that throughout a year 1516 Mg of total nitrogen and 155 Mg of total phosphorus reach the lake. Approximately 67% of nitrogen and 87% of phosphorus reaching the lake flows out of it, the rest remains in the lake. About 45% of the total loss of nitrogen results from denitrification, and about 53% from sedimentation. The greatest effect on the circulation of nutrients in Lake Gardno is exerted by the mixing of water caused by strong winds resulting in the upward movement of the surface layers of bottom sediments. This causes increased resuspension and sedimentation, which mask similar processes resulting from the outer load of nutrients and from autochtonic processes and products, which are one or two orders of a magnitude smaller.

INTRODUCTION

Trophic condition of a lake can be affected by a number of factors, but the decisive role is played by the inflow of various substances from the drainage area and by the processes taking place within the lake. Internal changes, especially the exchange of matter between the sediments and the water, are more intensive the greater the surface area of the lake and the smaller its depth is. In large and shallow lakes and other water bodies, strong water flows and winds cause stirring up of sediments. This can accelerate the release of phosphates [17, 20, 28, 33] which are re-used by plankton [9], or adsorbed on small sediment grains and carried outside the ecosystem or, alternatively, they can undergo re-sedimentation [7, 22, 38]. The internal load of nutrients can be defined as their upward flow from the bottom sediments [4, 10, 40]. This flow consists mainly of soluble and suspended forms of organic compounds and nutrients. In the deep water, there also exists a flow of nutrients in the reversed direction, which is most often measured with special traps [21] collecting the matter produced in the deep water as well as stirred up sediments.

In the release of nitrogen from a lake, a significant role is played by denifrification. Losses of nitrogen resulting from denitrification range over a very wide extent, i.e. From 0–10% [2] up to 86–90% [15]. In spite of the fact that the well-known method of Vollenweider [35] did not account for denitrification in the balance, it is taken into account in a number of other studies [1, 8, 11, 15, 39].

The purpose of the presented study was to determine the range of occurrence and directions of circulation of nutrients in Lake Gardno, and to estimate their balance.

MATERIAL AND METHODS

Description of studied area

Lake Gardno (54°79' N, 17°07' E) is a large and shallow estuarine lake located close to the Baltic Sea in the middle part of the Polish cost (Fig. 1). The surface area of the lake is 24.7 km^2 while its average depth is only 1.3 m [34]. The level of the water does not change considerably throughout the year; mean yearly amplitude of 0.32 m constitutes only a quarter of the average depth. The waters of the lake exchange nine times throughout the year. The area of the direct drainage area of Lake Gardno equals, excluding the lake itself, 893 km^2 and is 36 times greater than the surface area of the lake.

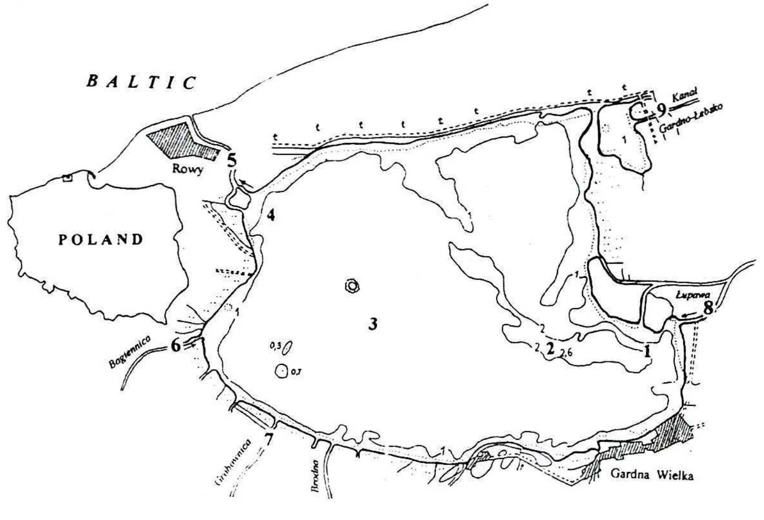

Fig. 1. Location of sampling stations in Lake Gardno

Lake Gardno is located in the drainage area of the River Łupawa, which flows into the lake in its eastern part, and out of it in its north-western part, and connects the lake with the sea. The length of the River Łupawa between the lake and the sea is 1.5 km. The fall of the land is very small there, facilitating periodical inflow of sea waters into the lake. Changes in the level of sea water exert a strong effect on the biocenosis of the lake, as they can cause sudden rise or outflow of water and large changes in the salinity level. Average flow rate of the River Łupawa in this place is 8.3 m^3/s.

