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SEDIMENTARY PHOSPHORUS DYNAMICS IN EPICONTINENTAL SYSTEMS: A LITERATURE REVIEW

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SUMMARY

Sedimentary phosphorus dynamics being a very complex process involving a large number of different mechanisms, literature data present a wide range of variations both from the quantitative and from the qualitative point of view. Three main aspects are considered in this paper: the range of sedimentary phosphorus observed in lakes worldwide and relationships with other lake characteristics such as trophic status, depth, sedimentary iron and organic matter; phosphorus release rates and factors controlling them, and forms in which phosphorus is bound in sediments and their ecological significance. Because of the complexity of the mechanisms involved, no general conclusions valid for any kind of lakes may be drawn on the basis of the information now available.

KEY WORDS: Sedimentay phosphorus, lake trophy, release rates, fractionation, NAI-P, AI-P, organic-P.

INTRODUCTION

There is now little doubt about the major role played by phosphorus in the eutrophication process of natural waters. From the classical papers of EINSELE (1936, 1937, 1938) and MORTIMER (1941, 1942), many workers have demonstrated the importance of the sediment as source or sink for water phosphorus. A great volume of investigation has focussed on the quality and quantity of sediment phosphorus and on the process affecting its exchange between bottom and water. A good example of this interest is the high proportion of studies involving aspects related to phosphorus presented at several International Congresses on Interactions between Sediment and Water (GOLTERMAN, 1977a; SLY, 1982). In spite of this, however, the variety and complexity of factors influencing sedimentary phosphorus behavior has not yet led to a global interpretation of its dynamics.

Many different approaches have been used in the study of phosphorus in sediments. Among the major ones, three may be considered:

A) Studies that mainly focus on vertical or horizontal variations of phosphorus concentrations in sediments of one or more lakes. Other lake or sediment characteristics are also studied simultaneously in order to establish relationships between different lake descriptors.

B) Studies on phosphorus release rates and the factors controlling them. This approach has received major attention in recent years because release from sediments seems to be one of the major processes

TABLE I. Total phosphorus concentrations in the sediment and trophic status of worldwide lakes. o: oligotrophic. om: oligomesotrophic; m: mesotrophic; me: meso-eutrophic; e: eutrophic; h: hypereutrophic. vv: vertical variation; hv: horizontal variation; lv: interlakes variation; tv: temporal variation. Values in mg P kg^{-1} dw. *, Poland, Italy, Finland, Canada, USA, Japan. **, Poland, Italy, Japan. ***, Poland, Italy, Finland, USA, Malawi, India, Japan.

Lake	Trophic status	Study	TP	Reference
Char, Arctic	o	hv	570- 620	26
E.L.A. (16), Canada	o	lv	1300-3300	11
Ennerdale, England	o	vv	600-2300	25
Weber, U.S.A.	o	vv	2710-3950	8
Mowich, U.S.A.	o	vv	750-2170	21
Florida (8), U.S.A.	o	lv	100-1100	13
Worldwide (9) *	o	lv	910-4060	16
Maggiore, Italy	om	-	1470	16
Wisconsin (2), U.S.A.	om	vv,lv	894-9940	8
Poland (2)	m	lv	1100-1400	38
Wuras Dam, South Africa	m	hv	5000-11000	19
Lucerne, Switzerland	m	vv	400-1700	5
Winnipeg, U.S.A.	m	vv,hv	380-740	1
Worldwide (3) **	m	lv	1010-1600	16
Mulwala reservoir, Australia	me	hv	350-1188	17
Little John, U.S.A.	me	vv	3880-12100	8
Australia (3)	e	lv,hv	378-1760	33
Austria (2)	e	lv	258-705	27
Wabamun, Canada	e	hv	1700-2300	30
Denmark (6)	e	lv	800-8000	3
Pluβsee, Germany	e	tv	1460-2260	15
Kinnereth, Israel	e	vp	1000-4500	32
Lugano, Italy	e	hv	1000-4500	29
Nakanoumi, Japan	e	vv	500-1200	39
Poland (3)	e	lv	1500-2700	38
Coastal lagoons, Spain	e	lv	300-1000	23
Spanish reservoirs (2)	e	lv	350-1190	22
Lilla Ullevifjarden, Sweden	e	hv	1000-2000	31
Rotsee, Switzerland	e	hv	1000-1200	5
Long Lake reservoir, U.S.A.	e	vv	1000-4700	35
Mendota, U.S.A.	e	vv	850-1630	7
Monona, U.S.A.	e	vv	950-2000	9
Potomac Estuary, U.S.A.	e	vv,hv	310-1860	12
Worldwide (10) ***	e	lv	900-3050	16
Esrom, Denmark	h	hv	2440-6380	18
Sobygaard, Denmark	h	vv	2000-12000	34
Poland (3)	h	lv	2200-3700	38
La Massona, Spain	h	vv	496-1022	24

