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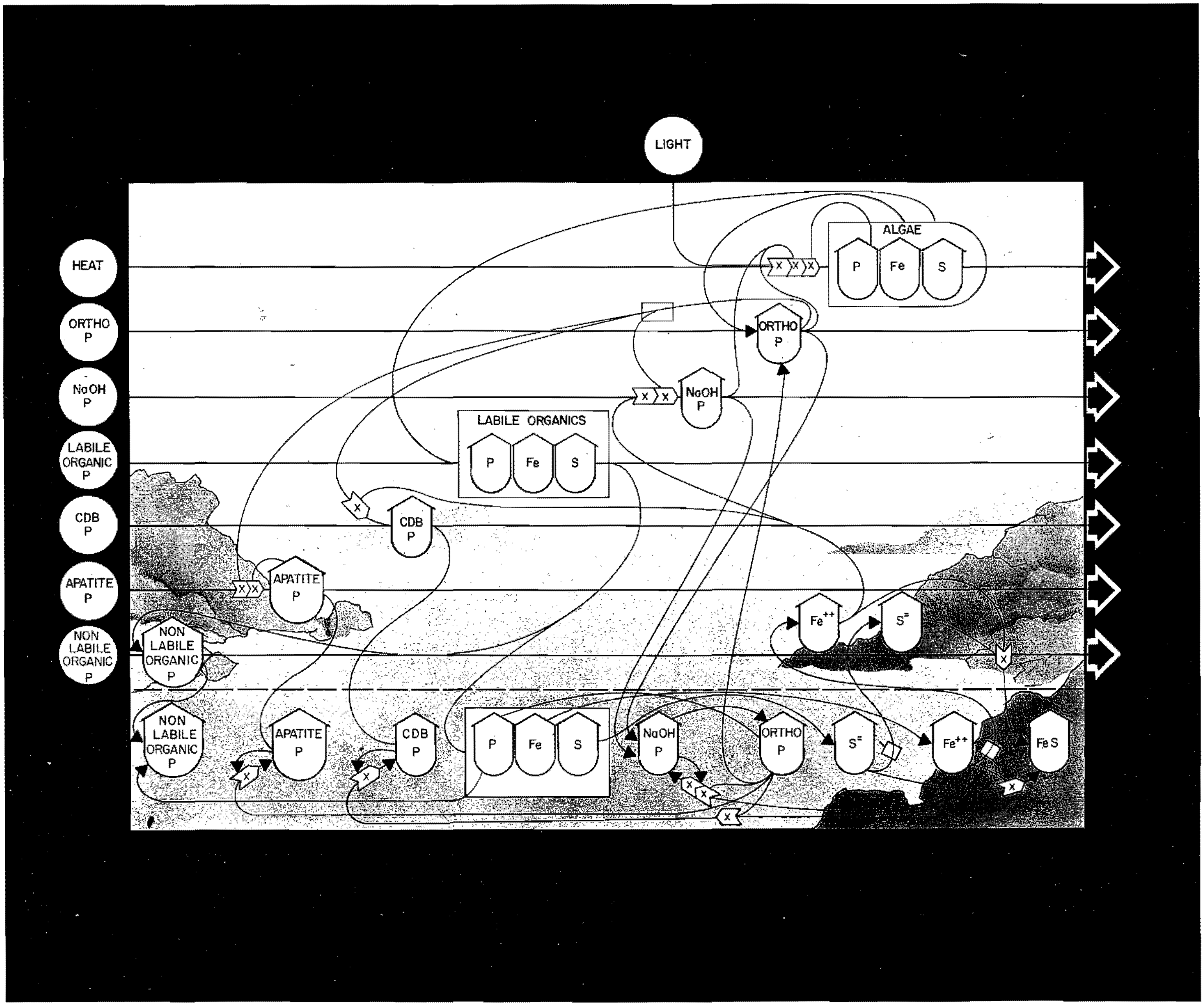

Utah Water Research Laboratory
Utah State University
Logan, Utah 84322

1984

WATER QUALITY SERIES
UWRL/Q-84/01

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SUMMARY AND CONCLUSIONS

Laboratory analyses of sediment samples recovered from Deer Creek Reservoir showed the sediments to have a moderate potential for serving as a source of phosphorus (P) for the overlying water column under anaerobic conditions. This source could account for the occurrence or exacerbation of blue-green algal blooms in the upper end of the reservoir when the sediment surface becomes anaerobic late in the summer. It could also delay the response of the reservoir to programs that decrease external P loading, if the upper end of the reservoir still has large enough algal blooms to render the sediment-water interface anaerobic. The redox cycle of Fe is closely associated with P release in the reservoir sediments, and aerobic P release rates are probably insignificant in the phosphorus budget of the reservoir. Sediment profiles indicate that the trophic state of the lake has probably not changed significantly since the reservoir was first filled. The profiles do indicate, however, that much of the P input to the lake may be in the relatively unreactive apatite-P fraction, and attempts at reducing P loading from external sources should take into account the degree of availability of the P thus removed.

INTRODUCTION

Phosphorus inputs from tributary streams and nonpoint sources are well-known contributors to nuisance algal growths that degrade water quality for potable and recreational uses in lakes and reservoirs. However, phosphorus may also enter the euphotic zone from within the lake itself, as a result of releases from both oxic and anoxic sediments. Such releases may originate from phosphorus inputs to a lake or reservoir during high runoff periods in the previous winter or spring, or they may represent phosphorus trapped in the sediment many years earlier, when phosphorus contributions from natural or anthropogenic sources were higher than at present. Whatever their origin, phosphorus loading from sediments may exacerbate the eutrophication process or delay the recovery of a eutrophic lake or reservoir following reductions in external phosphorus loading aimed at water quality restoration (Bengtsson 1978, Larsen et al. 1975, 1981). This phenomenon has been graphically likened to the "memory" of a lake for its previous trophic state: oligotrophic lakes tend to trap phosphorus in their sediments, thus remaining oligotrophic, while eutrophic lakes "mine" their sediments for phosphorus during summer stratification and further contribute to the production of late summer and fall phytoplankton blooms (Imboden 1974).

Virtually no information is available on the extent to which internal phosphorus loading is important in reservoirs in the Intermountain West, or on the factors controlling phosphorus uptake or release in such sediments. In fact, there remains considerable debate over the accuracy of the simple paradigm outlined above for all lakes and reservoirs. Under certain circumstances, oxic release rates of phosphorus from some sediments can be substantial, while anoxic release rates may be relatively low (Holdren and Armstrong 1980). For this reason, a series of studies on sediments in several reservoirs in the Intermountain West is being conducted at the Utah Water Research Laboratory in order to further our understanding of important sediment-water interactions in the phosphorus cycles of such reservoirs (e.g., Messer and Ihnat 1983a, Messer et al. 1983b). The data reported here represent results from the first full year of these studies on Deer Creek Reservoir. The data relate to the phosphorus chemistry of the sediments themselves, and to phosphorus release simulations carried out on intact sediment cores incubated in the laboratory. The aim of the discussion that follows is to compare the chemistry and release rates of cores from Deer Creek Reservoir with some values obtained in studies of other reservoirs, and to discuss some implications of these results with regard to potential problems that could be encountered with internal phosphorus loading from the sediments if external phosphorus loadings were to be reduced.

The studies reported here do not address the importance of reservoir hydrodynamics in transporting phosphorus released from the sediments to the euphotic zone, nor is the significance of the timing of such transport considered in relation to the growth of phytoplankton populations. Böstrom et al. (1982) and Messer et al. (1983b) recently have reviewed the pertinent sediment geochemical literature, and these reviews will not be repeated here. Stauffer (1981) has provided a quantitative rationale for relating sediment release data, such as those reported in this study, to the impact on the overlying water column, but insufficient data presently exist to apply them to Deer Creek.

METHODS

Sediment cores were collected from the reservoir on five dates, beginning in November 1982, and ending in October 1983, at four stations shown in Figure 1. The cores were collected either using a gravity corer equipped with an acrylic core liner (Tapp Plastic Co., Salt Lake City), or by SCUBA diver using the core liner alone. Core liners were prewashed with 6N nitric acid and thoroughly rinsed with reagent grade (MILLEQ, Millipore Corp.) water in the laboratory. Cores to be used for release experiments were pre-soaked in 2 mg/l Na_2HPO_4 solution for 48 hours prior to use to prevent sorption of P by the tube walls during the incubation. The tubes were subsequently rinsed in lake water immediately prior to collecting the cores. It was generally necessary to drop the corer from 1-2 meters above the sediment surface in order to allow the core tube to penetrate to a sufficient depth to retain the core. Therefore, cores were discarded if there was any evidence of loss of the interfacial layer caused by the bow wave of the descending corer. This problem was avoided by diving with SCUBA, but the high altitude and depth of the reservoir resulted in relatively short down-time, and thus all cores could not be collected by this procedure. The cores were returned to the laboratory within 10 hours of collection.

Phosphorus Release Studies

In order to compare aerobic and anaerobic release rates of phosphate from the sediments, two cores taken from each reservoir station were incubated in the laboratory. Incubations were begun on cores that had been held overnight following collection. Prior to incubation, the sediment height in all cores was adjusted to approximately the same height by allowing the sediment core to drop through the bottom of the core tube until the sediment-water interface was at the desired level. Water collected at the time of sampling was used to bring the water level in each core back up to the same height. This was done to minimize differences among cores in turbulent shear caused by stirring or bubbling, or in the amount of microbial biomass growing on the exposed surface of the core tube.

The aerobic cores were incubated with an open headspace, into which was inserted a paddle attached to a jar test apparatus to provide mechanical stirring (4 rpm). The paddles were painted with an epoxy resin that has been determined to be inert to surface chemical reactions. Before each sampling, deionized water was added to each core to make up for evaporation, and after 20 minutes of stirring, a 12 ml aliquot of water was withdrawn into an acid washed flask containing a drop of 6N sulfuric acid (inclusion of the acid acted as a control for the anaerobic cores, to which acid was added to prevent the oxidation of iron and the subsequent precipitation of phosphate when the sample was aerated during filtration). The aliquot was filtered immediately through a 0.45 um Gelman membrane filter prior to analysis for ortho-P, using the manual ascorbic acid method (APHA 1981).

Paired anaerobic cores were incubated by sealing the top of the core with a three-hole rubber stopper through which pass two glass tubes that extended into the water overlying the sediment,

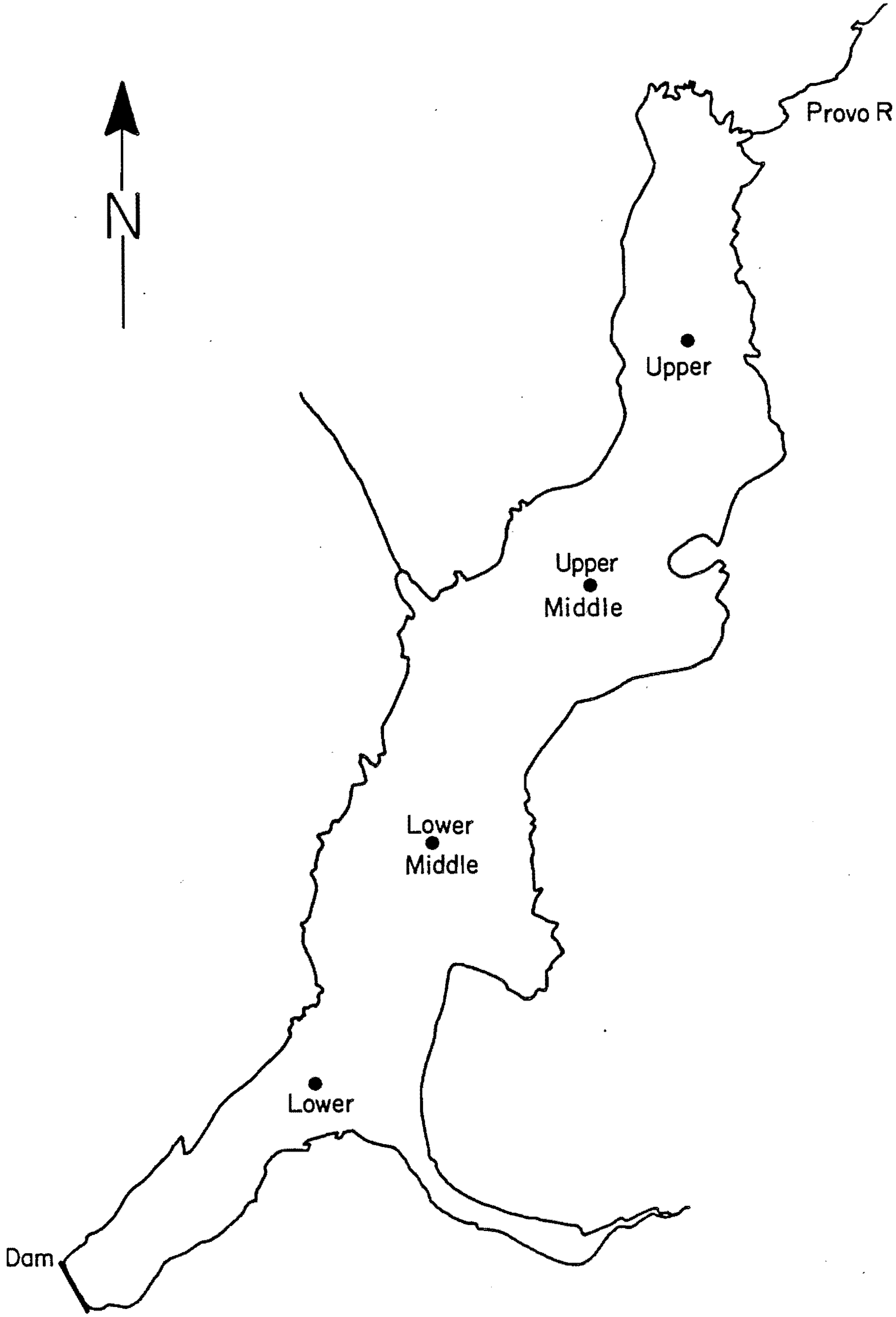


Figure 1. Map of Deer Creek Reservoir showing sediment sampling sites.

