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Reservoir Fishery Management and Development in Asia

Proceedings of a workshop
held in Kathmandu, Nepal,
23–28 November 1987



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ABSTRACT

This publication presents the results of an IDRC-funded workshop held in Kathmandu, Nepal, 23-28 November 1987. Representatives from 15 countries reviewed the status of reservoir fishery research in Asia under the following topics: existing fisheries, limnological aspects, biological and resource aspects, management aspects, and culture. Papers were presented on these topics, but the discussion sessions were the main element of the workshop. Summaries of these discussions as well as a series of general recommendations that were generated during the final discussion are presented in this book. The potential for increased fish production in reservoirs and the need for early involvement of fisheries scientists in the planning and preimpoundment studies before dam construction are emphasized.

RÉSUMÉ

Cet ouvrage présente les résultats d'un atelier financé par le CRDI à Katmandou, au Nepal, du 23 au 28 novembre 1987. Des représentants de 15 pays ont examiné l'état de la recherche sur l'élevage du poisson en étangs en Asie, en particulier les aspects suivants : les systèmes actuels, les aspects limnologiques et biologiques, les ressources, la gestion et l'élevage. Des exposés ont été présentés sur ces sujets, mais les discussions ont été l'élément le plus important de l'atelier. L'ouvrage présente également un résumé des discussions ainsi que les recommandations générales issues de ces discussions. On met l'accent sur la possibilité d'augmenter la production de poissons en étangs et la nécessité pour les ichtyologistes de participer très tôt aux études de planification, notamment de la mise en étangs du poisson, qui précèdent la construction d'un barrage.

RESUMEN

Esta publicación presenta los resultados de un taller auspiciado por el CIID en Kathmandu, Nepal, del 23 al 28 noviembre de 1987. Representantes de 15 países analizaron el estado de la investigación sobre pesquería asiática en embalses desde los siguientes ángulos: pesquería existente, aspectos limnológicos, aspectos biológicos y de recurso, aspectos de manejo y cultivo. Las ponencias versaron sobre estos temas, pero las sesiones de discusión fueron el principal elemento del taller. Este libro ofrece los resúmenes de estas discusiones, así como una serie de recomendaciones generales emanadas de la discusión final. Se subraya el potencial para incrementar la producción pesquera en embalses y la necesidad de una participación temprana de los científicos del área en la planificación y los estudios de apropiación que anteceden a la construcción de represas.

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NUTRIENT CYCLING IN TROPICAL ASIAN RESERVOIRS: SOME IMPORTANT ASPECTS WITH SPECIAL REFERENCE TO PARAKRAMA SAMUDRA, SRI LANKA

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Abstract General aspects of phosphorus and nitrogen cycling are discussed in this paper. In the temperate region, lakes are found mostly to be phosphorus limited. Based on information derived from primary production and some nutrient-enrichment experiments for a few African lakes, it was postulated that tropical lakes are nitrogen limited. Experiments conducted with radiophosphate in some African lakes, however, provided strong evidence for the existence of P-limited lakes. Investigations carried out in Parakrama Samudra, Sri Lanka, a reservoir with very low soluble reactive phosphate (SRP) level (average, 9-12 $\mu\text{g/L}$) indicated the existence of a diel phosphate cycle. The phosphate deficiency indicators measured included alkaline phosphatase activity (PA) and changes in the algal internal P-pool measured as labile phosphate (LP). Because of the enhanced phosphatase activity during the period of maximum production (1200-1500), a depletion of the soluble phosphate level was observed with a parallel increase in the SRP concentration. There appears to be an inverse relationship between the above P-deficiency indicators and the phosphate level in lake water during the day. Experiments carried out with radioactive tracers showed fast turnover rates from 1 to 3 min. Gel filtration analyses of labeled soluble phosphate (SP) indicated the presence of a larger fraction of high molecular weight P bound as colloidal P during midday, which is not readily available. All this evidence show clearly a P-deficient situation in the lake, which can limit primary production. In comparison with overlying water, the sediment nutrient content is higher by two orders of magnitude and mineralization processes seem to play an important role. Because of the resuspension of sediments, a larger proportion of the benthic mineralization is shifted to the pelagic zone. Combined pelagic and sediment-water interface mineralization serve as important mechanisms for the replenishment of the dissolved nutrient pool.