The River Łupawa carries on average 0.262 km^3 of water per year into Lake Gardno, containing approximately 3860 Mg of debris [6]. As the result of filling of the lake basin with sediments, a progressive silting of the lake is observed, especially in its eastern part. In the middle part of the eastern shore, river debris caused the formation of a large delta, continuously extending its surface area. With the silting of the shores, vegetation zones move towards the central part of the lake, while the shores become overgrown with marshy vegetation.

Apart from the River Łupawa, some minor rivers, namely the Bagiennica, Grabownica, and Broda, also flow directly into the lake. The largest of them, the River Grabownica carries 17 times less water than the River Łupawa, while the Bagiennica – 40 times less. In its north-eastern part Lake Gardno is connected by a cannal with Lake Łebsko.

Lake Gardno is separated from the Baltic coast by a strip of land 0.8–2 km wide, which forms a bar with diversified but rather small sand hills usually covered with pine woods. Extensive areas surrounding the lake from the south-western and eastern sides are covered with marshes and peatland, and cross-cut by a dense network of drainage ditches.

Lake Gardno is non-stratified because of strong winds, which cause continuous deep mixing of waters. Transparency measured with the Sechi disc ranges from 0.3 to 0.8 m. High contents of nitrogen and phosphorus causes continuous blooms in the lake. Biomass of the phytoplankton and chlorophyll *a* usually reaches its maximum in June and August.

Sampling

In 2002, twice a month, three water samples were taken from each site with the Rutner sampler. Samples of bottom sediments, 15 cm thick, were taken once a month with the Kajak sampler and were subsequently divided into 2-cm layers. The location of the study stations is given in Figure 1. The first four stations are located in the most characteristic parts of the lake:

1. the region of the inflow of the River Łupawa,
2. the place of the greatest depth (2.6 m),
3. the centre of the lake in the vicinity of the island,
4. the region of the outflow of water from the lake.

The remaining five sites were located on the outflow of water from the lake (5), and on the main tributaries: 6 – the Bagiennica, 7 – the Grabownica, 8 – the Łupawa and 9 – Gardno-Łebsko channel.

Basing on the analysis of water exchange in Lake Gardno [6], water balance in this lake can be expressed by the equation:

$$\Delta W = W_L + W_M + W_A - W_P - W_O \quad (1)$$

where: W_l – water flowing from the land,

W_M – periodic inflow of marine water,

W_A – atmospheric precipitation,

W_P – water loss resulting from evaporation,
W_O – water flowing from the lake to the sea.

Annually, an average of 284.40 • 10^6 m^3 of water reaches the lake from the land. In this amount, water carried by the Łupawa River alone constitutes 94%. In the case of Gardno Lake, it has been assumed that the inflow and outflow of the underground water are balanced. Atmospheric precipitation provided 19.00 • 10^6 m^3 of water in this period. The loss of water due to evaporation amounted to 13.11 • 10^6 m^3. The amount of sea water entering the lake throughout a year was estimated at the level of 17.98 • 10^6 m^3; 308.42 • 10^6 m^3 of water flew out of the lake in this period.

In order to describe the flow and exchange of nutrients in Lake Gardno, the amount of nutrients carried into the lake (LW) and out of the lake (LO) was taken into account. This allows for calculation of the amount of nutrients remaining in the lake (ΔLR):

$$\Delta LR = LW - LO \quad (2)$$

The outer load (LW) consists of the inflow from the land, from the sea and from the atmosphere. In the calculation of nutrient reduction, the outflow to the sea and denitrification should be included.

Changes occurring inside the lake can be calculated as a balance ΔLI reflecting nutrient changes in the water in the period t_o - t_n (two weeks on average):

$$\Delta LI = C_{to} V_{to} - C_{tn} V_{tn} \quad (3)$$

where: C – nutrient concentration,
V – volume of the lake,
t_o - t_n – time span between sample collection.

This difference, calculated for nutrient concentrations measured at study sites within the lake (st. 2 and 3) illustrates nutrient increase or decrease resulting from internal changes in the lake, including their sedimentation and release from sediments.