and one tube that extended only into the 5 mm air space between the water and the stopper. The glass tubes were each attached to a length of Tygon™ tubing secured with a pinch clamp. Before each sampling, reagent grade nitrogen gas (99.995 percent purity, subsequently passed through an Alltech gas purifier) was bubbled into the water for 4-5 minutes to provide thorough mixing of the water column (but no sediment suspension). This was done by passing the gas into the long inlet tube and out through the short tube connecting to the headspace. The short exhaust tube was then sealed, and the gas pressure was increased to force a 15 ml aliquot of water out of the long exhaust tube into a flask containing a drop of sulfuric acid. A 15 ml aliquot of deionized water was added through the short tube to replace that withdrawn for the sample, and the tube was then bubbled for 10 minutes with N_2 to remove any O_2 inadvertently admitted during sampling. Toward the end of the experiment, the replacement water was bubbled with N_2 to remove any oxygen admitted inadvertently during sampling. However, no significant change in P release was observed as a result of this added precaution. Both aerobic and anaerobic incubations were carried out in the dark.

Additionally, five cores collected in October 1983 were incubated in an environmental chamber under a nitrogen atmosphere. These cores were set up as described above for the paired anaerobic incubations with the following exceptions. An additional 25 mm diameter hole was placed in the core cap to facilitate the measurement of Eh and pH. This hole was sealed with a small rubber stopper when not in use. Eh and pH measurements were taken after the cores were sampled as described above, but prior to addition of the replacement water. Aliquots of 30 ml of chamber water were withdrawn into 6N sulfuric acid for analysis of metals and ortho-P as described above, and an additional 10 ml were withdrawn into a glass test tube, which was stoppered and analyzed within 2 hours for total inorganic carbon on an Oceanographic International TOC Analyzer. Replacement water for these cores was deionized water made up to 150 mg/l as $CaCO_3$.

Both aerobic and anaerobic incubations were carried out at 12°C, except for two experiments. In November 1982 the cores were incubated at 9°C. In another experiment in October 1983 triplicate cores collected at the upper sampling station were incubated at three different temperatures; 5°C, 12°C, and 20°C. The results of this experiment were used to correct the results of the November incubations to 12°C for comparison with the other data.

Sediment Chemistry

On the day following the incubations, the cores were extruded and sectioned into 2 cm slices. Wet weights were determined on each section, before drying to constant temperature in a 105°C oven. Dry weights were also measured, thus allowing fractional dry weight to be calculated.

In the early stages of the study, phosphorus fractionation and analyses were performed following the general outline of Mayer and Williams (1981). These results were reported by Messer and Ihnat (1983a) and were subsequently found to underestimate the phosphorus fraction associated with iron in the sediments, and to overestimate the amount associated with calcium phases (see Hieltjes and Lijklema 1980, and Messer and Ihnat 1983a). Subsequent analyses utilized an adaptation of the technique of Hieltjes and Lijklema (1980) that appears to avoid the effects noted above. Although the basic procedure is outlined below, a complete protocol has been published by Ihnat and Messer (1983).

A 60 mg aliquot of dried sediment was first extracted in two sequential 30 ml volumes of neutral 1N NH_4Cl for 2 hours on a shaker table at room temperature. SRP was determined on the combined, filtered supernatants from the two extractions using the ascorbic acid technique (APHA 1981). This fraction is thought to include SRP in interstitial water, as well as P held on anion exchange sites. The pellet then was extracted in 30 ml of cold 0.1 N NaOH/1 N NaCl solution for 18 hours on a reciprocating shaker table. The resulting suspension was centrifuged and filtered through a Gelman 0.45 µm membrane filter, and soluble reactive P (SRP) was determined on the neutralized filtrate by the ascorbic acid method (APHA 1981). This fraction is referred to as NaOH-P, and is thought to consist of ortho-P dissolved in sediment interstitial water, as well as that bound on ion-exchange sites and on the surface of hydrous iron oxide gels (Williams et al. 1976).

The pellet was subsequently extracted in 30 ml of 0.22 M Na-citrate/-0.11 ml NaHCO for 15 minutes in an 85°C water bath. One gram of Na-dithionite was then added, and the solution was incubated for an additional 15 minutes. SRP was determined on the CDB extracts using the colorimetric finish of Weaver (1974). One ml of 1 M $FeCl_3$ was added to each extract and the solution was bubbled with wet air for 4 hours to oxidize the dithionite, which would otherwise interfere with color development. The sample was diluted to 60 ml, and an aliquot of this solution was analyzed for P. This fraction, CDB-P, is thought to include SRP shielded by iron oxide gels, and consequently not extractable by the NaOH solution (Williams et al. 1976). The sum of the NaOH-P and CDB-P is referred to as non-apatite inorganic phosphorus (NAI-P), following the practice of Williams.

The sediment pellet was then extracted in 30 ml 0.5 N HCl at room temperature on a shaker table for 18 hours. The supernatant was centrifuged and filtered, and SRP determined on the neutralized filtrate using the ascorbic acid method (APHA 1981). This fraction is referred to as apatite-P, and has been shown by Williams et al. (1980a) to be comprised of Ca-bound P species.

Total P was determined by the persulfate digestion method (APHA 1981) on a separate 60 mg aliquot of each sediment added to 30 ml of deionized water. The difference between total P and the sum of NAI-P and apatite-P is assumed to represent organic-P by Mayer and Williams (1981).

CDB-Fe and CDB-Mn

CDB-extractable iron and manganese were determined on an aliquot of the CDB extracts, acidified to pH < 2 with HNO_3, by atomic absorption spectrophotometry on an IL Model 357 spectrophotometer. The standard curve was prepared using standards carried through the entire extraction procedure. In unpublished experiments on Deer Creek sediments, it was found that minimal Fe is extracted by NH_4Cl or NaOH/NaCl, although some Mn is extractable in the NH_4Cl extraction.

Total S

Total S analyses were performed on 1 g aliquots of the oven-dried, powdered sediments by a Leco induction furnace method by Rocky Mountain Geochemical Corp., Salt Lake City, Utah.

^{137}Cs

Cesium dating was performed on ground 2 cm sections of sediment following the technique of Ritchie et al. (1973).

RESULTS AND DISCUSSION

Sediment Chemistry

Mean values from sediment analyses conducted on the Deer Creek cores are shown in Table 1, along with some results from other reservoirs in the Intermountain West for comparison. All values represent the surface 12 cm of sediment. This depth was chosen to allow a comparison to be made with the Flaming Gorge data (Messer et al. 1983b), but it also corresponds to the relatively active diagenetic zone of most reservoir sediments (e.g., Allan and Williams 1978).

NH_4Cl-P, or "exchangeable" P, concentrations can be seen to be lower in the Deer Creek sediments than in any of the other reservoirs. The amount of NaOH-P in a sediment is thought to be primarily associated with phosphorus loosely bound to colloidial iron oxy-hydroxide gels, and thus is a function, not only of anthropogenic P loading, but also of the Fe content of the sediment (Williams et al. 1971b). Deer Creek not only has several sources of anthropogenic phosphorus in its watershed, but it also can be seen to have a relatively high iron content, relative to that of the other reservoirs. This may be the reason that the otherwise phosphorus-rich sediment has so little P easily removed by the NH_4Cl extractant (cf. Panguitch and Flaming Gorge in Table 1).

NaOH-P is of particular interest, because it has been shown to be highly correlated with anaerobic P release rates from sediment cores taken from upper Flaming Gorge and other Intermountain reservoirs and incubated in the laboratory (Messer and Ihnat 1983b, Messer et al. 1984). This observation is consistent with the view that the NaOH-P represents primarily P loosely bound to the surface of ferroso-ferric hydrous oxide gels, and which would be readily released upon reduction of the iron to Fe(II) when the sediment interface becomes anaerobic (Mortimer 1941, 1942). Therefore, the NaOH-P concentration may provide a useful indicator of the relative potential for P release into an anoxic hypolimnion.

NAI-P concentrations averaged 470 mg/kg in the sediment cores, and thus are in the >200 mg/kg range cited by Allan and Williams (1978) to be typical of sediments found in midwestern eutrophic lakes. We have argued elsewhere (Messer and Ihnat 1983a) that the CDB-P component of NAI-P, which is virtually identical at the four stations, may represent Fe-P inputs from the watershed to a greater extent than does the NaOH-P fraction, although this hypothesis remains to be proved.

HCl-P, or apatite-P, concentrations in the Deer Creek cores averaged 394 mg/kg, and were intermediate among the five reservoirs. This fraction accounted for 40 percent of the total P in the cores. It is important to note that under the ambient chemical conditions in the bottom waters of the reservoir (e.g., neutral to high pH), the corresponding apatite-P would remain trapped in the sediment, with little possibility of interacting with the overlying water. Thus, if the majority of this P form is detrital in origin, rather than having been formed diagenetically from other forms of P in the interstitial water, a large fraction of the P loading to the lake may be unavailable for

Table 1. Comparison of P fractions and CDB-Fe in some Intermountain reservoir sediments based on the extraction procedure of Hieltjes and Lijklema, as modified by Ihnat and Messer (1983).

P fraction	Deer Creek	Panguitch	Scofield	Flaming Gorge	Strawberry
NH_4Cl-P	35	128	63	48	69
NaOH-P	295	248	177	271	132
Σ-P	330	376	240	319	201
CDB-P	140	76	143	75	71
NAI-P	470	452	383	394	270
HCl-P	394	146	423	487	278
Organic-P	123	246	284	81	154
Total P	987	864	1090	962	712
CDB-Fe	8800	4800	10400	5700	4900
CDB-Fe:NAI-P[1]	10	6	15	8	10

[1] Mole basis

phytoplankton growth. It would be extremely valuable for watershed management to know whether the origin of this potentially unavailable fraction is equally distributed among all of the tributaries.

Two other sediment chemical parameters that are useful in determining the importance of internal P loading are the stoichiometric ratios of reactive Fe to both NAI-P and S in the sediments. Allan and Williams (1978) held that the ratio of CDB-Fe to CDB-P is indicative of the degree of overloading of potential Fe reaction sites with anthro-inputs of P from the watershed. They cited a range of ratios for a group of Canadian prairie lakes known to exhibit significant internal P loading of from 6 to 12 (mole basis), while lakes with apparently little internal P loading had values above 20. The Deer Creek sediments have a CDB-Fe: NAI-P ratio of 10, and thus would appear to be at the extreme upper range for reservoirs culturally overloaded with phosphorus. These sediments thus might show some resistance to P release under anoxic conditions, relative to reservoirs such as Panguitch with a similar amount of NAI-P, but with much less iron to bind it.

The mobility of NAI-P also depends on the stoichiometry of Fe, ortho-P, and sulfide in the interstitial water (Stauffer 1981). Sulfide in lake sediments originates either from the anoxic decomposition of organic sulfur compounds, or from sulfate that is reduced by the respiratory activities of bacteria such as Desulfovibrio. If the resulting sulfide concentration exceeds a 1:1 stoichiometric ratio with Fe^{++}, the P that was released from the Fe-P complex will be free to migrate upward in the sediment column until it encounters an oxidized Fe gel. In sediments overlain by oxygenated water, this encounter will occur in the so-called oxidized microzone at the surface of the sediment, and P release to the overlying water will be minimal (e.g., Mortimer 1941, 1942). If the 0.2 eV Eh isopleth moves above the sediment surface into an anoxic lake hypolimnion, however, P will be released to the overlying water column.