The biological processes occurring in a water body are greatly influenced by the chemical environment. Some of these processes involve energy interconversion, ultimately leading to the production of organic compounds; nutrients play a key role in regulating the rate and pattern of this energy flow through the aquatic ecosystem. Primary production links carbon assimilation and element incorporation into the tissue; it is influenced by both biotic and abiotic factors. At the organism level, the energy to drive nutrient cycles is derived from carbon, which also provides the skeleton to store other elements.

In aquatic ecosystems, plant growth relies on the availability of some 20 nutrient elements, of which the majority are required to trace amounts (Reynolds 1984). The movement of these elements and inorganic components from one compartment (pool) to another in the system is referred to as nutrient cycling. Nutrient dynamics determine the fundamental environmental conditions governing the primary and, thus, the overall biological production. Oxygen, carbon, nitrogen, and phosphorus are required in large amounts; P and N are considered to be the most essential nutrients for plant growth. The short supply of any one of these nutrients leads to limited growth (Likens 1972). In most aquatic systems in the temperate region, the limiting nutrient is phosphorus (Vollenweider 1968; Fricker 1980); to a smaller degree, nitrogen is also limited (Golterman 1975).

A great deal of work has been done on temperate lakes and reservoirs but such investigations are lacking for the tropics. The work done on nutrient cycles during the International Biological Programme (IBP) in Africa (Viner 1973, 1975; Peters and MacIntyre 1976) clearly emphasized the features that make tropical aquatic ecosystems different from temperate aquatic ecosystems. So far, little attention has been paid to detailed investigations on nutrient cycling in tropical Asian reservoirs (Gunatilaka 1980). There is some sparse information available on nutrient cycling in Laguna de Bay, a shallow brackish water lake in the Philippines (Barica 1976; Bautista 1983), Sankey tank in South India, and Nakhaupatna pond in North India (Ayyappan et al. 1986). Gunatilaka (1983, 1984) and Gunatilaka and Senaratna (1981) discuss in detail the nutrient dynamics in Parakrama Samudra, an ancient man-made reservoir in Sri Lanka, during the dry and wet seasons. As there is detailed limnological information available on this reservoir (Schiemer 1983), it is used as a model study here to discuss nutrient cycling in reservoirs in the tropical Asian region.

Nutrient Cycling

Golterman (1975) summarized the phosphorus and nitrogen cycles in lakes schematically by phosphorus and nitrogen flow diagrams (Figs. 1 and 2). In Fig. 1, the recycling of phosphorus through the biological compartments and the sediments are shown with arrows indicating the direction of flow. Phosphorus is supplied by the surrounding inputs and parent geological material. Exchange of phosphorus between the dissolved and particulate compartments is a dynamic process and the supply and rate of cycling of P controls the size of the biological and organic components. If phosphate is present above growth-limiting levels, it may lead to luxury uptake in algae (Kuenzler 1970) and be stored as polyphosphates. The ratios between cellular carbon and phosphorus are more or less constant and according to Redfield et al. (1963). For marine algae this ratio is around 106:1; for most IBP lakes, 50:100; for phosphate-limited phytoplankton, around 60:1 (Golterman 1975). During primary production, if the phosphate supplies are low, mineralization has to occur either in the water column or at the bottom (Fig. 1) to supplement the demand. The phosphate recycling in the water column (central part of the Fig. 1) is referred to as an "internal" or "metabolic" P cycle. The phosphate recycling through the sediments is known as a "geochemical" or "external" P cycle and various aspects of it are dealt with in Golterman (1977).