involved in eutrophication, and may thus be taken into account in protection and restoration programs.

C) Studies on chemical fractions in which phosphorus is bound in sediments. The contradictory results observed, when comparisons between sediment or lake characteristics are made, and when factors controlling release rates are evaluated, have led to the conclusion that the chemical speciation of phosphorus is almost certainly among the more important factors regulating phosphorus dynamics.

These three approaches will be considered in the next sections.

TOTAL PHOSPHORUS IN SEDIMENT RELATED TO OTHER LAKE AND SEDIMENT CHARACTERISTICS

The concentrations of total phosphorus observed in the sediments of lakes around the world are highly variable, as can be observed in Table I, where values reported by different authors have been summarised. The range of variation has similar magnitude when concentrations are compared at various levels of a vertical profile, at various sites of one lake or at different lakes (see Table I for references). There is little information about temporal changes of sedimentary phosphorus, but the results observed at Lake Plußsee (GOLACHOWSKA, 1979) and in Spanish reservoirs (MORGUÍ & LÓPEZ, unpublished data) also show wide variation.

Numerous attempts have been made to relate the variation of sedimentary phosphorus to other lake or sediment characteristics, but until present no general relationships valid for any lake have been found.

Because of the relation between water phosphorus and eutrophication, a similar relation between sedimentary phosphorus and trophic status of lake could be suspected. Although some authors have reported higher concentrations of total phosphorus in eutrophic sediments than in oligotrophic sediments (FLANNERY *et al.*, 1982; WISNIEWSKY & PLANTER, 1985), a general relationship between these two variables cannot be established when lakes from different regions are considered. For example, GOLACHOWSKA (1984) found similar values of total phosphorus in the sediments of oligotrophic Lake Char (an Arctic lake) and in eutrophic Lake Chilwa (a tropical African lake). From the literature data compiled in Table I, no relation can be deduced.

In a few cases, sedimentary phosphorus has been related to water depth. Results are not conclusive, since both significant (RYDING & BORG, 1976) and non-significant (KAMP-NIELSEN & HARGRAVE, 1978; KEULDER, 1982) correlations have been found. Data from the literature has been plotted in figure 1, in order to evaluate this relationship in a wide variety of lakes. As can be observed, sedimentary phosphorus is not dependent on water depth, when different lakes are