If sulfide is present at less than the 1:1 stoichiometry described above, Fe^{++} will be free to form a variety of phosphate minerals which will greatly reduce (but not eliminate) the migration of P upward in the sediment. Such minerals include vivianite ($Fe_3(PO4)_2 \cdot 8H_2O$) and anapatite ($Ca\ Fe(PO_4)_3 \cdot 4H_2O$). Vivianite has been found to be both present and thermodynamically stable in the sediments of Lake Greifen, Switzerland (Emerson 1976, Emerson and Widmer 1978), and in the North American Great Lakes (Nriagu and Dell 1974). Williams et al. (1980) found that vivianite and rockbridgeite, an iron hydroxyphosphate, are both represented quantitatively in the NAI-P extraction procedure. The appropriateness of the 1:1 Fe-S stoichiometry was determined by Nriagu (1968) and Doyle (1968), who found that mackinawite (FeS) was the stable reduced Fe-S phase in most lacustrine sediments. Stauffer (1981) raises the point that if the source of P to the overlying water derives primarily from mineralizing detritus on the surface of the sediment, the Fe:S stoichiometric ratio may be relatively low because of the correspondingly low ratio in biomass. If allochthonous Fe inputs are also low, then such lakes may experience relatively heavy P loading from sediments, even under oxic conditions.

The Fe:S molar ratios in the top 12 cm of the Deer Creek cores was 6.2, and thus it is unlikely that sulfide would interfere with P release from Fe complexes under anoxic conditions. It should be noted that the Fe:S ratio, as measured here, represents a minimum estimate, because the Fe value may not include pyrite-Fe, while S from this mineral would be included in the Leco furnace analysis.

Mean concentrations of various sediment phosphorus and metal fractions at each of the sampling stations are presented in Table 2. Two different patterns in the chemical data are apparent. HCl-P, which would be expected to be associated with heavier-grained phosphorus fractions such as apatite, that would settle rapidly toward the head of the reservoir, can be seen to be present at higher concentrations in the upper reservoir stations. Conversely, those sediment fractions normally associated with the lighter or finer-grained particles (i.e., NaOH, CDB-Fe and CDB-Mn) increased down gradient in the reservoir. These observations are consistent with the percent dry weight values, which also decrease in a downstream direction.

Figures 2-4 display the variations in constituent properties with depth in cores taken at each of the sampling sites in July 1983. Percent dry weight increases with sediment depth as expected in the cores, although many of the curves do not show the monotonic exponential decreases typical of pelagic marine sediments (e.g., Berner 1980). The absence of smooth compressional density increases suggest that different layers of the sediment might be expected to have a mineralogical composition determined by historical input events, in addition to steady-state diagenesis.

Neither NaOH-P nor NAI-P (Figure 3) show significant vertical trends, such as those observed in cores from Canadian prairie lakes (Allan et al. 1980) or in Panguitch Lake, Utah (Messer and Ihnat

Table 2. Mean concentration of extractable phosphorus and metal fractions, and percent dry weights for all dates at each sampling station. All values are in mg/kg and represent the top 8 cm of the sediment cores.

	Fraction							
Sampling Location	NH_4Cl-P	NaOH-P	NAI-P	HCl-P	TOT-P	CDB-Fe	CDB-Mn	%/Dry Wt
Upper	54.3*	155.2	355.8	542.0	825.6	6,400	50	41.6
	24.5	51.9	22.8	84.2	120.6	1,700	23	5.6
	(16)	(16)	(12)	(12)	(12)	(8)	(8)	(16)
Upper Middle	43.9	148.3	334.1	448.3	674.5	7.600	64	48.2
	14.6	42.6	72.9	108.3	168.0	1,700	19	14.1
	(16)	(16)	(12)	(12)	(12)	(8)	(8)	(16)
Lower Middle	50.0	249.1	438.6	432.5	815.1	10,000	95	36.9
	40.5	120.9	138.6	59.5	147.4	1,900	42	19.8
	(23)	(23)	(23)	(23)	(23)	(15)	(15)	(23)
Lower	47.0	342.7	475.5	396.4	912.8	11,400	160	16.9
	15.3	95.0	115.7	92.1	82.4	800	76	2.3
	(11)	(11)	(11)	(11)	(8)	(11)	(11)	(11)

*Mean, standard deviation, and number of sections analyzed, respectively.

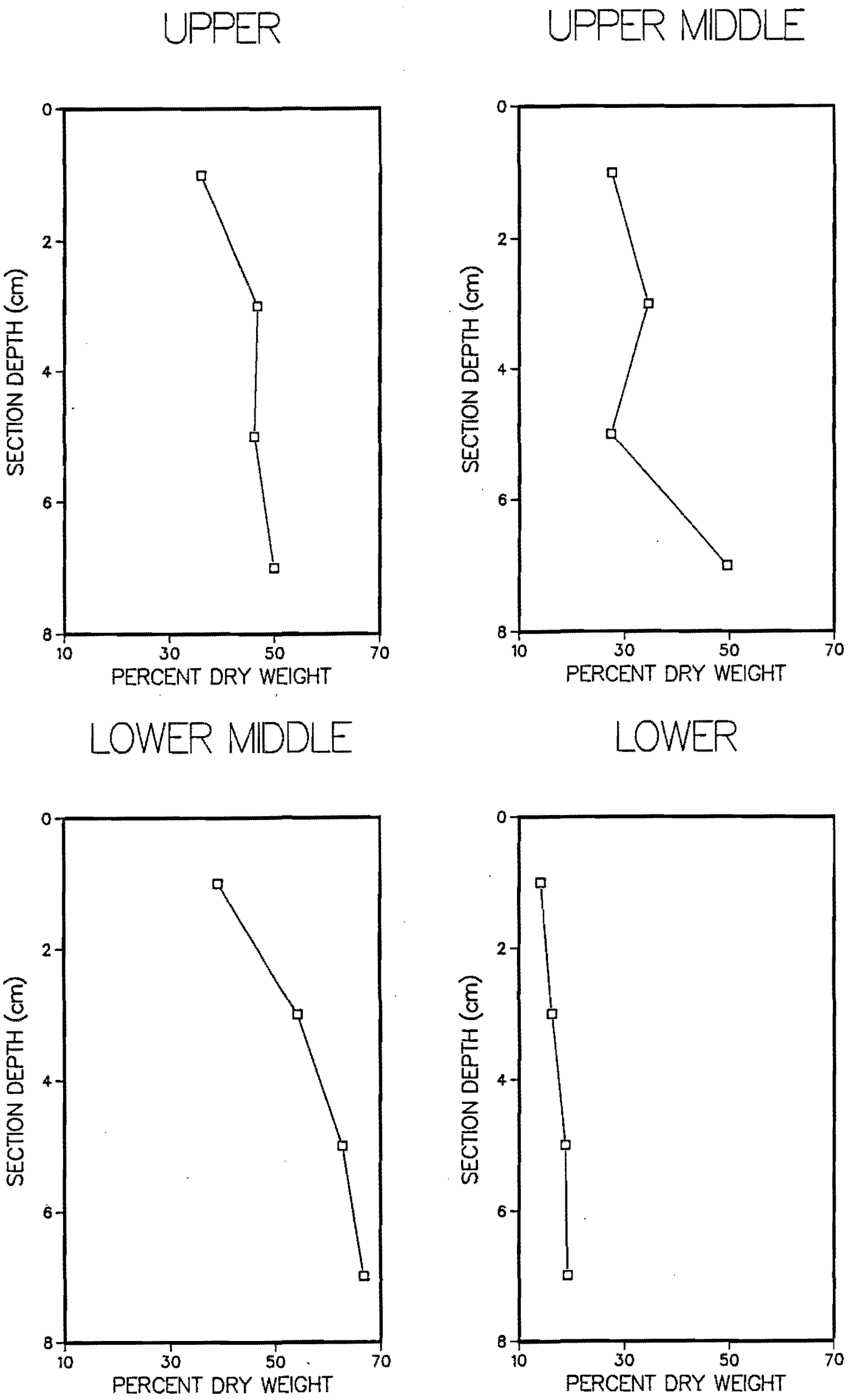


Figure 2. Percent dry weight as a function of depth in sediment cores collected in July 1984 from four sampling sites in Deer Creek Reservoir (see Figure 1).

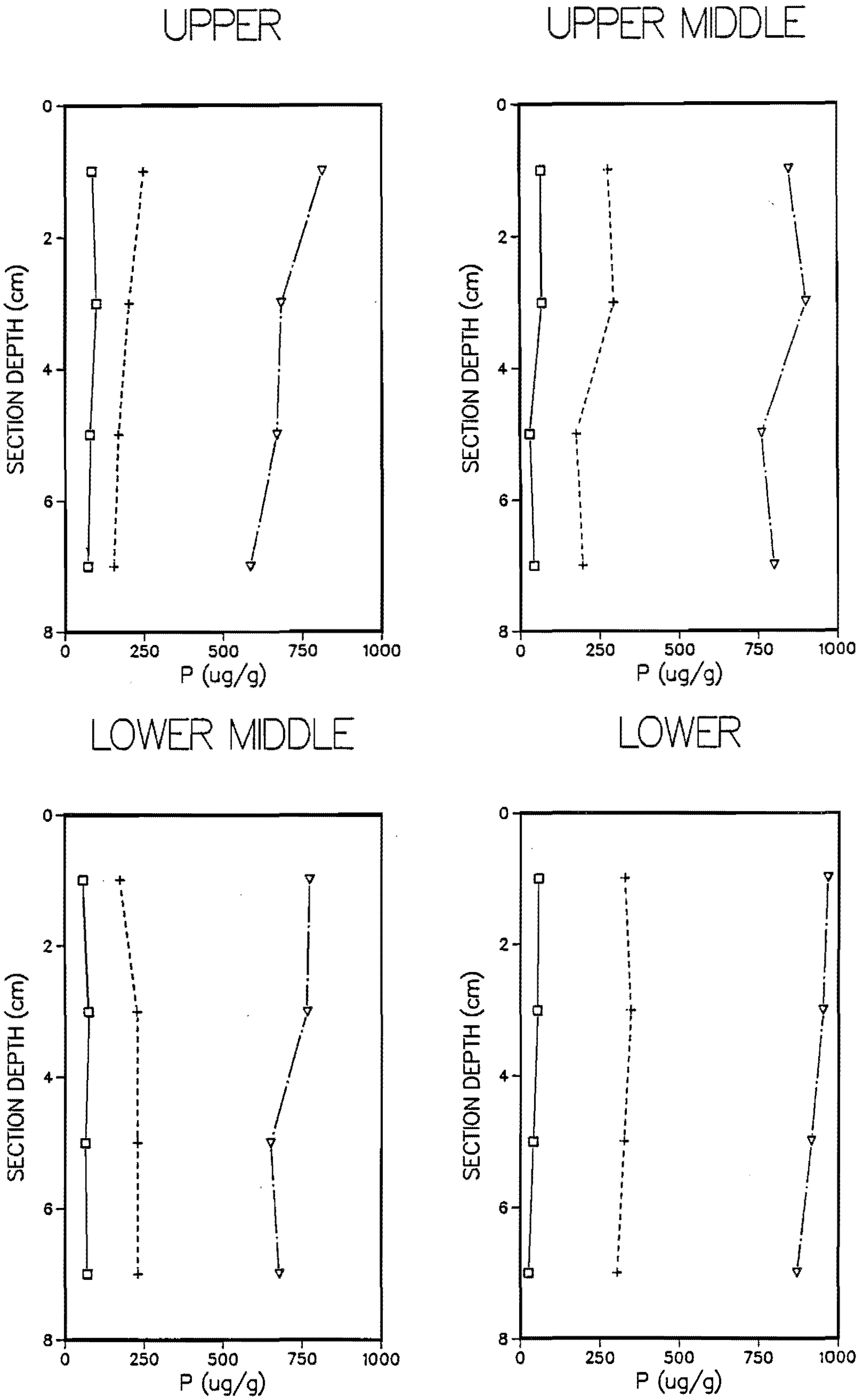


Figure 3. NaOH-P (□), NAI-P (+), and total P (▽) as a function of depth in sediment cores collected in July 1984 from four sampling sites in Deer Creek Reservoir.