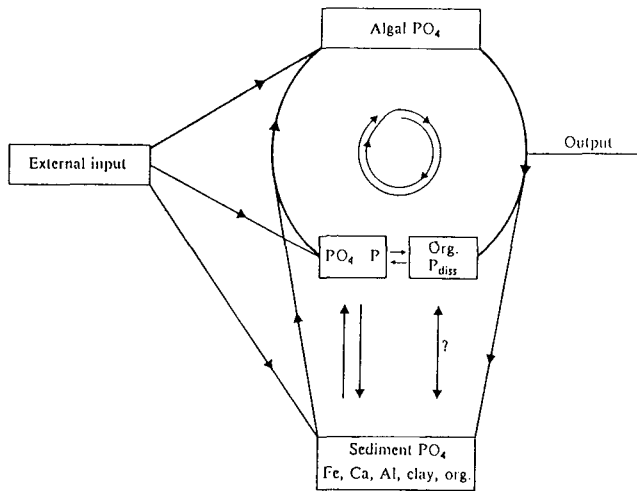


Fig. 1. Phosphate flow diagram visualizing the recycling of phosphate through the biological compartments (adapted from Golterman 1975).

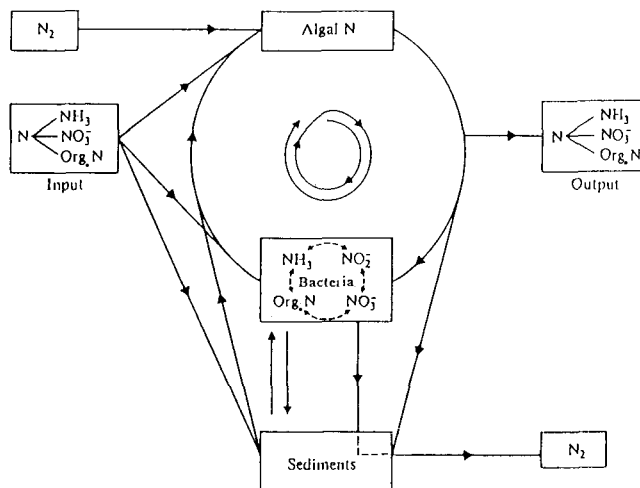


Fig. 2. Schematic representation of the nitrogen cycle (adapted from Golterman 1975).

For nitrogen, the primary source is the atmosphere (Fig. 2). The nutrient cycling, whose source of energy is carbon, is controlled by phosphorus. The main differences between the nitrogen and phosphorus cycles are twofold. First, nitrogen may enter and leave the cycle as gaseous nitrogen through fixation and denitrification, respectively (which make nitrogen budget calculations more complicated). Second, amino acids provide an important part of the energy available to bacteria and to zooplankton that assimilate algae.

Inorganic sources of N for algae are ammonia, nitrates, and gaseous nitrogen in cases where N fixation occurs. Cyanobacterial

nitrogen fixation is generally accepted as one of the major factors controlling primary production in N-limited environments. The fixed nitrogen in aquatic environments is readily oxidized and reduced by biologically catalyzed reactions. The uptake of inorganic nitrogen is dependent on carbon sources, either from active photosynthesis or from heterotrophic growth from carbon accumulated during photosynthesis under N deficiency. The algal nitrogen content will be up to 10% of the dry weight and, after the death of algae, a rapid mineralization will occur, mostly by bacterial action. By this process, nitrogen is liberated mainly as ammonia with some organic nitrogen compounds. The phytoplankton preference of ammonia as a nitrogen source is well documented (Reynolds 1984) and Viner (1973) reports that in Lake George (Uganda) ammonia compounds were used by algae rather than nitrate.