In order to determine the total net balance of nutrients ΔNL showing the changes of the amount of nutrients in the water of the lake, the difference between internal balance ΔLI and external balance ΔLR should be calculated according to the formula:

$$\Delta NL = \Delta LI - \Delta LR \quad (4)$$

This balance is equivalent to the sedimentation and resuspension of nutrients. When the value of this balance is negative, the process of sedimentation predominates in the lake; when it is positive, resuspension predominates. Therefore, this balance accounts for the difference between the rate of upward nutrient flow (UW) and the rate of sedimentation (DW):

$$\Delta NL = UW - DW \quad (5)$$

In order to calculate the rate of upward flow of nutrients UW, formula 5 should be transformed, i.e. the rate of sedimentation DW and the net balance ΔNL should be added:

$$UW = \Delta NL + DW \quad (6)$$

In the studied lake, the rate of sedimentation was measured at three study stations (2, 3, and 4) from 10th March until 28th October with the use of special traps. Each trap contained six glass cylinders 50 cm high, with the diameter of the opening equal 8 cm, arranged in two rows of 3 cylinders. The traps were located in such a way that the openings were 0.6 m above the lake bottom. Sediments could not get out of those traps in spite of the movement of water due to the winds. This means the sediments did not participate in the secondary upward movement and sedimentation. Every two weeks, material from the traps was collected, drained and desiccated; chemical analysis was carried out according to Januszkiewicz [13]. Total nitrogen and total phosphorus were analyzed by spectrophotometric method using SHIMADZU UV-1202 after the samples had been boiled in mixture of $HClO_4$ and H_2SO_4.

Primary production of phytoplankton (PP) was measured twice a month at the study stations 2 and 3 with the ^{14}C method [18]. For this purpose, light and dark bottles were placed at the depth of 0.2, 0.6, 1.0, and 1.5 m. The exposure time was 8 hours. After incubation *in situ*, the contents of the bottles were filtered through Millipore filters (0.45 μm). The filters with their contents were washed with 0.1 M HCl and dried. Afterwards, radioactivity of the samples was measured with the ZR-16 apparatus. The primary production was calculated according to Vollenweider [36]. Consumption of nutrients by phytoplankton was estimated on the basis of the primary production and the Reddfield ratio [26] accounting for the use of nutrients during carbon assimilation.

Assuming that the TN : TP ratio in the material collected in the trap reflects the ratio of those substances in the surface layer of bottom sediments, and knowing the net sedimentation TP, it is possible to calculate the sedimentation TN according to the formula:

$$TN_{sed} = (TN : TP) \cdot TP_{sed} \qquad 7)$$

According to the suggestions expressed by Ahlgren *et al.* [1] and Vollenweider [35], and applied by Dudel & Kohl [8] and Jensen *et al.* [15], the amount of nitrogen released in the process of denitrification (N_d) was calculated as a difference between the amount of nitrogen released throughout the year (UW_{TN}) and the amount of nitrogen accumulated in the sediment (TN_{sed})

$$N_d = UW_{TN} - TN_{sed} \qquad (8)$$

Those calculations take into account also free nitrogen (N_2) fixed by the algae.

Data concerning the speed and direction of the wind were obtained from the hydrometeorological station in Ustka (located approximately 15 km from Lake Gardno).

Determination of the contents of nitrogen and phosphorus in the lake water was carried out according to Standard methods [29]. Concentration of ammonia nitrogen (NH_4-N) was determined with the use of the phenolhypochloride method, nitrite nitrogen (NO_2-N) – with the use of sulphanilic acid and naphtyloamine, nitrate nitrogen (NO_3-N) – similarly as nitrites, but after their reduction with cadmium. The sum of all nitrogen forms (NH_4-N + NO_2-N + NO_3-N) constituted inorganic nitrogen (IN). Total nitrogen (TN) was determined in the same way as nitrates in a sample previously mineralized with potassium persulfate in an autoclave. The concentration of mineral phosphorus (IP) was determined with the use of the molybdate method, with ascorbic acid as a reducing agent. Total phosphorus (TP) was determined in the same way as phosphates in a mineralised sample.

RESULTS

The total balance of nutrients in Lake Gardno is presented in Figure 2. Basing on the amount of water carried into the lake and on the data given in Table 1, it was calculated that 1 523 Mg of total nitrogen per year enters Lake Gardno from the outside, and 1 m^3 water 49.2 g. In this amount, the inflow from the land constitutes 96%, from the atmosphere – 3%, and from the sea – 1%. Small fraction of nitrogen inflow from the sea is caused by the fact that nitrogen concentration in the sea water is 20 times lower than in the water flowing from the land. Additionally, the inflow from the sea occurs only periodically, during the lifting of sea water or lowering of lake water in the dry period.