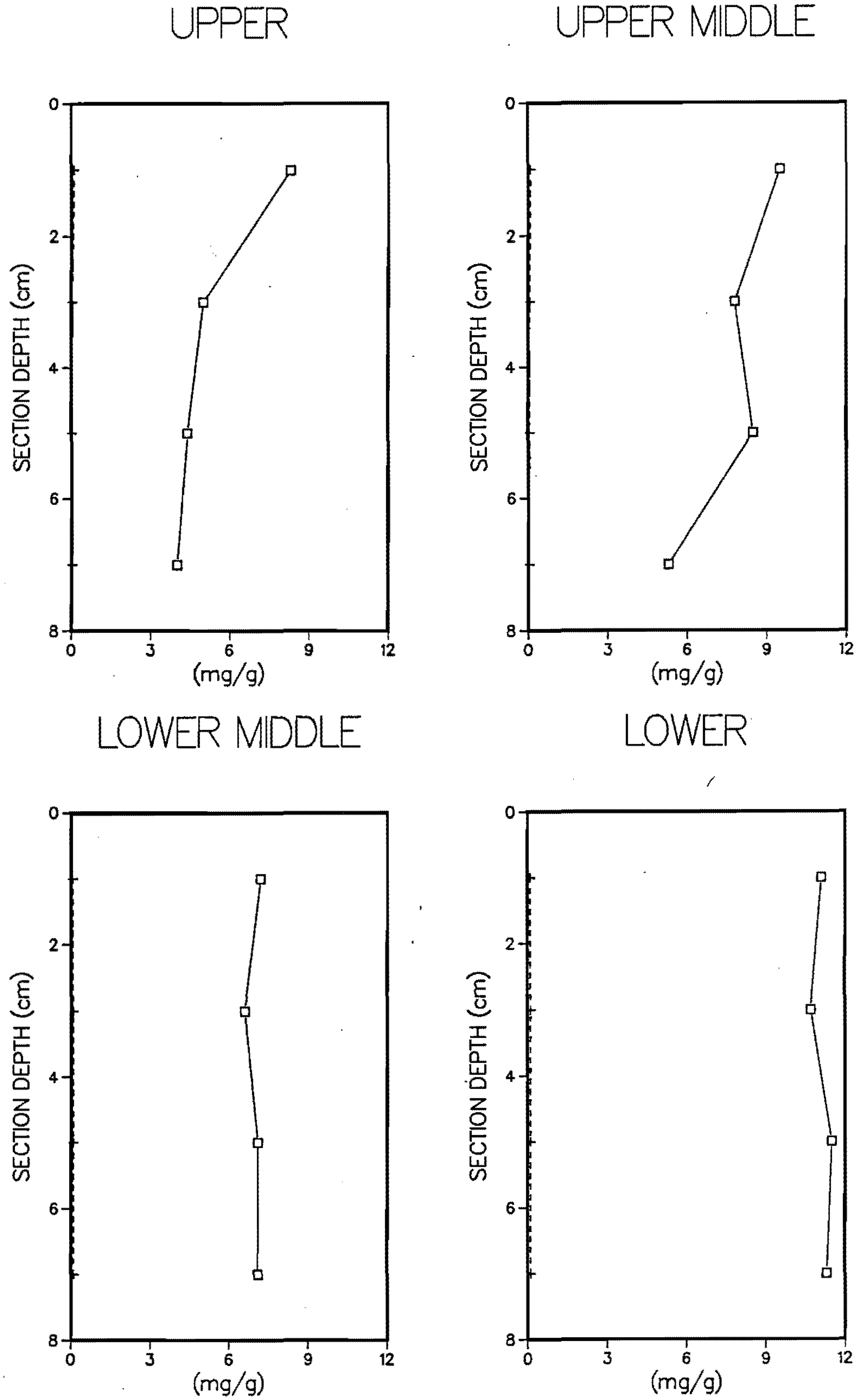


Figure 4. CDB-extractable manganese (+) and iron (□) as a function of depth in sediment cores collected in July 1984 from four sampling sites in Deer Creek Reservoir.

1983a). This suggests that there have been no recent historical trends in phosphorus loading to the sediments of the reservoir. The higher extractable iron concentrations toward the surface of the cores collected from the upper and upper-middle sites in the reservoir are typical of sediments that are frequently anoxic at the surface, in which iron migrates toward the sediment-water interface and is trapped in the surficial layers of the sediment. The low concentrations of manganese in these cores are unique in our experience with Utah reservoirs, but are consistent with the low release of manganese from these sediments under anaerobic conditions (see below).

Phosphorus Release Studies

The results of some typical phosphorus release incubations are shown in Figure 5 for duplicate cores collected from each station in July 1983. During the 48-day anaerobic incubation, phosphorus in the overlying water gradually increased to a peak of 600-1100 µg/l and then declined to somewhat lower values. Both the maximum soluble reactive phosphorus (SRP) concentration and the timing of the peak varied from station to station and from one sampling date to another in the reservoir, but the general pattern of a peak followed by a subsequent decline in SRP was typical of all of the cores studied. Aerobic release curves were generally flatter than the anaerobic release curves, with SRP concentrations remaining well below 50 µg/l. It should be noted that, because each sample aliquot was replaced with water containing no SRP, a flat concentration curve indicates a low, constant release rate, rather than no release.

The results of long-term incubations of cores from the upper and lower middle sampling sites in Deer Creek are shown in Figure 6. While both cores exhibited peaks in SRP concentrations during the first 45 days of incubation, a second major peak in SRP concentration was observed to occur between 50 and 60 days following the beginning of the experiment. SRP subsequently declined to values (300-400 µg/l) similar to the peaks in the first 45 days of incubation. These results indicate that there may exist two Fe-P fractions in the sediments: one that is released fairly readily, and a more abundant fraction released only at lower redox potentials. Alternatively, the second peak may result from some indirect effect of the low redox potential. As in most other cores, aerobic release rates were minimal.

A more complete set of chemical data were obtained for five cores collected from the reservoir in October 1984, and incubated in an N_2-filled environmental chamber. The results of these experiments are shown in Figures 7a-d. These plots indicate that the initial rise and subsequent decline in SRP concentrations is driven by redox reactions involving Fe (Figure 7a-d). A decline in Eh occurred during the initial increase in SRP concentrations, and Eh increased during the subsequent decline in SRP around days 18 to 30. However, the second rise in the SRP concentrations was not accompanied by a drop in Eh and a coincident drop in the Fe concentration. Rather, the Fe concentrations continued to increase, thus suggesting that this second peak is not redox controlled, but rather is mediated by some other process. Equilibrium modeling using REDEQL.EPAK (Ingle et al. 1980) indicated that only in the core with the highest iron concentration at the first peak (Figure 7e) was the water supersaturated with respect to siderite ($FeCO_3$). However, several of the cores became saturated with this iron mineral as the iron concentration rose late in the incubations. At no time were the overlying waters saturated with vivianite ($Fe_3(PO_4)_2$), thus suggesting that the decline in iron and phosphate following the first phosphate maximum was not driven by precipitation of a phosphate mineral (e.g., Emerson 1976), nor

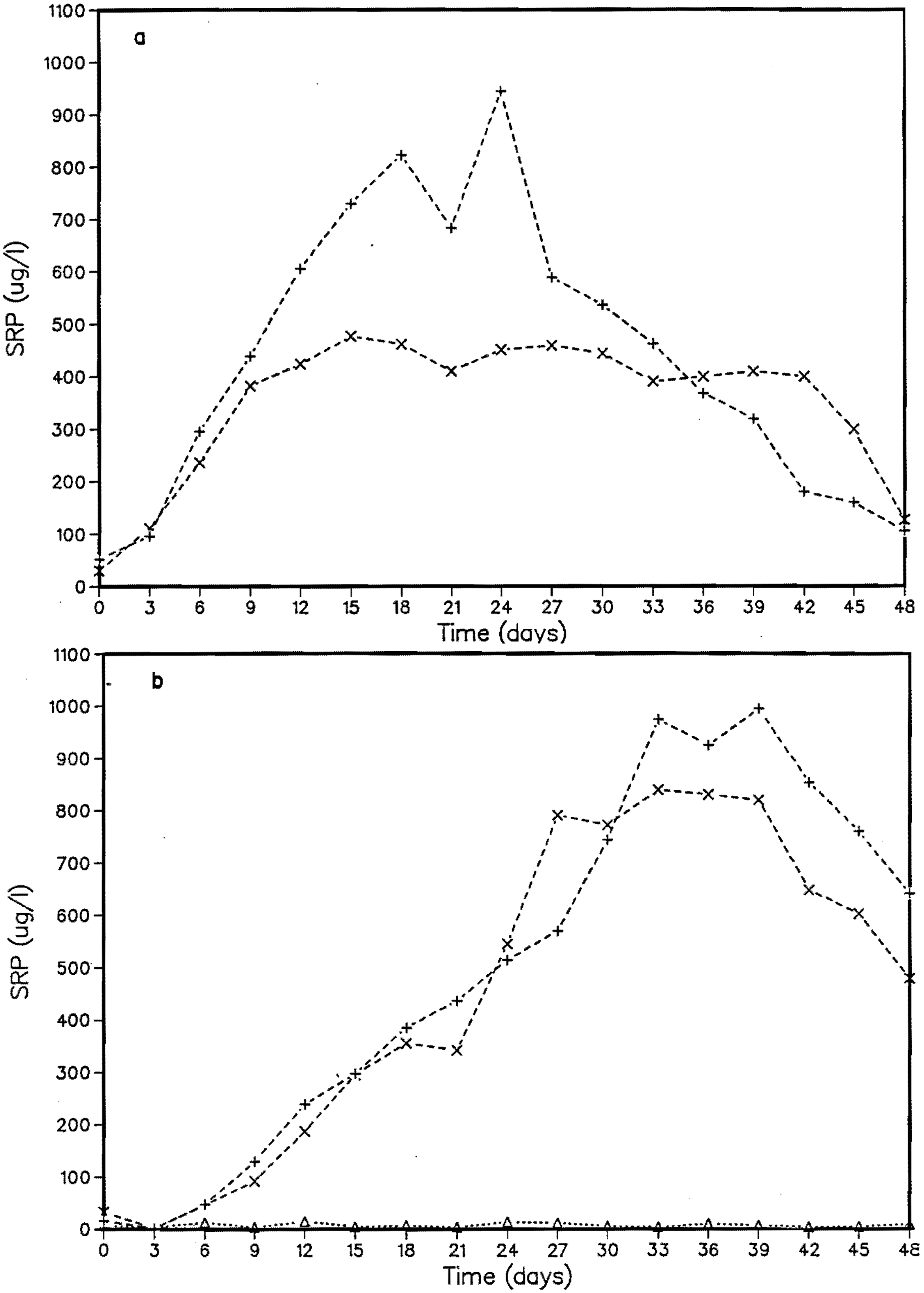


Figure 5. Release rates of soluble reactive phosphorus from aerobic (Δ) and anaerobic (x and +) sediment cores collected from four sampling sites in Deer Creek Reservoir in July 1984. See Figure 1: a) upper site, b) upper-middle site, c) lower-middle site, d) lower site. Multiple lines represent duplicate anaerobic cores.

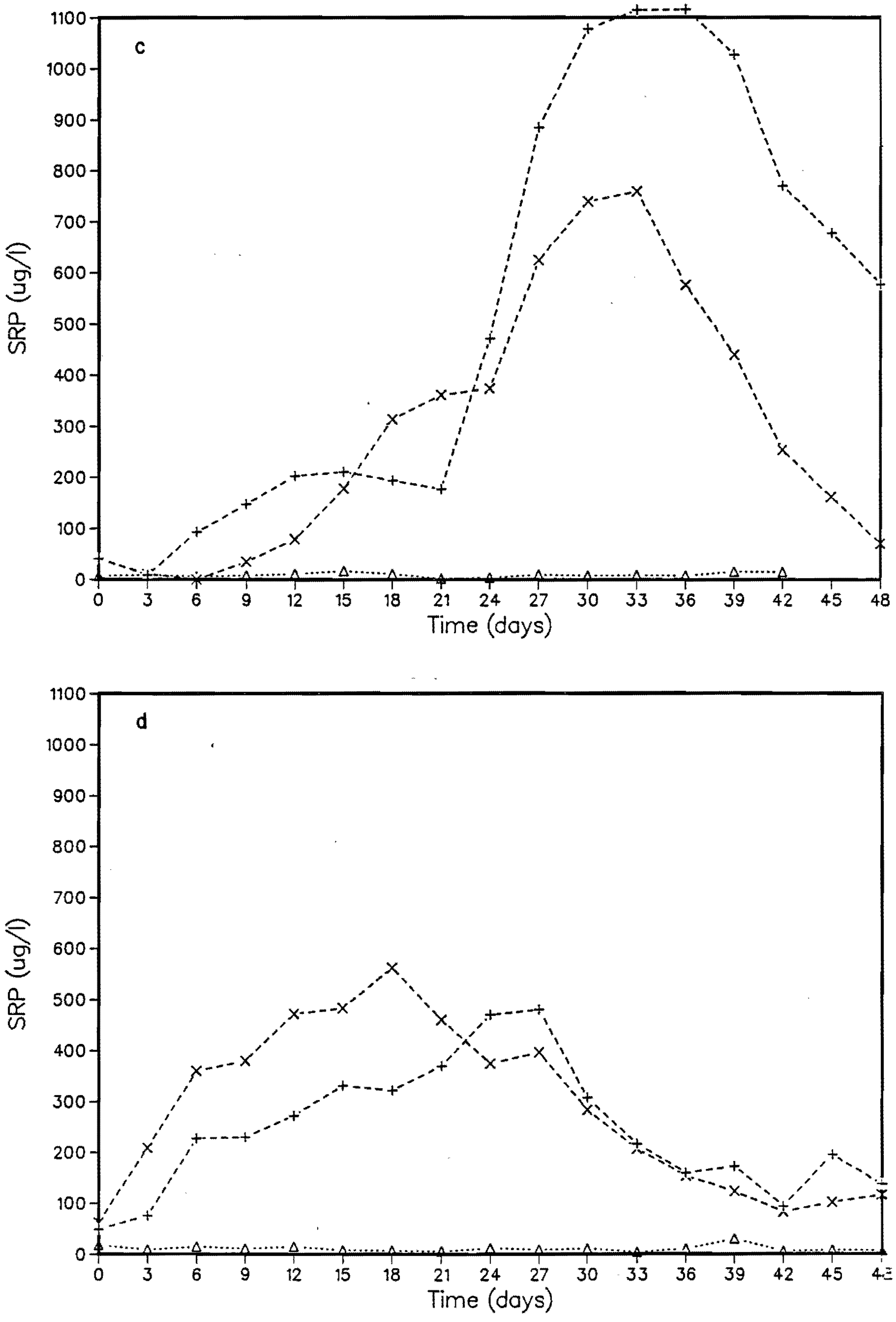


Figure 5. Continued.