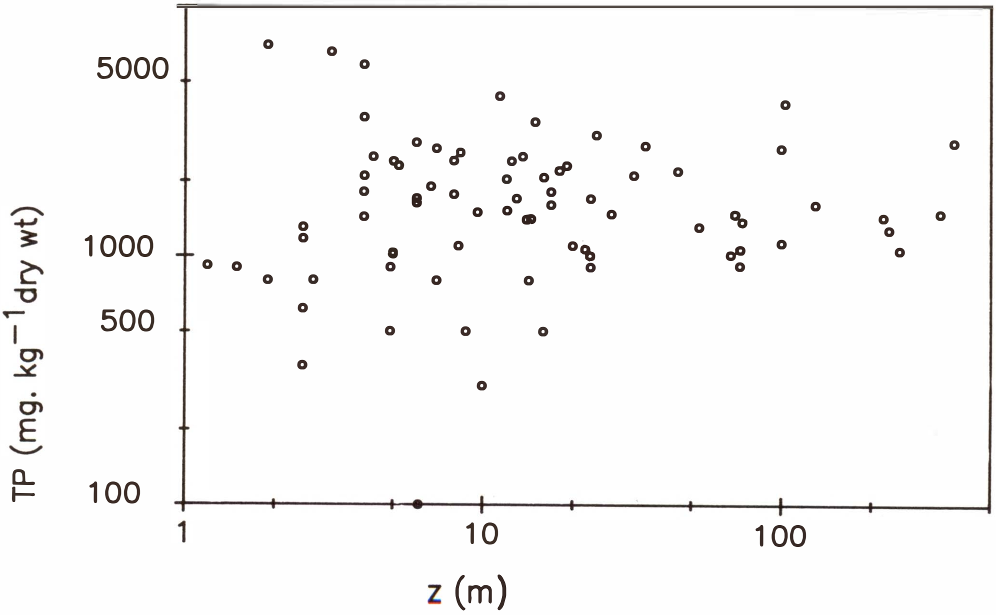

FIGURE 1. Relationship between total phosphorus concentration in sediment and water depth (z). (Data from BORTLESON & LEE, 1974, 1975; BRUNSKILL *et al.*, 1971; FLANNERY *et al.*, 1982; GOLACHOWSKA, 1984; KEMP *et al.*, 1978; KLAPWIJK *et al.*, 1982; SLATER & BOAG, 1978).

taken into account.

The concentrations of iron in sediment is among the variables most frequently studied in relation to sedimentary phosphorus, because of the chemical association between these two compounds revealed by EINSELE (1936, 1937, 1938) and MORTIMER (1941, 1942). Water phosphorus can precipitate associated to ferric hydroxides and then it can be released into solution under favorable conditions. Nevertheless, the results observed are very contradictory. High correlation between phosphorus and iron has been noticed for vertical variation in eutrophic lakes (BORTLESON & LEE, 1972, 1975; LÓPEZ, 1986b), for horizontal variations in oligo- and mesotrophic lakes (ALLAN & BRUNSKILL, 1977; KEMP *et al.*, 1978) and for interlake variations (BRUNSKILL *et al.*, 1971; SHUKLA *et al.*, 1971). In contrast, no significant correlation has been reported by other authors in similar conditions: for vertical profiles of both oligo- and eutrophic lakes (MACKERETH, 1966; BORTLESSON & LEE, 1974; THOMAS & SOLTERO; 1977; CROSS & RIGLER; 1983), horizontal variations (PREMAZZI & RAVERA, 1977) or interlake variations (FLANNERY *et al.*, 1982; LÓPEZ, 1986a). One cause of these contradictory results could derive from the fact that usually only small groups in lakes with similar characteristics are considered. OSTROFSKY (1987) studies this relationship in 66 very different lakes of North America, reporting a significant correlation by using a logarithmic transformation of phosphorus values ($r = 0.58$, $p < 0.01$). Literature data for 78 lakes (Ostrofsky values are not included) have been plotted in figure 2, where shallow (< 10 m) and deep (> 10 m) lakes are clearly distinguishable. A weak but significant correlation has been found for shallow lakes ($r = 0.36$, $p < 0.05$), whereas for deeper lakes correlation becomes non-significant ($r = 0.21$). This is in agreement with the observation made by SLY (1977) that in shallow sediments the