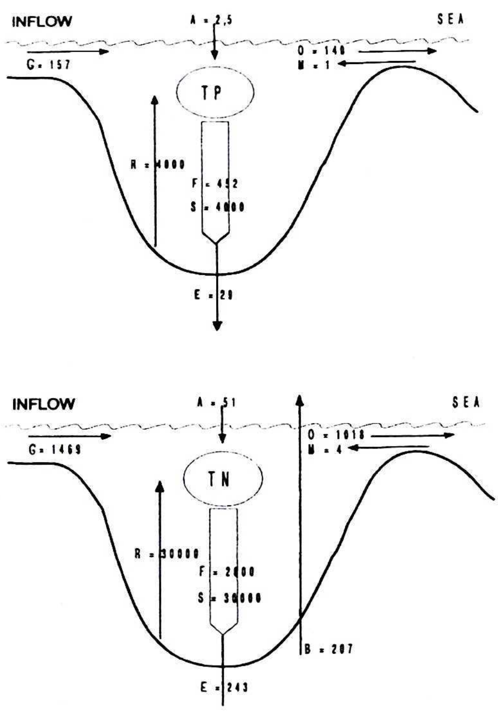

Fig. 2. Annual balance of total nitrogen and total phosphorus in lake Gardno (2002) in Mg
A – atmospheric precipitation, B – denitrification, G – inflow from land, M – inflow from sea, E – acumulation in sediment, O – outflow, F – primary production sedimentation, R – resuspension and diffusion, S – total sedimentation

According to the data presented in Table 1, inorganic nitrogen (IN) constituted 1/3 of the total nitrogen (TN). Organic nitrogen N_{org}, calculated as a TN - IN difference, predominated and amounted to 65%. Inorganic nitrogen originating from the atmosphere accounted for 10% of the total inorganic nitrogen (IN) and 3% of the total nitrogen load entering the lake. The inflow of nitrogen from the sea is small and accounts for about 0.5% TN. Yearly in the lake remains approximately 48% IN and 21% organic nitrogen. On the whole approximately 460 Mg of nitrogen per year remains in the lake.

Table 1. Fluxes of nutrients through Lake Gardno in 2002 (IN – inorganic nitrogen, N_{org} – organic nitrogen, TN – total organic, IP – inorganic phosphorus, P_{org} – organic phosphorus, TP – total phosphorus)