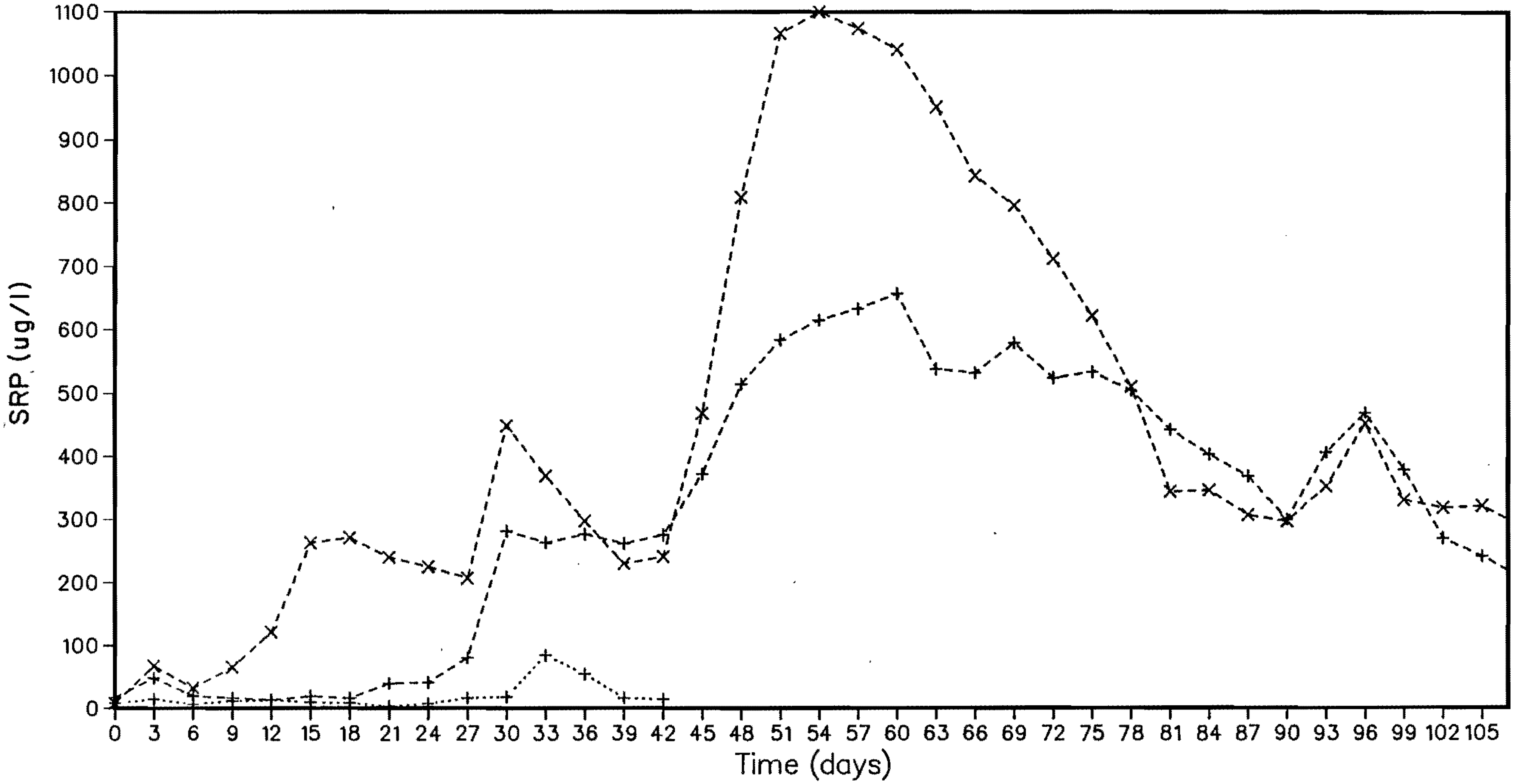


Figure 6. Soluble reactive phosphorus release from intact sediment collected in June 1984 from Deer Creek Reservoir. (+...+) aerobic upper site; (+--+) anaerobic upper site; (x--x) anaerobic lower middle site.

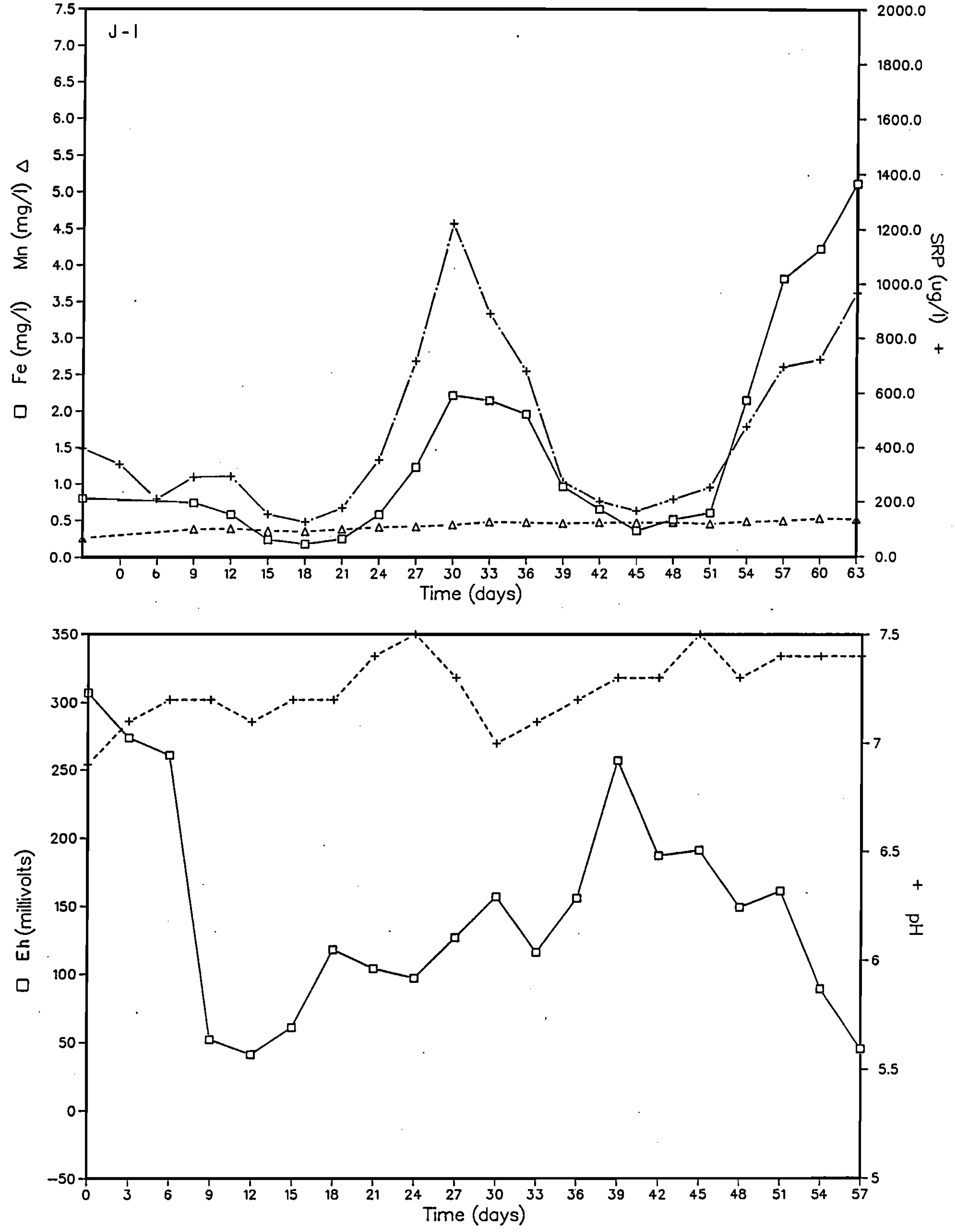
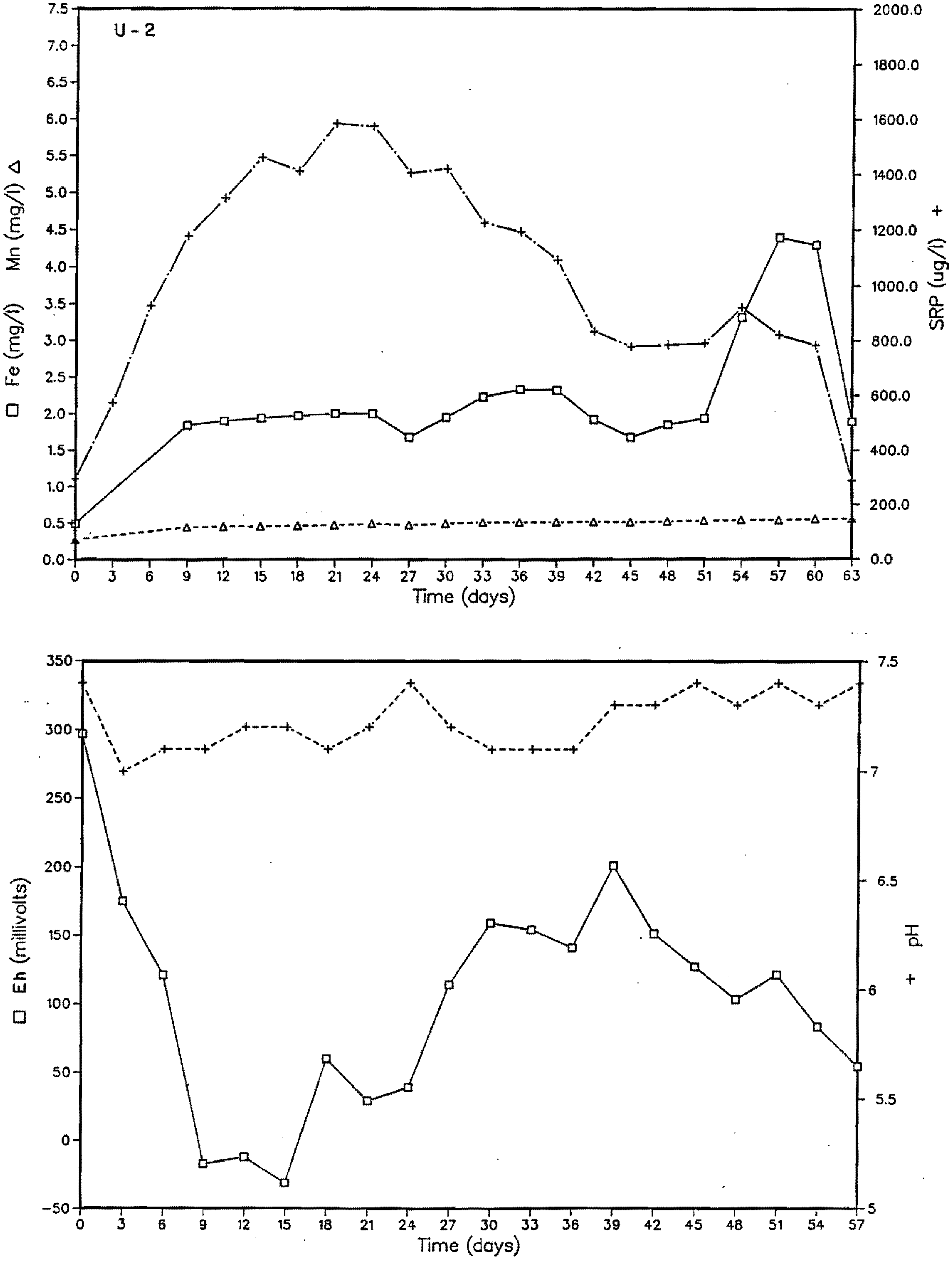


Figure 7. SRP, Fe, Mn, Eh, and pH in the water overlying sediment cores collected from sites U, UM, and LM (Figure 1) in Deer Creek Reservoir in October 1984 and incubated under an N_2 atmosphere.