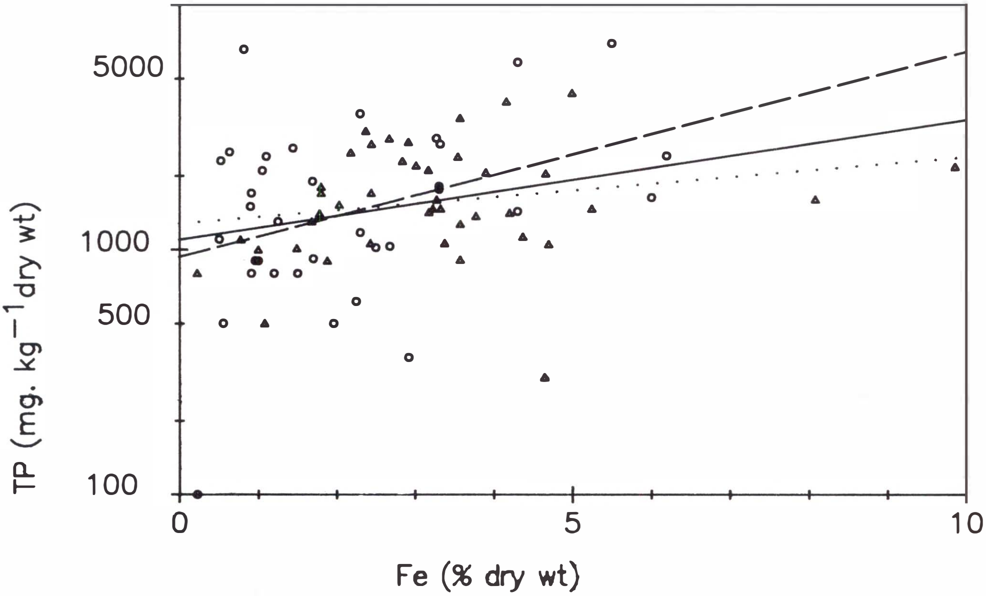

FIGURE 2. Relationship between total phosphorus and total iron concentrations in sediments. Data from the same sources as in figure 1. Circles and dashed line correspond to lakes with depth lower than 10 m; triangles and dotted line, to deeper lakes.

quotient Fe/P remains constant, but in deeper sediments phosphorus should appear closely related to organic carbon. However, it must be noted that correlation between sedimentary phosphorus and organic matter has been found both in shallow and deep lakes (BRUNSKILL *et al.*, 1971; HART *et al.*, 1976; PREMAZZI & RAVERA, 1977; LARSON *et al.*, 1976; REYNOLDSON & HAMILTON, 1982; FLANNERY *et al.*, 1982), non-significant values being reported less frequently (KAMP-NIELSEN & HARGRAVE, 1978; KEMP *et al.*, 1978).

Calcium is another element that can play an important role in phosphorus dynamics. Precipitation of phosphorus adsorbed on calcium carbonate surfaces has been demonstrated (KUO & LOTSE, 1974) and GOLTERMAN (1982a) has also suggested a direct precipitation as apatite. However, the relationship between calcium and sedimentary phosphorus has not been studied in terms of total concentrations but in terms of phosphorus species and will be discussed later.

PHOSPHORUS RELEASE

Phosphorus release (often called internal phosphorus loading) is defined by the net flux of phosphorus from sediment to lake waters, which occurs when solubilization and upwards transport exceed phosphorus sedimentation. Since the phosphorus concentration in sediment is much higher than in lake water, phosphorus release can enhance the eutrophication of lakes. So, internal phosphorus loading is an important factor that must be taken into account in the prediction models used to provide the basis of lake restoration programs.

Two strategies have been used to estimate phosphorus release. One is the experimental approach where fluxes are studied in the field or in the laboratory. With the other strategy, phosphorus release is determined by mass balance calculations in whole lakes.

The magnitude of phosphorus release has been related to lake trophic status. NURNBERG *et al.* (1986) have established