Nutrients	Month												Average
(mg · m^{-3} · d^{-1})	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	
IN inflow	36.0	52.0	80.9	92.1	74.0	30.1	10.9	8.0	20.0	18.0	27.0	33.0	40.0
atm. input	4.3	5.0	8.9	6.1	5.2	3.8	2.3	1.5	2.6	3.8	5.5	4.5	4.5
sea input	0.3	0.5	0.4	0.6	0.3	0.1	0.2	0.2	0.2	0.3	0.3	0.2	0.3
total input	40.6	57.5	90.2	98.8	79.5	34.0	13.4	9.7	22.8	22.1	32.8	37.7	44.8
outflow	17.9	28.4	34.8	50.8	35.8	22.4	11.8	6.9	17.0	13.6	21.2	22.2	23.5
retention	22.7	29.1	55.4	48.0	43.7	11.6	1.6	2.8	5.8	8.5	11.6	15.5	21.3
retention (%)	56	51	61	48	55	34	26	28	25	38	35	41	48
$N_{org.}$ inflow	77.2	98.0	122.1	137.2	119.2	96.1	75.0	61.0	72.8	74.0	80.1	70.2	90.2
sea input	0.1	0.3	0.4	0.3	0.5	0.2	0.1	0.0	0.1	0.1	0.1	0.2	0.2
total input	77.3	98.3	122.5	137.5	119.7	96.3	75.1	61.0	72.9	74.1	80.2	70.4	90.4
outflow	60.5	75.1	86.3	107.2	96.2	80.6	72.4	45.0	60.3	50.2	65.0	53.2	71.0
retention	16.8	23.2	36.2	30.3	23.5	15.7	2.7	16.0	12.6	23.9	15.2	17.2	19.4
retention (%)	22	24	30	22	20	16	17	26	17	32	19	24	22
TN inflow	117.9	155.8	210.7	236.3	197.2	132.3	88.5	72.7	95.7	96.2	113.0	108.1	135.2
% IN	34	37	42	42	39	27	15	16	24	23	29	35	35
% $N_{org.}$	66	63	58	58	61	73	85	84	76	77	71	65	65
outflow	78.4	103.5	121.1	158.0	132.0	103.0	84.2	51.9	77.3	63.8	86.4	75.4	94.5
% IN	22	27	29	32	27	22	14	13	22	21	25	29	25
% $N_{org.}$	78	73	71	68	73	78	86	87	78	79	75	71	75
retention	39.5	52.3	89.6	78.3	65.2	29.3	4.3	20.8	18.4	32.4	26.6	32.7	40.6
retention (%)	34	34	43	33	33	22	5	29	19	34	24	30	30
IP inflow	2.10	3.25	4.07	4.23	3.29	2.23	1.32	2.07	1.93	2.06	2.07	1.98	2.55
atm. input	0.16	0.20	0.26	0.28	0.22	0.17	0.12	0.18	0.28	0.30	0.26	0.20	0.22
sea input	0.03	0.04	0.08	0.08	0.05	0.06	0.03	0.02	0.09	0.08	0.09	0.07	0.06
total input	2.29	3.49	4.41	4.59	3.56	2.46	1.47	2.27	2.30	2.44	2.42	2.25	2.83
outflow	1.14	1.38	1.67	2.02	2.08	1.84	1.55	1.79	1.36	1.64	1.39	1.18	1.59
retention	1.15	2.11	2.74	2.57	1.48	0.62	–0.08	0.48	0.94	0.80	1.03	1.07	1.24
retention (%)	50	60	62	56	42	25	-5	21	41	33	43	47	43
$P_{org.}$ inflow	7.95	10.42	12.81	17.88	15.93	11.23	8.85	9.87	7.45	9.86	9.69	8.63	10.87
sea input	0.01	0.01	0.03	0.03	0.05	0.06	0.05	0.04	0.03	0.03	0.02	0.02	0.03
total input	7.96	10.43	12.84	17.91	15.98	11.29	8.90	9.91	7.48	9.89	9.71	8.65	10.90
outflow	7.10	8.98	11.77	16.03	14.34	10.26	9.02	9.24	5.41	5.04	6.85	7.77	9.32
retention	0.86	1.45	1.07	1.88	1.64	1.03	–0.12	0.67	2.07	4.85	2.86	0.88	1.58
retention (%)	11	14	8	10	10	9	-1	7	28	49	29	10	15
TP inflow	10.25	13.92	17.25	22.50	19.54	13.75	10.37	12.18	9.78	12.33	12.13	10.90	13.74
% IP	22	25	26	20	18	18	14	18	24	20	20	21	21
% $P_{org.}$	78	75	74	80	82	82	86	82	76	80	80	79	79
outflow	8.24	10.36	13.44	18.05	16.42	12.10	10.57	11.03	6.77	6.68	9.27	8.95	10.98
% IP	14	13	12	11	13	15	15	16	20	25	15	13	14
% $P_{org.}$	86	87	88	89	87	85	85	84	80	75	85	87	86
retention	2.01	3.56	3.81	4.45	3.12	1.65	–0.20	1.15	3.01	5.65	2.86	1.95	2.76
retention (%)	20	26	22	20	16	12	-2	9	31	46	24	18	20

The load of phosphorus entering the lake throughout the year amounts to 160 Mg (Fig. 2) (5.1 g/m^3). Organic phosphorus $P_{org.}$ calculated from the TP - IP difference, constitutes 79% of this load, while reactive inorganic phosphorus (IP) constitutes 21% (Tab. 1). The atmospheric load of phosphorus constituted 8% of inorganic phosphorus and about 2% of the total phosphorus. About 3% of the total inorganic phosphorus (IP) was brought into the lake with the sea water. The very small fraction of organic phosphorus originating from the sea was due to the fact that it is inorganic phosphorus that predominates in the sea water. Retention of phosphorus compounds in Lake Gardno amounts to 20% which means that 31 Mg of phosphorus remains in the lake during a year. In the summer period in July, retention had a negative value of -0.08 in the case of IP and -0.12 mg P m^{-3}d^{-1} in the case of organic phosphorus; this means that a considerable amount of inorganic phosphorus was transformed into organic phosphorus in this period.