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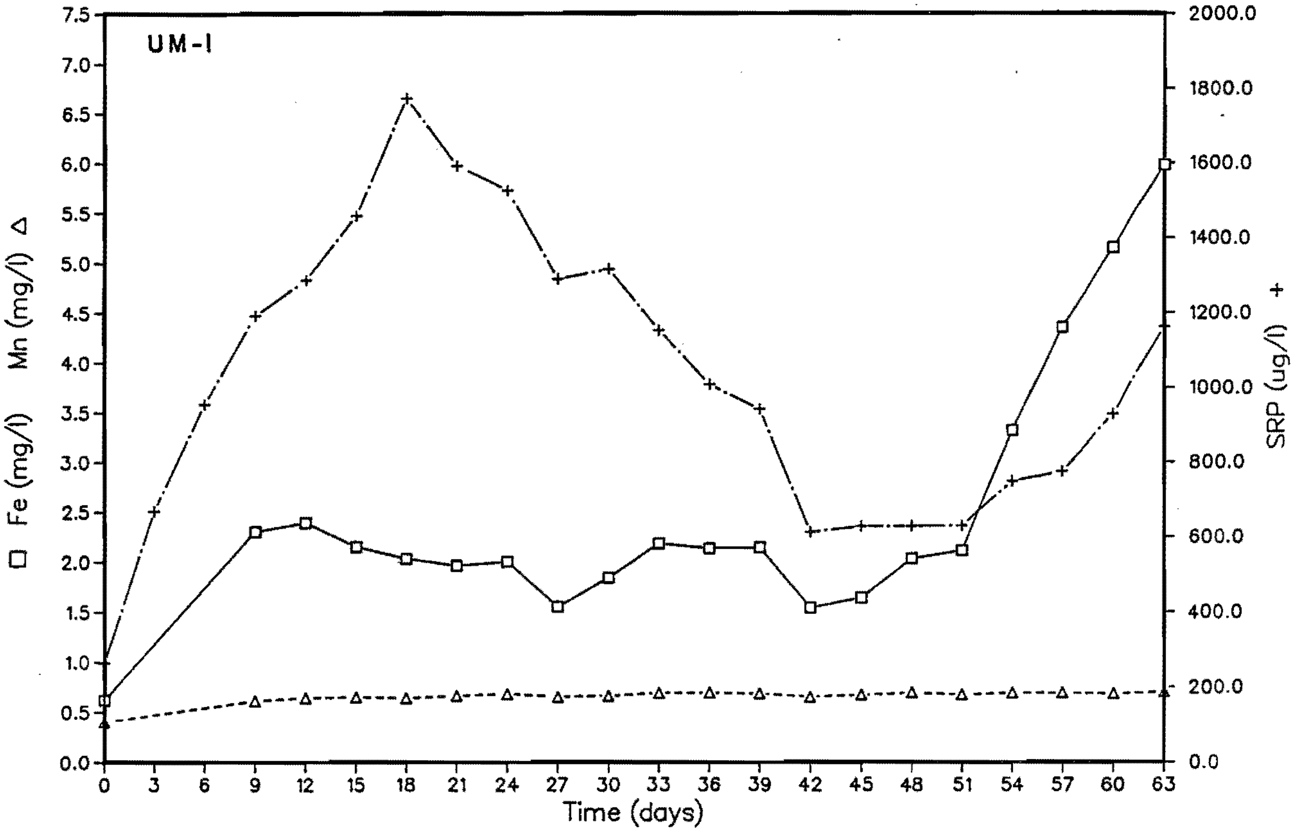


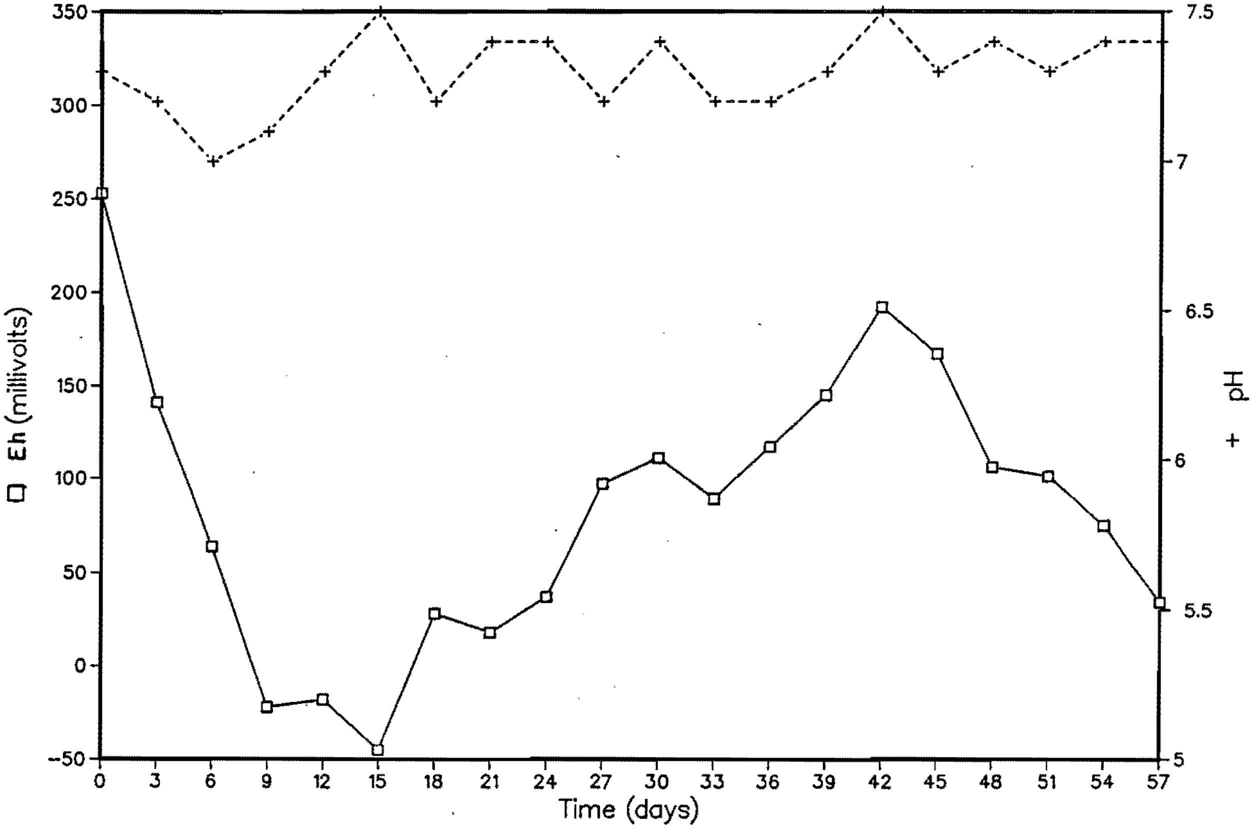
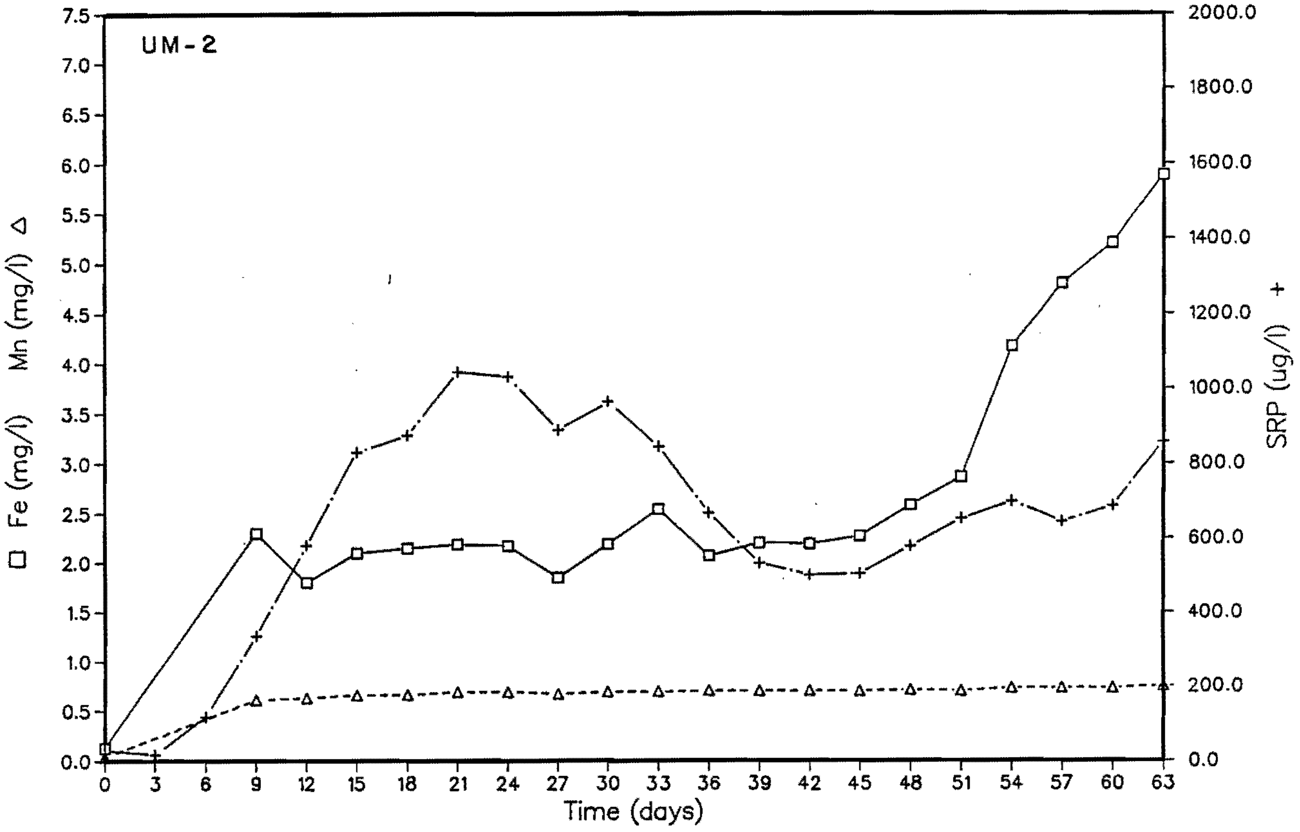
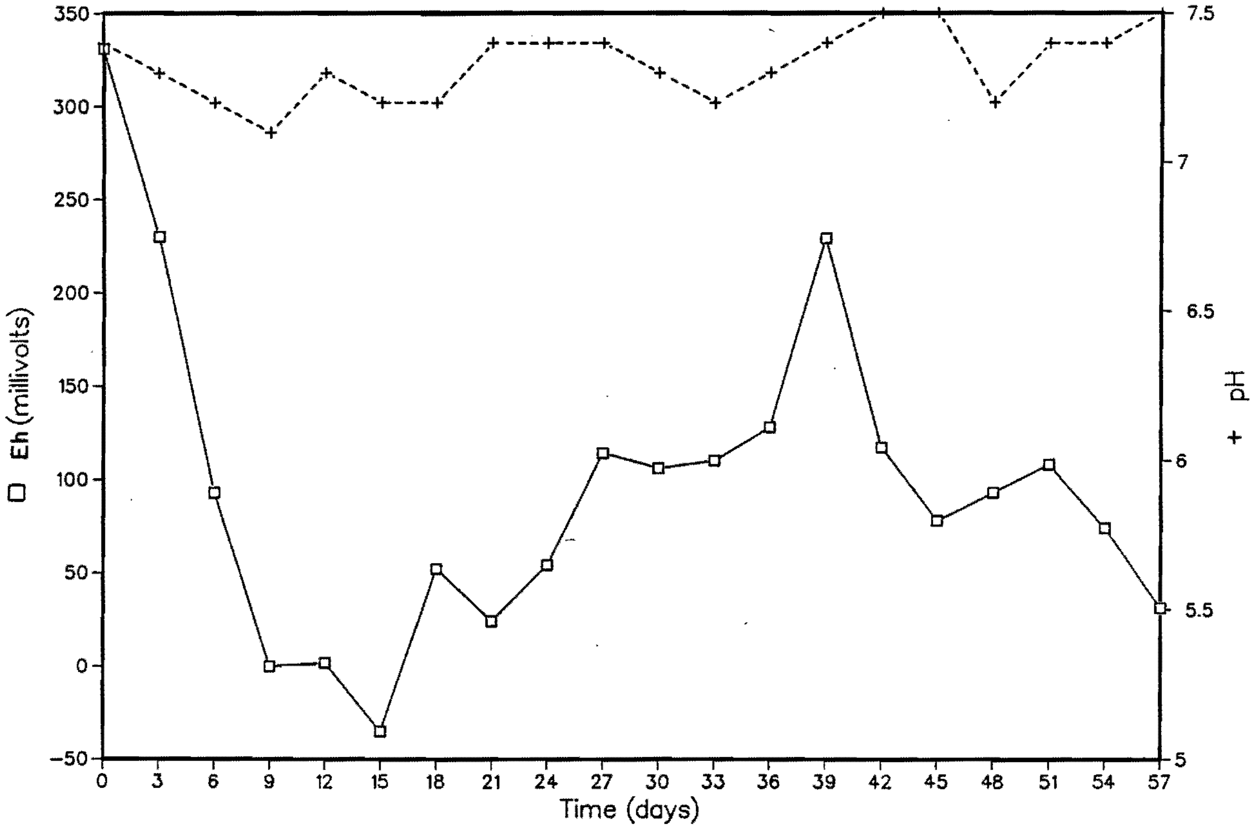


Figure 7. Continued.