Talling and Talling (1965), based on their observations of East African lakes, suggested nitrogen could be a limiting factor in tropical waters. Subsequently, P- and N-enrichment experiments carried out with natural plankton in Lake Chilwa (Moss 1969) and Lake George (Viner 1973) showed that nitrogen produced a greater stimulus to algal production than did phosphorus. Similar experiments in reservoirs in Brazil, the vazeza Lago Jacartinga (Zaret et al. 1981), Lake Titicaca (Wurtsbaugh et al. 1985), and turbid waters of the Amazon River (Grobbelaar 1983) demonstrated the relative importance of nitrogen. However, rapid rates of radiophosphate turnover have been recorded (Peters and MacIntyre 1976) for some East African lakes (Table 1). A similar situation is reported for Parakrama Samudra, Sri Lanka (Gunatilaka 1983; Gunatilaka 1984), indicating a phosphorus limitation. Nutrient enrichment experiments in Lake McIlwaine, Lake Kariba, and three other man-made reservoirs in Zimbabwe, phosphorus appeared to show a great stimulus (Robert and Southall 1977).

Nutrient Cycling in Parakrama Samudra

Parakrama Samudra, in Sri Lanka, is one of the larger reservoirs (22 km²) of an ancient (386 A.D.) irrigation system. The reservoir is located in the north central province (7°55' N, 81° E, 58 m above sea level) at Polonnaruwa within the dry zone; the seasonal hydrological regime reflects the monsoonal cycle and the irrigation demands for rice cultivation in the district. A comprehensive account of the limnology of the lake is given in Schiemer (1983).

According to the lake classification scheme of Vollenweider (1968), Parakrama Samudra could be described as a highly eutrophic lake. The nutrient loading of the lake is mainly a result of comparatively high nutrient content of the inflow, runoff from the catchment area (especially during monsoonal periods), cattle droppings and human wastes in dry falling zones of the lake, the impact of birds (especially cormorants), and dry precipitation. The dissolved nutrient concentrations measured in lake water, however, are relatively low (0-6 µg/L premonsoon; 3-6 µg/L postmonsoon). As SRP concentration is relatively low, the high primary production rates recorded for the lake (Dokulil et al. 1983) are indicative of an efficient P-recycling mechanism.

Diurnal measurements of phosphate deficiency indicators such as inducement of phosphatase activity (PA), changes in the algal internal

Table 1. Rate constants for orthophosphate incorporation (k) and PO_4^{3-} turnover times (tt) in Parakrama Samudra, Sri Lanka, and some Sri Lankan lakes.

Date (day-month-year)	Lake ^a	Time (h)	k (min^{-1})	SRP ($\mu\text{g/L}$)	tt (min)
Sri Lanka^b					
27-7-1982	PSN	1300	0.713	4	1.41
30-7-1982	PSN	1300	0.788	5	1.27
31-7-1982	PSN	1300	0.780	4	1.31
10-8-1982	PSM	1300	0.761	6	1.31
12-8-1982	PSN	0700	0.330	9	3.02
Kenya^c					
28-6-1974	Elementeita		1.50	<3	0.66
26-6-1974	Naivasha, main basin		1.00	<3	1
27-6-1974	Naivasga Crater		0.20	<3	5
24-6-1974	Nakuru		0.0029	23	345
25-6-1974	Nakuru		0.0014		714
30-6-1974	Nakuru		0.0010		1000
17-7-1974	Nakuru		0.0039	7	256
26-6-1974	Crescent Island Crater		0.0000	117	

^aPSN, Parakrama Samudra north; PSM, Parakrama Samudra middle.

^bGunatilaka (1984).

^cPeters and MacIntyre (1976).