Seasonal changes in the inflow of nutrients into the lake depend, among others, on hydrological changes. The greatest inflow of nutrients into the lake was observed in the spring, from February to May (approximately 75 mg m^{-3}d^{-1} of inorganic nitrogen, 119 mg m^{-3}d^{-1} of organic nitrogen, 3.7 mg m^{-3}d^{-1} of inorganic phosphorus, and 13.8 mg m^{-3}d^{-1} of organic phosphorus). During the first five months of 2002, two thirds of the yearly load of inorganic nitrogen, half of the organic nitrogen and a majority of phosphorus compounds were carried into the lake. An increased inflow of nutrients observed in this period is doubtlessly caused by an increased amount of water flowing from the land into the lake and by an increased concentration of nutrients in this water. Also in this period, approximately 50% of total nitrogen and 60% of inorganic phosphorus carried into the lake underwent the process of accumulation. On the other hand, the largest part of the introduced organic phosphorus $P_{org.}$ (35%) remained in the lake during the winter. The smallest retention of nutrients was observed in the summer (on average approximately 19% of nitrogen and 3% of phosphorus). The minimum was in July, therefore in this month the balance of nitrogen compounds was close to zero, which means that the amount of the nitrogen compounds introduced into the lake was nearly equal to the amount flowing out of the lake. Only in the case of phosphorus compounds, especially inorganic phosphorus, the amount flowing out of the lake exceeded the amount flowing in by about 5%. This probably results from the fact that a considerable amount of inorganic phosphorus was transformed into its organic form by living organisms. Additionally, it should be noted that the flow of nutrients from the drainage area diminished considerably in the summer and autumn, especially in the case of inorganic nitrogen – on average by 70%, and other nutrients – by 50%. Large atmospheric precipitation in November and December increased the concentration of nutrients in the waters flowing into the lake, resulting also in an increased retention. As has been shown, in the total inflow of nutrients the fraction of nitrogen and phosphorus of atmospheric origin was small in comparison to land sources. Nevertheless, the atmospheric inflow of nitrogen is significant in the spring comprising approximately 10% of the total nitrogen, while the inflow of phosphorus is significant in the autumn, when it comprises about 15%.

Nutrients carried into the lake are consumed mainly by the plants inhabiting the lake. Consumption of nutrients greatly affects their subsequent sedimentation. The abundance of plankton in the water is strongly correlated with the abundance of nutrients. Primary production determined for Lake Gardno ranges between 582 and 6431 mg C m^{-3}d^{-1}. This allows for the calculation of the consumption of nutrients by phytoplankton (Tab. 2). It reached a maximum (643 mg N $m^{-3}d^{-1}$ and 89 mg P $m^{-3}d^{-1}$) in May, and was subsequently decreasing. The lowest values were observed in winter (approximately 60 mg N $m^{-3}d^{-1}$ and 8 mg P $m^{-3}d^{-1}$). The average yearly nutrient demand is 230 mg N $m^{-3}d^{-1}$ and 40 mg P $m^{-3}d^{-1}$.

Table 2. Internal nutrient fluxes in Lake Gardno in 2002 (TN – total nitrogen, TP – total phosphorus)

Flux ($mg \cdot m^{-3} d^{-1}$)	Month I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Average
TN													
Phytoplankton uptake	60	91	132	240	643	503	566	511	355	204	112	58	230
Trap catch			3071	2452	1558	1263	2085	3647	4560	3021			2707
Upward flux			3085	2463	1552	1252	2095	3678	4637	3075			2729
Net sedimentation	40.9	33.5	39.4	-10.1	-28.2	-27.5	-13.3	-2.1	58.0	91.9	42.7	32.5	21.5
Denitrification	18.1	10.3	16.7	18.2	22.1	16.4	26.4	22.7	19.3	16.0	18.8	15.0	18.3
TP													
Phytoplankton uptake	8	13	18	33	89	70	79	71	51	28	15	8	40
Trap catch			300.7	248.6	196.6	169.2	254.3	456.7	682.4	604.2			364.1
Upward flux			305.3	247.4	193.3	166.0	252.7	456.5	689.2	615.0			365.7
Net sedimentation	4.82	3.94	4.64	-1.19	-3.32	-3.24	-1.57	-0.25	6.83	10.81	5.03	3.86	2.53

The masses of sediments collected in the traps differed in particular months (Tab. 2). The greatest amounts of deposited material were collected in September, the smallest in June. In spite of differences in the amount of those materials their composition was rather constant. Organic matter (determined as a loss at roasting) comprised 31.4% of the total dry mass. The ratio of the determined mass of nitrogen to the mass of phosphorus was 8.5 and was similar to the ratio of those components in the surface layers of bottom sediments in this lake (8.2). The contents of nitrogen and phosphorus in the material contained in the traps considerably exceed (2 to 13 times) their contents calculated for the potential sediment, which could have originated from primary production. This means that approximately 80% of the material in the traps, i.e. also of the material circulating in the water, originates from the stirred up bottom sediments.