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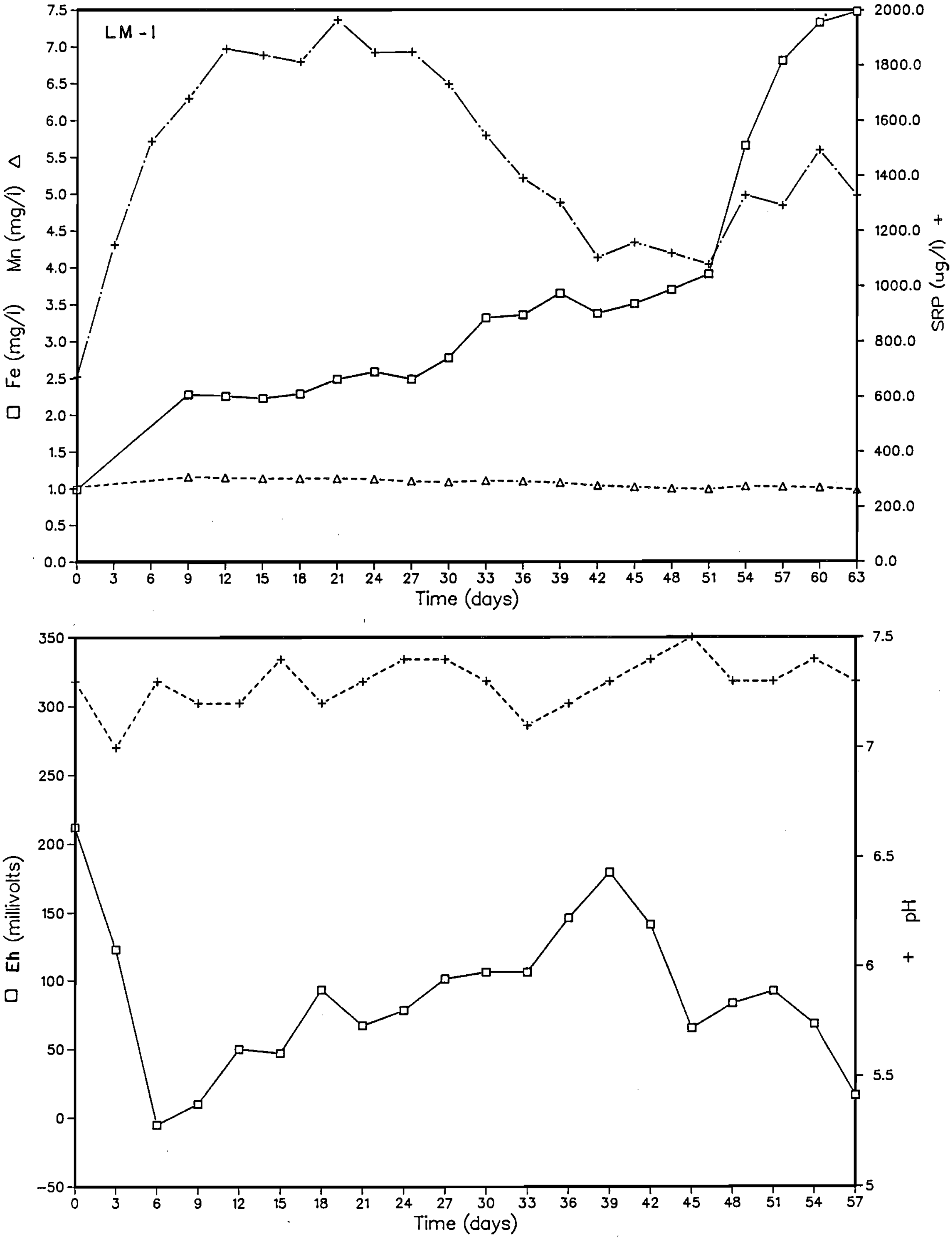

Figure 7. Continued.

could phosphate have precipitated onto siderite. Also, although all of the chambers were supersaturated with respect to apatite, none were ever saturated with respect to the more kinetically labile Ca-P phases such as tricalcium or octacalcium phosphate (e.g., Nancollas et al. 1979). Also, calcite was never supersaturated, thus precluding coprecipitation of phosphorus onto calcite. These observations suggest that the control of phosphorus concentrations in these cores may be controlled by some unknown clay mineral complex (e.g., Nriagu 1976), or by a nonequilibrium biological process.

We have found in previous studies (e.g., Messer and Ihnat 1983b), that SRP release rates are often predictable on the basis of NaOH-P in the sediments, and that SRP and Fe release rates often are highly correlated (Messer et al. 1983b). Figure 8 demonstrates that, while high levels of both Fe and SRP release occurred in the cores, the correlation was not strong. This observation suggests that high rates of both SRP and Fe are released under anaerobic conditions, but not at a constant ratio. Similarly, NaOH-P is not a good predictor of P release in these sediments (Figure 9).

Examination of various sediment parameters, including total sulfur, Fe and Mn extractable in the CDB-P fraction, percent $CaCO_3$, percent dry weight, percent organic carbon, and X-ray mineralogy, failed to show any consistent differences between the Deer Creek sediments and those from the other reservoirs studied. However, Deer Creek is unusual among these reservoirs in that it receives a higher proportion of its P loading from municipal wastewater inputs. Because most of the data were collected during a very wet water year with such low hydraulic retention times, the reservoir did not develop the usual anaerobic conditions in the hypolimnion. Also, an unusual dense inflow current flowing along the bottom of the reservoir and directly into the hypolimnetic outlet works probably removed sedimenting detritus that normally would have settled to the sediment surface, which may have altered the amount or quality of phosphorus available for release.

Table 3 summarizes the results of a number of phosphorus release simulations carried out over the course of the study. Cores were not always collected at each station on each date because of logistic problems with either sampling or incubating the cores. There are sufficient data, however, to see some definite trends. First, it is obvious that aerobic release rates are only a small fraction of the anaerobic release rates from these cores. This observation points strongly to the involvement of the redox cycle of iron in controlling phosphorus release from these sediments.

The second major observation with respect to the release rates relates to spatial and temporal patterns within the reservoir. Both aerobic and anaerobic release rates from the sediments appear to be higher in the fall at all stations than in the summer. This observation is consistent with the interpretation that much of the SRP release is ultimately driven by the decomposition of blue-green algae blooms that develop in the reservoir during late summer. The low aerobic release rates, relative to the anaerobic release rates on the same dates, suggest, however, that when oxidized iron gels are present at the sediment-water interface, SRP released by decaying phytoplankton is trapped within the surficial sediments. It might also be expected that the early summer release rates, ranging from approximately 1.6 to 3.0 mg P/m^2-day, may represent a reasonable estimate of the "background" SRP release rate that could be expected to result from phosphorus trapped in the sediment in previous years or deposited during spring runoff.

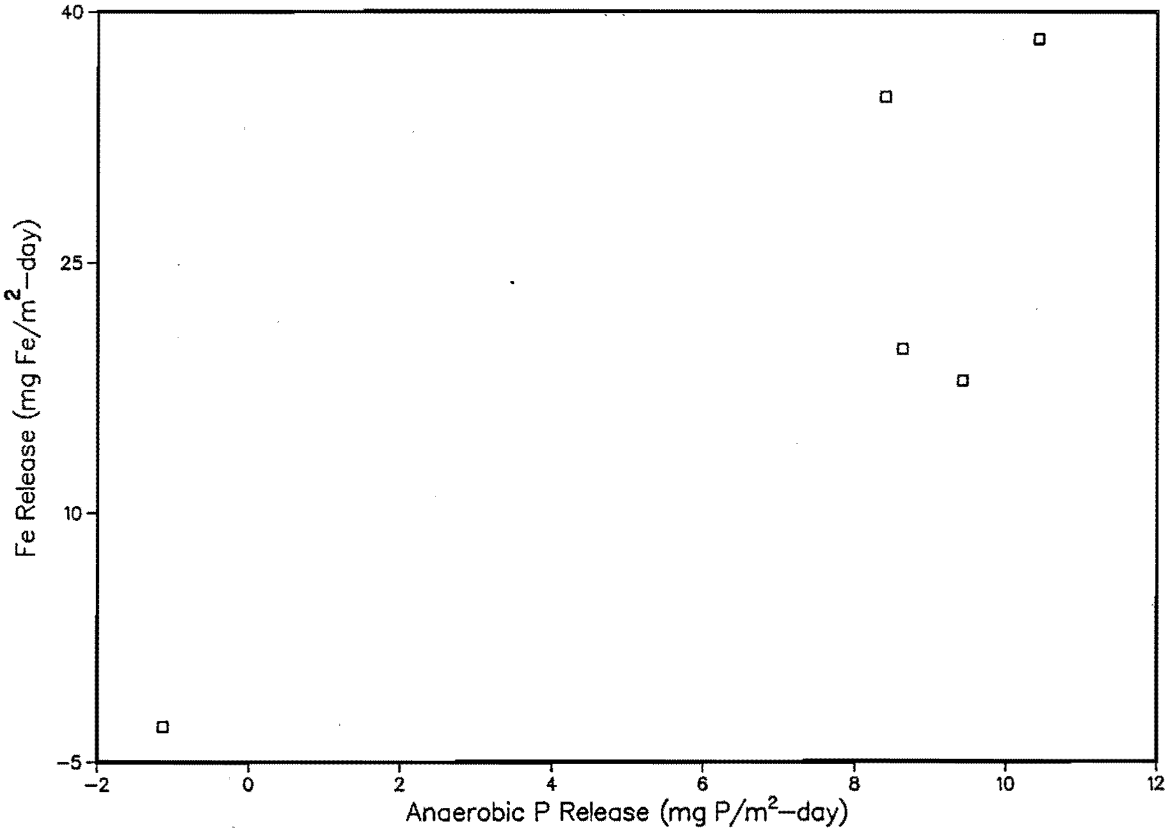

Figure 8. Relationship between SRP and iron release rates from Deer Creek sediment collected in October 1984 and incubated under an N_2 atmosphere.