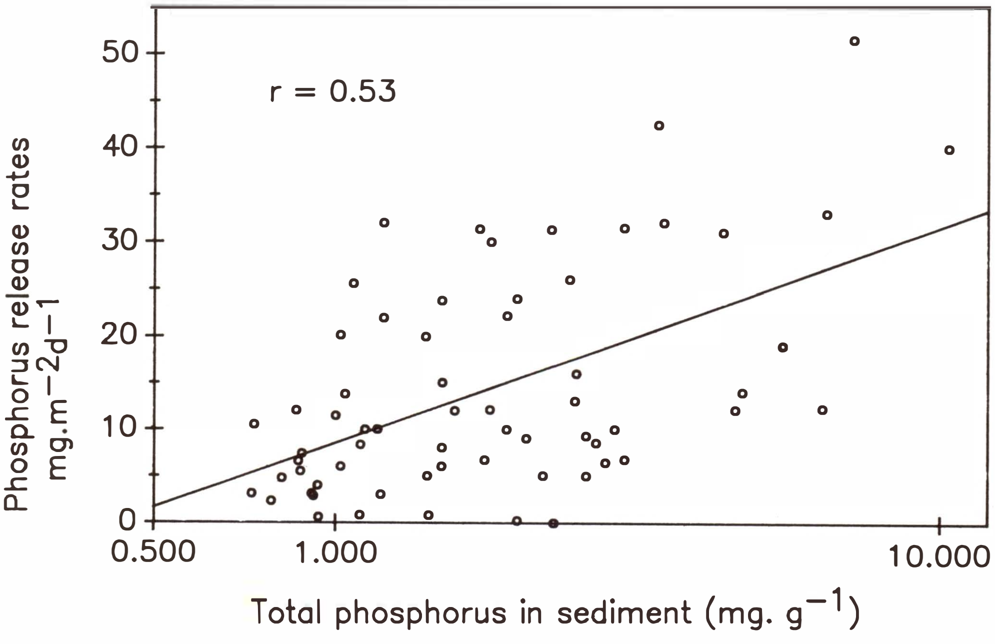

FIGURE 3. Relationship between total phosphorus concentration in sediment and phosphorus release rates. Data from NURNBERG (1988).

a dependence of phosphorus anoxic release rates on water phosphorus concentrations in 56 lakes from the literature (r = 0.50). Oligrotrophic lakes show anoxic release rates below 1 mg m^{-2} d^{-1}, whereas in eutrophic lakes values up to 50 mg m^{-2} d^{-1} can be observed (NURNBERG, 1988).

Several authors have also looked for a correlation between total phosphorus concentration in sediment and phosphorus release rates. BOSTROM (1984) did not found such a correlation, but NURNBERG (1988) reported a regression line PR= -5.59 + 0.0079 TP (r^2 = 0.53, n=14) for several North American lakes. In figure 3, literature data in lakes worldwide compiled by NURNBERG (1988) have been plotted in a semilogarithmic graph. A weak correlation can be observed using a logarithmic transformation of TP values, but the range of variation is very wide and the relation observed cannot be used for prediction purposes.

In the last decade, several articles have reviewed the phosphorus release concept (BOSTROM *et al*., 1982; RYDING, 1985; NURNBERG, 1988; JANSSON *et al*., 1988). Different mechanisms have been suggested as main factors influencing the rates of phosphorus release: redox conditions, pH, water temperature, mineralization, nitrate concentration, bioturbation, effects of macrophytes and periphytic biolayer, diffusion and wind turbulence and different sediment characteristics.

CHEMICAL FACTORS AFFECTING PHOSPHORUS RELEASE

The best documented mechanism of phosphorus release involves the chemical reduction of Fe(III) to Fe(II). The works of EINSELE (1936, 1937, 1938) and MORTIMER (1941, 1942) pioneered this interpretation. Since iron reduction occurs under anaerobic conditions, it was suggested that phosphorus release would be only significant in lakes with stagnant anaerobic bottom waters. On the basis of this, aerobic sediments had been regarded as exclusively phosphorus sinks (HAKANSON & JANSSON, 1983). In laboratory and/or field experiments, many authors have observed high rates of phosphorus release under anaerobic conditions, supporting this classical approach (for example, LI *et al*., 1972; SERRUYA *et al*., 1974; VINER, 1975; RILEY & PREPAS, 1984; NURNBERG, 1985).

However, the role of iron controlling the overall phosphorus dynamics in lakes was demonstrated to be much less general than previously thought (GOLTERMAN, 1977a; LEE *et al*., 1977).

On the other hand, phosphorus release under aerobic conditions has been reported for both eutrophic and oligotrophic waters (STEVENS & GIBSON, 1977; LEE *et al*., 1977; RYDING & FORSBERG, 1977; TWINCH & PETERS, 1984), whereas some lakes with hypolimnetic anoxia for much of the year showed very small internal phosphorus loading (LEVINE, 1986; SCHINDLER *et al*., 1987).

Water pH can also affect phosphorus release rates. Several laboratory studies reveal that a drastic increase of phosphorus flux from sediments takes place when pH increases (ANDERSEN, 1975; RIPPEY, 1977; LIJKLEMA, 1977), this dependence being in part a function of the initial P:Fe ratio in the sediment (LIJKLEMA, 1977). So, it was believed that pH changes were the major factor controlling phosphorus release in shallow productive lakes (BOSTROM *et al*., 1982).