The rate of upward flow of nutrients in the water of Lake Gardno was calculated as a sum of the ΔNL balance and the contents of a trap (equation 6). As indicated by the results presented in Table 2, the rate of sedimentation of nutrients and the rate of their upward movement are nearly the same. Their average flow, both upward and downward, was 2707 mg N $m^{-3}d^{-1}$ and 365 mg P $m^{-3}d^{-1}$ (Tab. 2). This made possible to estimate that 30 000 Mg of nitrogen and 4 000 Mg of phosphorus per year are transported this way (Fig. 2). In order to determine the factors affecting the rate of upward movement of nutrients, statistical analysis was carried out. Basing on a multiple regression analysis including the flow of nutrients as a function of the load of nutrients introduced into the lake, of the wind speed and of the primary production, it was determined that it is the wind that exerts the greatest effect ($r = 0.483$ for nitrogen and $r = 0.416$ for phosphorus). When there is no ice on the lake, upward movement of sediments caused by the wind plays a major role in the total upward nutrient flow. Its magnitude considerably outweighs the external load as well as the autochtonic production in the lake.

Average monthly rates of sedimentation of phosphorus calculated from the balance (equation 3) are given in Table 2. Those rates range from -3.32 to 10.81 mg P $m^{-3}d^{-1}$. Negative values indicate the predomination of phosphorus release from the sediments. That occurs mainly in the end of spring and in the summer. In the autumn and winter, the predomination of sedimentation processes (positive values) was observed. Average yearly sedimentation (2.53 mg P $m^{-3}d^{-1}$) was similar to average yearly amount of phosphorus retained in the lake (2.76 mg P $m^{-3}d^{-1}$). It was estimated that 29 Mg of the phosphorus undergoing sedimentation per year are accumulated in bottom sediments (Fig. 2).

Basing on the rate of sedimentation of phosphorus and on the N : P ratio in the sediment material collected in the traps (8.5 on average), the rate of sedimentation of nitrogen (equation 7) was calculated. It ranges from – 28.2 to 91.9 mg N $m^{-3}d^{-1}$. In the summer, the process of nitrogen release from the sediments exceeded the process of its sedimentation.

The difference between the internal monthly balance of nitrogen (equation 4) and the average amount of nitrogen undergoing sedimentation determines the amount of nitrogen released in the process of denitrification (equation 8). As results from the values given in Table 2, the process of denitrification was most intensive in the summer period, reaching its maximum in July (over 26 mg N $m^{-3}d^{-1}$). If nitrogen fixation by the algae is not taken into account, denitrification occurring in Lake Gardno accounts for about 45% of nitrogen loss, while 53% is accumulated in bottom sediments.

DISCUSSION

In 2002, tributaries of Lake Gardno, especially the Łupawa River, carried large amounts of nutrients (49.2 g N $m^{-3}y^{-1}$, 5.0 g P $m^{-3}y^{-1}$) into the lake. Those values are much higher than in an Estonian Lake Võrtsjärv (2.5 g N $m^{-3}y^{-1}$ and 0.1 g P $m^{-3}y^{-1}$) [21] and are comparable with the nitrogen load recorded in Finnish lakes (42.5 g N $m^{-3}y^{-1}$) [25] and Danish lakes amounting to approximately 45–62 g N $m^{-3}y^{-1}$ [14, 17]. A high load of phosphorus (3–7 g $m^{-3}y^{-1}$) was also observed in the Sulejowski Basin [9], in Lake Łebsko [30], in lakes in Germany [8, 16] and in Russia [7, 19]. A high concentration of nutrients (4 mg N dm^{-3}, 0.4 mg P dm^{-3}) and of organic matter (90 mg m^{-3}), a high level of primary production (2 g C $m^{-3}d^{-1}$) and low transparency (0.3 m) indicate a very high level of eutrophication of Lake Gardno. High turbidity of the water is caused not only by a high biomass of plankton but also by the stirring up of bottom sediments lying close to the surface of the water [3]. Strong winds cause continuous mixing of the water resulting in moving and carrying up of the surface layers of sediments. Permanent mixing increases circulation of nutrients, which accompanies a high level of their diffusion resulting from a large difference in concentration at the border of sediment-water [5, 24, 33, 40].