P pool measured as labile phosphate (LP), as well as soluble reactive phosphate (SRP), soluble phosphate (SP), soluble unreactive phosphate (SUP), and particulate phosphate (PP), have shown the existence of a diel phosphate cycle (Table 2). The higher phytoplankton and bacterial biomass (Table 2) and production during the period of maximum light intensity would have contributed to the distinct diel patterns of SRP, SP, SUP, LP, and PA in the water column. The diel changes in these parameters indicate the varying external conditions as well as the physiological conditions of the phytoplankton and microbial populations. The slow disappearance of SP during the period of highest production may be due to the high SRP demand. This is evident from the increase of PA in the water column. It is probable that some of the SUP is hydrolyzed as a result of the increased enzymatic activity, which is reflected by the drop in the SP level. The ability of the phytoplankton to hydrolyze dissolved organic phosphate compounds and inorganic polyphosphates is well documented. The slight drop in LP at midday corresponds to the depletion of the internal algal P pool at the time of maximum production. In Parakrama Samudra, there appears to be an inverse relationship between external inorganic phosphate concentration and both phosphorous deficiency parameters: the labile P (LP) and phosphatase activity.

Radiophosphate uptake experiments with lake water showed fast turnover rates (Table 1, Fig. 3) and the large rate constants demonstrate dynamic exchange between particulate phosphate and soluble reactive phosphate (SRP). A turnover time of around 1 min measured during the peak production period clearly indicates that the algal and bacterial populations are P deficient. Gel filtration analysis of

Table 2. Diel changes in soluble reactive phosphate (SRP), soluble phosphate (SP), particulate phosphate (PP), labile phosphate (LP, measured as hot water extractable P), total and dissolved phosphatase activity (PA-T and PA-D, respectively), and total bacterial counts (TB) at station 14, Parakrama Samudra north, 6 August 1982.

Time (h)	Depth (m)	SRP ($\mu\text{g/L}$)	SP ($\mu\text{g/L}$)	PP ($\mu\text{g/L}$)	LP ($\mu\text{g/L}$)	PA-Ta	PA-Da	TBb
0630	0.5	4	28	49	11	0.55	0.14	13
	1.0	4	22	39	9	0.73	0.03	16
	1.5	3	34	57	9	0.79	0.07	18
	2.3	4	34	58	10	0.74	0.13	25
0930	0.5	6	26	54	13	0.12	0.12	34
	1.0	5	29	64	11	0.07	0.07	18
	1.5	3	31	70	8	0.08	0.08	29
	2.3	5	28	50	8	0.14	0.14	32
1230	0.5	12	22	59	6	0.64	0.64	44
	1.0	2	23	66	4	0.15	0.15	38
	1.5	2	23	66	4	0.12	0.12	54
	2.3	6	28	51	8	0.10	0.10	18
1530	0.5	8	18	46	4	0.13	0.13	46
	1.0	8	16	76	4	0.11	0.11	59
	1.5	5	16	56	5	0.13	0.13	63
	2.3	9	10	46	4	0.13	0.13	36
1830	0.5	8	24	62	8	0.09	0.09	40
	1.0	4	32	59	8	0.15	0.15	38
	1.5	9	34	64	11	0.07	0.07	44
	2.3	6	33	37	9	0.07	0.07	34

(continued)

Table 2. Concluded.

Time (h)	Depth (m)	SRP ($\mu\text{g/L}$)	SP ($\mu\text{g/L}$)	PP ($\mu\text{g/L}$)	LP ($\mu\text{g/L}$)	PA-Ta	PA-Da	TBb
2400	0.5	9	24	44	7	0.08	0.08	26
	1.0	26	32	71	9	0.07	0.07	33
	1.5	24	36	74	10	0.07	0.07	17
	2.3	17	32	53	9	0.07	0.07	9
0600	0.5	4	32	47	8	0.12	0.12	22
	1.0	8	38	56	10	0.07	0.07	22
	1.5	4	34	63	13	0.11	0.11	17
	2.3	8	34	58	11	0.08	0.08	12

^aAlkaline phosphatase activity: micromoles PNPP hydrolyzed per hour per milligram protein (lake samples).

^bTotal bacteria $\times 10^5$ per millilitre.