Some field studies reporting closely related variations of pH and phosphorus (ANDERSEN, 1974; BOSTROM *et al*., 1982) were interpreted as the result of a causal relationship between the two variables. However, high phosphorus levels may be a sign of increased primary production, which in turn increases pH. In fact, when other conditions are taken into account it is not clear that pH is the key factor to explain phosphorus release in these systems, and probably the role of the pH as regulator of phosphorus release under natural conditions has been overemphasized (RYDING, 1985).

The other major chemical factor influencing phosphorus release rates is the concentration of nitrate, for which two counteracting effects have been described. On the one hand, nitrate can decrease the oxygen consumption and, thus, prevent phosphorus release from anoxic sediments by maintaining a high redox potential at the sediment surface (RIPL, 1976; ANDERSEN, 1982). On the other hand, addition of nitrate to oxygen depleted sediments leads to a stimulation of the mineralization of organic matter during the denitrifying process (ANDERSEN, 1977), and thus organic-bound phosphorus may return to water (AHL, 1979; SORENSEN, 1982). TIREN & PETTERSSON (1985) concluded from different experiments that whether or not high nitrate loading will cause an increase of phosphorus release depends on several factors such as continuity of the nitrate supply, nitrate uptake rate and sediment properties. Moreover, the results observed by RYDING (1985), who found the relationship between nitrate and phosphorus release most significant over long intervals of time (3 or 6 years), indicate the need for long term studies in order to provide a reliable basis to understand nitrate effects.

BIOLOGICAL FACTORS AFFECTING PHOSPHORUS RELEASE

Activity of organisms is the other major controlling factor in phosphorus release. The widely observed relationship between water temperature and internal phosphorus loading (KELDERMAN, 1980; HOLDREN & ARMSTRONG, 1980; KELDERMAN & VAN DE REPPE, 1982; RILEY & PREPAS, 1984; BOERS, 1986) suggests that microbial activity can enhance phosphorus release rates. Such activity may result in a direct mobilization of phosphorus through degradation (i.e. mineralization) of organic matter, or it may lead to a lowering of Eh values due to O_2 and nitrate consumption. Results of some studies in which bacterial activity has been suppressed (by adding antibiotics or by γ-irradiation) in shallow eutrophic lakes are consistent with the theory that bacterial activity plays the key role in phosphorus release in aerobic sediments (VINER, 1975; BATES & NEAFUS, 1980; KAMP-NIELSEN, 1974; FILLOS, 1977; SINKA & CAPPENBERG, 1988). Moreover, it has been suggested that part of the anaerobically released phosphorus has its origin in bacterial cells (FLEISCHER, 1983).

Other organisms apart from bacteria can also affect the phosphorus exchange between sediments and water. The periphytic biolayer seems to reduce phosphorus release because of the biological uptake of phosphorus from sediments, although laboratory results may not be quantitatively transferred to natural conditions (HANSSON, 1989). Macrophytes also influence phosphorus release, since phosphorus is taken up by roots and transferred to plant tissues from which it can be released again. BARKO & SMART (1980) concluded that this process may be quite significant for phosphorus recycling.

The role of bioturbation (defined as the stirring of sediments by the activity of benthic burrowing organisms) on phosphorus release is not clear. DAVIES *et al.* (1975) reported a reduction of phosphorus concentrations in the uppermost interstitial water as a consequence of higher redox potential, caused by tubificid worms. On the other hand, GRANELI (1979) and WISNIEVSKY *et al.* (1985) showed an increased transport of phosphorus from sediments caused by benthic macro-invertebrates. In fact, bioturbation is a very complex process that probably depends on, among other factors, the chemical and physical characteristics of sediment in which it takes place (PETR, 1977).

TABLE II. Phosphorus species from the sediments of worldwide lakes. Species are described in text. Values in brackets correspond to percentages of total phosphorus. Data are in mg P.kg^{-1} dw. # NAI-P fraction obtained by sum of NaOH and BD extracts. * NAI-P values obtained directly by NaOH extraction.