The contents of nitrogen and phosphorus in the water carried into Lake Gardno have a N : P ratio equal to nearly 10. This value indicates that they originate mainly from household and industrial waste. This value of the N : P ratio is recorded also in the deep water. That means that the reduction of nitrogen and phosphorus in the water occurs at the same rate. The value of this ratio is lower in bottom sediments and suspended matter. In the suspended matter this value equals 8.8 : 1, in the surface layers of the sediments it equals 8.2 : 1, while in 10 cm sediment layers it is 7 : 1. The decrease in the value of this ratio results from the release of nitrogen in the process of denitrification. In Lake Gardno, denitrification accounts for 45% of the released total nitrogen and for 14% of the outer load. In Lake Müggelsee, denitrification accounted for 65% of nitrogen loss [16], in Danish lakes it accounted for 77% [8], while in Lake Võrtsjärr for as much as 81% [21]. Considerably lower effect of denitrification on the release of nitrogen in Lake Gardno results from the fact that it is much shallower (the average depth of 1.3 m) than the compared lakes. In shallow non-stratified lakes, bottom sediments are a very important place of denitrifcation. The shallower the lake the more often and to a greater extent the anaerobic layers of its sediments are disturbed leading to the reduction of the denitrification process. On the other hand, because of mixing with water the sediments have a greater contact with nitrogen, abundant in the water of this lake. Therefore, large amounts of nitrogen compounds are absorbed by sediment particles and in this way reach the bottom of the lake.

Abundance of nutrients in Lake Gardno causes mass growth of phyto- and zooplankton. Therefore, primary production in this lake is higher than in Lake Võrtsjärr [21] and Lake Hiidensvesi [12]. But similar levels of the primary production were obtained by Lau and Lane [18] and Olesen *et al.* [23]. A major part of this production underwent sedimentation. Unfortunately, the contents of the traps cannot be regarded as resulting from this sedimentation because of stirred-up bottom sediments predominating there. For this reason, sedimentation of phosphorus was calculated from the difference between the inner and outer balance, thus eliminating the effect of inflow and outflow. Changes underwent by the compounds of phosphorus in the water are affected mainly by exchanges between the water and the sediment [27, 28]. From April to August the process of upward flow of nutrients outweighs the process of sedimentation. The variation of those processes in time is great, which is characteristic for shallow lakes. A high variability of oxygen concentration was also observed in the surface layer of bottom sediments. In result of strong turbulence, the sediments are mixed with water and well oxidized; at that time, the concentration of oxygen at the sediment-water edge is high. On calm days, there are considerable differences between oxygen concentration in surface water and water close to the bottom [8, 17]. Aquatic organisms inhabiting shallow estuarian lakes such as Lake Gardno are exposed to drastic changes, including periodic inflow of sea water [31, 32] which change the salinity of those lakes. Therefore, it is an environment of a high chemical and physical variability.

The contents of nitrogen in the traps exceed on average 4 times the amount of nitrogen in potential sedimentation measured as phytoplankton nitrogen consumption. Similar results were obtained by [2], and by [21], where the contents of the traps exceeded the potential sedimentation 6.3 and 5 times respectively. Direct measurement of nutrient sedimentation resulting from the decay of plankton is extremely difficult in those conditions.

CONCLUSIONS

- Lake Gardno is a water body retaining about 30% of nitrogen and 20% of phosphorus of their total amount carried into the lake. The outer load of nutrients originates mainly from the land; the amount originating from the sea and from the atmosphere is comparatively small.
- In 2002, the reduction of nitrogen in the lake resulted in 47% from denitrification and in 53% from accumulation in bottom sediments.

- Changes occurring in Lake Gardno are affected mainly by upward movement of bottom sediments caused by water turbulence due to strong winds.
- The amount of nutrients carried up and down in result of water mixing outweighs to a great extent the amount resulting from primary production and accumulation in bottom sediments.
- Lake Gardno is a brackish ecosystem with fortuitous changes in the level of salinity. Transparency of water and concentration of nutrients undergo strong periodical changes. Sedimentation of nutrients was most intense in the autumn, while their most intensive release was observed in the summer. The yearly average rate of sedimentation was 2.53 mg P $m^{-3}d^{-1}$ and 21.5 mg N $m^{-3}d^{-1}$.
- Lake Gardno is an aquatic polymictic ecosystem with a considerable level of eutrophication.

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