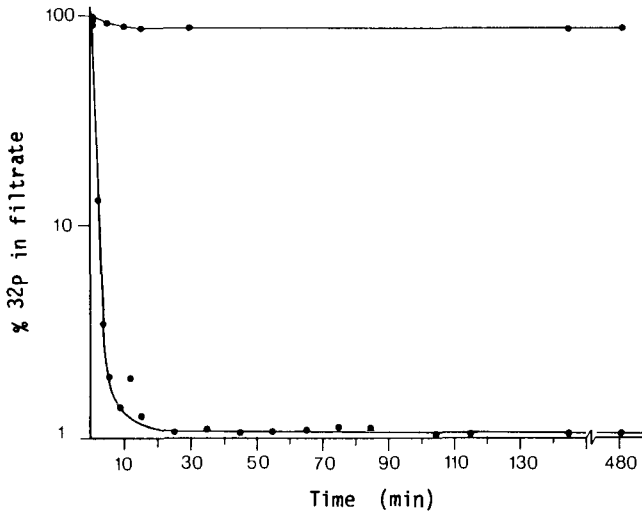


Fig. 3. $^{32}\text{P}_04$ uptake kinetics in Parakrama Samudra showing the percentage $^{32}\text{P}_04$ remaining in solution after addition to an integrated lake water sample from 0 to 1.5 m depth (station 14, Parakrama Samudra north). Distilled water was used as the control.

labeled soluble P suggested that a large fraction (ca. 70%) of it is high molecular weight P (Fig. 4). This shows that much of the dissolved P in the lake water is colloiddally bound and, therefore, not readily available to the plankton. In lakes with high colloidal levels, phosphate movements may differ from the scheme proposed by Lean (1973a,b).

In Lake George, Viner (1975) pointed out the importance of resuspended sediments for nutrient cycling. According to the investigations of Bauer (1983), in Parakrama Samudra, convective currents produced by thermal events appear to play an important role. Strong water currents will erode the uppermost layers of sediments and, as a result, a part of the benthic mineralization is shifted into the pelagic zone (Newrkla 1983). In Parakrama Samudra, the ratio of pelagic to benthic mineralization is 9:1. The oxygen supply to the sediments stimulates the benthic community metabolism, leading to increased metabolic rates, which imply faster decomposition of organic matter and recycling of much-demanded nutrients for primary production. Thus, 90% of the primary production is compensated for by pelagic decomposition processes; the remaining 10% is respired at the sediment surface (Newrkla 1983).

According to Hargrave (1973), benthic oxygen consumption is quantitatively related to the flux of oxidizable organic matter to the sediment and he derived an expression to calculate the photosynthetically fixed carbon respired at the sediment surface. The mineralization rates calculated using this relationship are given in Table 3. The contribution from the mineralization indicates the importance of nutrient flux from sediments in Parakrama Samudra to a nutrient-poor water column. This is in contrast to the findings of Viner (1977) in Lake George.