LAKE	ADS-P	NAI-P	AI-P	TP	References
Prairie Lakes (8) Canada	n.a.	120-1196 (22-62)#	205-307 (15-46)	542-1992	2
Balaton, Hungary	64 (10.5)	39 (6.4)*	284 (46.5)	610	36
Loosdrecht, Netherlands	30-200 (3- 6)	120-1550 (20-43)*	90-370 (6-19)	600-3620	6
Netherlands (4)	72-432 (9-39)	216-2232 (27-62)*	72-540 (8-39)	800-3600	20
La Minilla reservoir, Spain	n.a.	62-789 n.a.#	39-152 n.a.	n.a.	14
Sau reservoir, Spain	n.a.	310-787 (46-61)#	251-439 (19-59)	703-1388	4
Sweden (5)	6-42 (1-2)	44-375 (5-30)*	241-452 (19-37)	920-1670	36
Sweden (9)	6-250 (1-9)	44-4010 (5-68)*	240-710 (12-37)	917-5860	10
Eire, USA	n.a.	38-2329 (5-86)#	144-859 (13-86)	188-2863	37
USA (66)	0-872 (0-11)	140-5879 (9-68)*	43-737 (3-38)	1329-9212	28

PHOSPHORUS SPECIATION

Another approach to the study of sedimentary phosphorus dynamics is to analyze its fractional distribution, determining which fractions are potentially mobile within the natural range of variation for the main environmental factors.

Phosphorus is bound in the sediments to various chemical species which have different properties and behavior. The concentration of these forms depends on the whole characteristics of the lake. Moreover, since fractions differ in their behavior, the global dynamics of sedimentary phosphorus is greatly influenced by the fractional composition. For these reasons, quantitative and qualitative studies on phosphorus speciation should provide us with better knowledge and comprehension of the role of sedimentary phosphorus in water quality.

Different methods have been proposed for the analysis of phosphorus fractions. GOLTERMAN (1977b, 1982b, 1984) suggested the use of NTA extractions in order to evaluate the fraction available for algal growth. However further studies provided contradictory results for relationship between NTA-extractable and bioavailable phosphorus (KLAPWIJK *et al.*, 1982; GUNATILAVA *et al.*, 1988).

Other fractionation methods derive from the analysis of phosphorus forms in soils (CHANG & JACKSON, 1957) and go through sequential extractions with different solvents. Several procedures and solvents have been proposed, many of them by modification of those elaborated by WILLIAMS *et al.* (1971a, 1971b, 1976). Detailed discussion of the methods currently used are given by VAN ECK (1982) and PSENNER *et al.* (1988).

At present, the definition of the fractions is purely operational, four main forms being the most usually determined (PSENNER *et al.*, 1988):

A) Loosely-bound or adsorbed phosphorus, that is usually extracted with NH_4Cl (HIELTJES & LIJKLEMA, 1980) or distilled water (PSENNER, 1984). It gives an estimate of the immediately available phosphorus.

B) Non-apatite inorganic phosphorus (NAI-P), extracted with NaOH (HIELTJES & LIJKLEMA, 1980) or by successive addition of NaOH and buffered dithionite (BD) (PSENNER, 1984; PSENNER *et al.*, 1988). It corresponds to phosphorus associated with metal oxides and hydroxides. BD extracts reductant soluble phosphorus mainly from hydroxide surfaces (PSENNER & PUCSKO, 1988), although it has been suggested that in calcareous sediments BD could also extract some calcium-bound phosphorus (GABELLONE & GUISANDE, 1989). NaOH-P represents phosphorus which is exchangeable against OH^- and phosphorus compounds soluble in bases.

C) Inorganic apatite phosphorus (IA-P),

extracted with HCl. It represents phosphorus associated with calcium as carbonates or apatite (or similar compounds). BONZONGO *et al.* (1989) suggest that this fraction is usually overestimated by bacterial lysis.

D) Residual phosphorus. Obtained by the difference between total sedimentary phosphorus and fractions A,B and C. It includes organic and refractory phosphorus compounds.

Data from the literature about chemical fractionation of phosphorus in different lakes has been summarised in Table II. Some relations between fractions and other variables will be discussed next.

LOOSELY BOUND PHOSPHORUS

Adsorbed phosphorus is usually the smallest fraction, although in some cases it can rise to 39% of total phosphorus (Table II). It seems to be the most easily mobilized fraction. SONDEGAARD (1989) reports a reduction of 50-80% of this form in release experiments under aerobic conditions. However, decrease is restricted to the upper 2-4 cm of sediments, which agrees with the decrease observed in release rates with time (SINKE & CAPPENBERG, 1988) because diffusion from deeper sediments may be limited by distance. Because of its low percentage, adsorbed phosphorus has only small effects on global release rates. BOSTROM (1984) has observed that lakes in which loosely bound phosphorus is the main fraction mobilized have low release rates, which are not affected by redox or pH changes.

NON-APATITE INORGANIC PHOSPHORUS (NAI-P)

NAI-P is among the most variable fractions, wether the total concentration or percentage of total phosphorus is considered (Table II). It has usually been related to iron concentration (WILLIAMS *et al.*, 1976; OSTROFSKY, 1987) and it is associated with fine grained sediment (WILLIAMS *et al.*, 1976; GABELLONE & GUISANDE, 1989).

NAI-P seems to be the most important fraction for release and uptake mechanisms (PSENNER, 1984). Actually, phosphorus release has been related to NaOH-P in many studies (HOSOMI *et al.*, 1981; BOSTROM, 1984; TIREN & PETTERSSON, 1985; SONDEGAARD, 1989; OSTROFSKY *et al.*, 1989). The dithionite fraction shows a strong correlation with release rates in anoxic conditions (NURNBERG, 1988). Moreover, NAI-P can be related to water input of reactive soluble phosphorus (LOGAN, 1982; ARMENGOL *et al.*, 1986).

NAI-P has been assumed as the fraction that may be used for algal growth. Good agreement between NaOH-P and bioavailable phosphorus has been found by several authors (WILLIAMS *et al.*, 1980; YOUNG & DE PINTO, 1982), whereas in other cases results are not conclusive (KLAPWIJK *et al.*, 1982) or show no correlation (BOERS *et al.*, 1984).

APATITE PHOSPHORUS (AI-P)

Calcium-bound phosphorus has traditionally been considered as allogeneous or of detrital origin (WILLIAMS *et al.*, 1976; JONES & BOWSER, 1978) and it can be clearly related to water inflow and erosion rates (ARMENGOL & VIDAL, 1988). The narrow range of variation (especially when total concentrations rather than percentages of total phosphorus are considered) observed in Table II is in agreement with this. Because apatite does not dissolve at environmental conditions, AI-P is not related to release rates (HOSOMI *et al.*, 1981; BOSTROM, 1984) and it has been considered as non-available phosphorus (WILLIAMS *et al.*, 1976). However, it has been demonstrated that both algae and bacteria can grow with normally occurring apatite as the only phosphorus source (SMITH *et al.*, 1978). On the other hand, GOLTERMAN (1982a) shows that precipitation of apatite is possible in hard waters and suggests that calcium-phosphorus rather than iron-phosphorus is the controlling exchange factor in hard waters. Unfortunately, there is very little information about calcareous sediments and no general conclusions may be drawn about the role of this fraction.

ORGANIC AND REFRACTORY PHOSPHORUS

Organic phosphorus may also be a significant fraction of sedimentary phosphorus, and is usually related to the organic carbon content (WILLIAMS *et al.*, 1976; ARMENGOL *et al.*, 1984; OSTROFSKY, 1987). Its role in phosphorus release is not clearly understood: several studies demonstrate a decrease of this fraction during release experiments (BOSTROM, 1984; PETTERSSON, 1984; TIREN & PETTERSSON, 1985; SONDEGAARD, 1989). The organic phosphorus mobilized may be partially transferred to bacterial biomass and then released to water or transferred to NAI-P (PETTERSSON, 1984) or it may be directly transferred to the HCl-P fraction (TIREN & PETTERSSON, 1985). On the other hand other authors (KAMP-NIELSEN, 1974; OSTROFSKY *et al.*, 1989) have not found any relation between the organic fraction and phosphorus release.

As a whole, sedimentary phosphorus dynamics is a very complicated process involving a large number of mechanisms, so partial descriptions or models which are valid for one or more lakes may not be fully applicable to other lakes in which one or several factors differ. General models in which all possible mechanisms are included are extremely difficult, if not impossible, to construct with data now available.

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