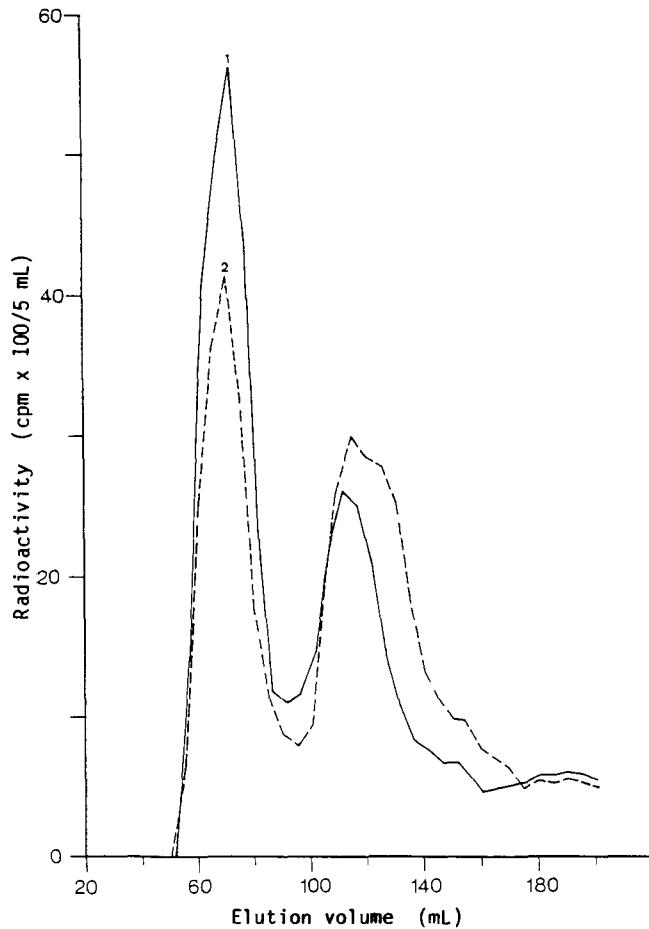


Fig. 4. Sephadex gel (G 25) filtration of filtrates after 30 min equilibration with $^{32}\text{P}\text{O}_4$. The peak (colloidal P) occurs from 51 to approx. 91 mL (void volume; MW, 5000). Curves 1 and 2 are from integrated lake water samples from 0 to 1.5 m at station 14, Parakrama Samudra north, collected at midday and morning, respectively.

Conclusions

The following features of Parkrama Samudra ecosystem bear direct relationship to nutrient cycling: comparatively low nutrient concentration in lake water; high algal biomass; and high sediment nutrient content. Because the dissolved nutrient concentrations are low, dependence on internal recycling of nutrients. According to Viner (1973) in Lake George, the primary production keeps pace with combined mineralization and influent rates; a similar situation is encountered in Parakrama Samudra.

In comparison to overlying water, the sediment nutrient content is higher by two orders of magnitude. This implies that large amounts of nutrients are buried in the sediments. The total phosphorus (TP)

Table 3. Predicted sediment-water nutrient flux in Parakrama Samudra calculated by coupling to primary production and in site benthic respiration measurements.

Location	Respiration rate (mg/m ² per h) ^b	Mineralization of carbon in sediment (mg C/m ² per h)	Rate of release of ammonia from sediment (mg NH ₄ /m ² per h)	Rate of release of phosphate from sediment (mg PO ₄ /m ² per h)
PSN, station 1	24.55-35.93	3.12-3.23	0.25-0.29	0.016-0.018
PSN, station 8	31.76-36.87	2.86-3.32	0.24-0.27	0.015-0.017
Middle of lake	46.79-51.05	4.21-6.84	0.33-0.53	0.021-0.033
Average values				
PSN	34.92	3.14	0.26	0.016
PSM	69.30	4.42	0.34	0.021
PSS	68.00	4.34	0.35	0.022

^aPSN, PSM, and PSS: Parakrama Samudra north, middle, and south, respectively.

^bNewricka (1983).

content is around 1:5 mg/g dry weight. Organic phosphate accounts for 1/5 of the TP and the concentration drops with depth (at 15 cm, a reduction of 45-50%). This indicates that the organic phosphate is actively mineralized to supplement the depleted dissolved P pool. The alkaline phosphatase activity measured was three times higher than in water but decreased with depth (parallel to the drop in P concentration). All these observations show that mineralization processes are playing an important role in the flux of phosphorus from the sediments. The total nitrogen content of the surface sediments is 16-18 mg/g and a decrease of 29-36% was observed with depth. Although there are slight fluctuations in N:P, C:P, and C:N ratios, they lie within the values described in the literature from eutrophic lakes. The high algal biomass seems to contribute toward the autochthonous sedimentation and is evident from the high N:P ratios and C values recorded for sediments in the upper 5 cm, (N:P ratio approaches 15:1, which is similar to that of algae).

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