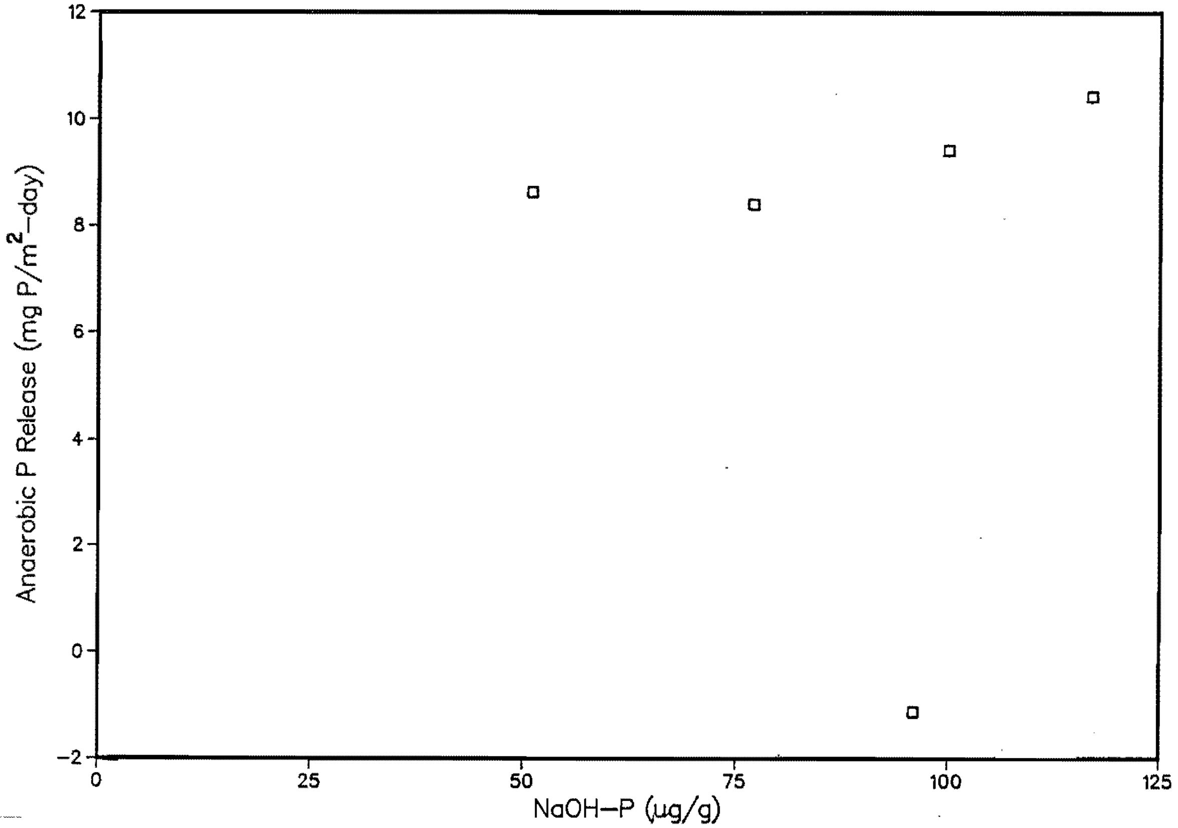

Figure 9. Relationship between SRP release rates from Deer Creek sediment collected in October 1984 and NaOH-extractable P in the top 8 cm of each core.

Table 3. Aerobic and anaerobic P release rates based on 45-day laboratory incubations of intact sediment cores.

Station	Release rate (mg P/m^2-day) 11/4/82	6/18/83	7/20/83	8/26/83	10/4/83
Upper	0.3[a]	0.1		-	1.4
	8.8[b]	2.1	3.0[c]	-	9.4
Upper middle	0.3	-	<0.1	-	<0.1
	5.0	-	6.5[c]	-	8.5[c]
Lower middle	0.9	0.1	<0.1	-	0.1
	6.8	2.9	3.0[c]	2.5	10.4[c]
Lower	0.6	-	<0.1	-	-
	12.1	-	1.6[c]	0.3	3.2

[a] Aerobic
[b] Anaerobic
[c] Mean of duplicate incubations

Although insufficient data were collected for rigorous statistical analyses, the spatial pattern of SRP release appear to be related to the distribution of phytoplankton blooms and the hydrodynamics of the reservoir. Phytoplankton blooms in Deer Creek are generally focused in the upper and upper middle basins of the reservoir, represented by the first two sampling sites. In the fall of 1982, the highest release rates were found at the upper reservoir station. Labile phosphorus originating either from senescing phytoplankton or zooplankton fecal pellets, is focused onto the sediment surface from a relatively shallow water column, thus maximizing the areal deposition rate. When phytoplankton blooms render the sediment-water interface anoxic at the upper end of the reservoir, SRP is released to the water column where it exacerbates the phytoplankton bloom. When phytoplankton subsequently are rafted toward the dam by wind or currents, biomass P transported to the downstream sediments is likely to be more or less permanently trapped at the oxygenated sediment-water interface.

The SRP release pattern in Table 3 could suggest that, in a downstream direction in the deeper parts of the reservoir, the SRP release rate increases due to the longer time that the sediment-water interface has remained oxic, thus trapping any SRP mineralized from detritus. This scenario is supported by several other bits of evidence. Extractable manganese concentrations in the surficial sediments increase in a downstream direction in the reservoir (Table 2), possibly indicating mobilization in the upper reservoir and deposition in the middle and lower ends. Extractable Fe:P ratios also decrease in a downstream direction in the reservoir, which would make sense if one were to reason that the low Fe:P ratios in the upper end of the reservoir result from a combination of high P loading combined with frequent Fe migration out of these frequently anoxic sediments (cf Figure 8). The high release rates from the most downstream sediments then would result from the fact that these sediments had relatively little chance to release P during the year because the overlying water was usually aerobic.

During the following year, this pattern was slightly altered by unusual hydrodynamic events associated with an unusually large snowmelt hydrograph. During the summer, prior to the onset of heavy blooms in the lake (which began in early July), "background" P release rates were observed, until the mid-July sampling date, when maximum SRP release rates at the upper middle station in the reservoir coincided with the spatial peak of phytoplankton biomass. The low P release rates at the lower reservoir site during mid-1983 may have resulted from a density-driven interflow in the mid- to lower reaches of the reservoir during this summer, which probably drove much of the settling phytoplankton detritus out of the reservoir through the hypolimnion withdrawal. SRP release rates during the fall of 1983 were higher than in the previous year, at all but the lower reservoir station. The higher release at the upper-reservoir sites may result from the earlier sampling date, or from the generally higher phytoplankton biomass observed in the reservoir during the latter year.

A temperature experiment was conducted on triplicate cores from the upper end of the reservoir in 1983 in order to provide data for adjusting SRP release rates from the laboratory columns to in situ temperatures. The results of this experiment are shown in Figure 10, and they provide useful information about the probable nature of the SRP-release process in the upper reservoir. The data were analyzed using the Arrhenius relationship, which relates process rates to temperature (Stumm and Morgan 1981) according to the formula:

$$\ln(\text{release rate}) = \ln A - E_a/RT \;. \quad (1)$$

where

A = an empirically determined pre-exponential factor
E_a = the energy of activation for the reaction
R = the gas constant
T = Kelvin temperature

The model provided an excellent fit to the data (r^2=0.95), and indicated an energy of activation for the reaction of approximately 24.9 kcal/mole. This value is somewhat higher than the value of 18.1 kcal/mole found for phosphorus mineralization in Lake Erie sediments, but it is certainly in the range of values associated with reactions driven by the metabolic activities of microorganisms, rather than by simple dissolution or ion exchange (Matisoff et al. 1981). This observation further strengthens the argument for phytoplankton detritus driving the phosphorus release, but the process appears to be complicated by the buffering effects of iron in preventing or delaying release of the mineralized SRP. This result might also suggest a reason for the decline in SRP concentration (related to the release rate) in the later stages of the core incubations noted above.

Significance of Release Rates

The potential impacts of the release rates measured here depend on the timing and spatial relationships surrounding actual releases in situ, as well as on the hydrodynamics of the reservoir (e.g., Stauffer 1981). However, comparison of the values in Table 4 with results obtained in similar studies helps to put the release rates into perspective. Holdren and Armstrong (1980) observed release rates during 2 to 27 day incubation periods ranging from 0.02 to 83 mg P/m^2-day from some Wisconsin lake sediments, depending on the incubation conditions. Bioturbation by benthic invertebrates was found to greatly increase the rates of P release from

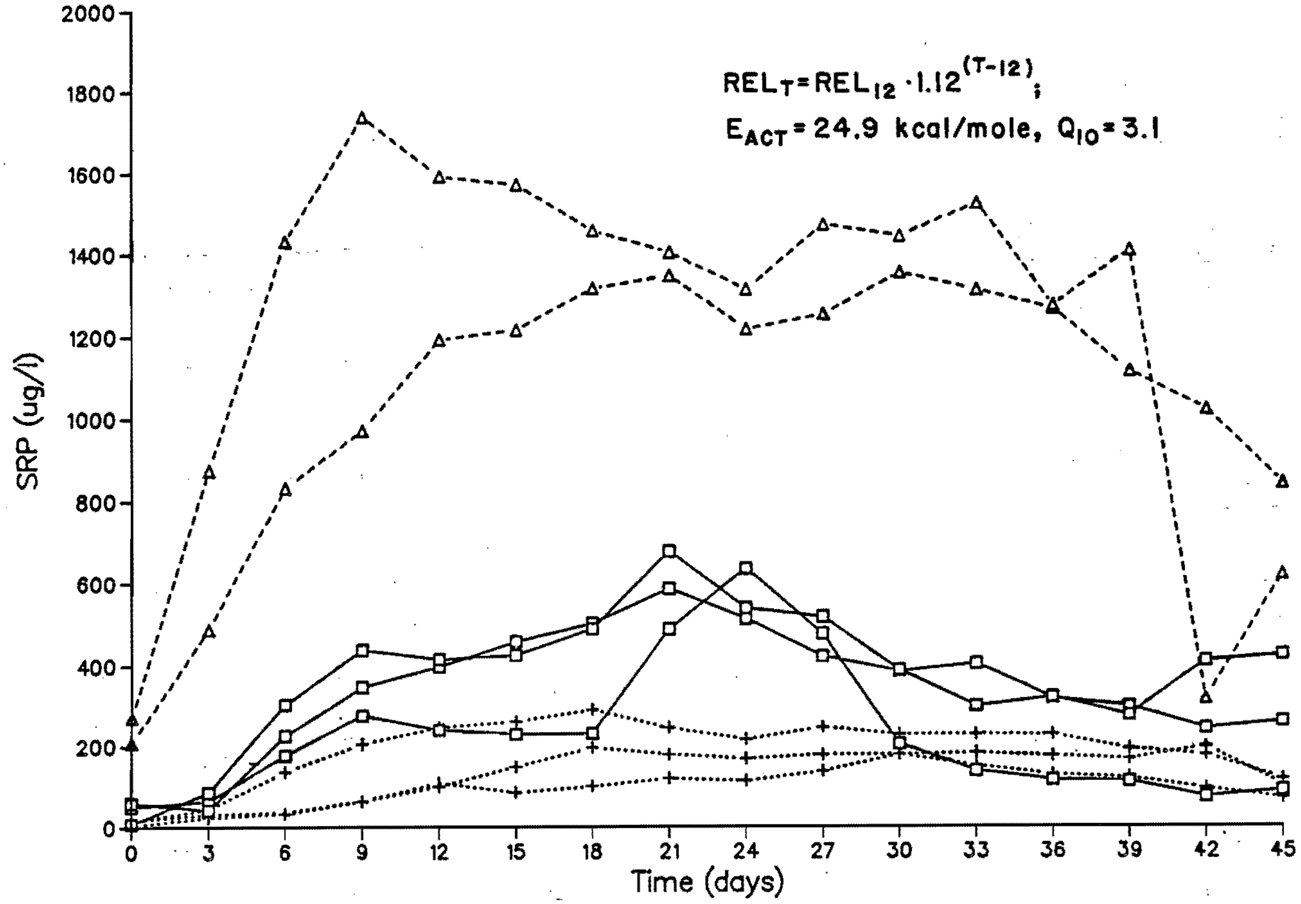

Figure 10. SRP release from intact cores collected from the upper reservoir sampling site in October 1984 and incubated under N_2 atmosphere at (+) 5.8°C, (□) 11.1°C, and (Δ) 19.7°C.

Table 4. Comparison of aerobic and anaerobic P release rates from sediment cores collected from some Intermountain reservoirs and incubated in the laboratory.

	Aerobic	Anaerobic
	(mg P/m²-day ± 1 S.D)	
Flaming Gorge	0.8±0.8 (5)	4.6±4.7 (5)[1]
Deer Creek	0.3±0.4 (12)	4.6±3.5 (25)
Panguitch	0.2 (11)	1.4 (1)
Scofield	0.1±0.1 (3)	0.4±0.4 (4)
Strawberry	0.0±0.0 (7)	0.2±0.4 (9)

Number of cores tested.

their epilimnetic sediments, but virtually no benthic invertebrates have been found in cores collected from Deer Creek. These authors also found temperature to be important in regulating SRP release from calcareous sediments and observed higher SRP release rates in the summer, when phytoplankton were abundant. Rates were often 5 to 100 times lower from cores collected from the same lake during the winter. These results confirm that labile organic P pools from senescent phytoplankton or macrophyte detritus may be a significant source of P release from epilimnetic lake sediments.

The results of in situ P release studies by Sonzogni et al. (1977) on the eutrophic, non-calcarious Shagawa Lake, Minnesota, are especially interesting in light of the confirmatory P budget calculations of Larsen et al. (1980). Using benthic release chambers, Sonzogni et al. (1977) determined release rates of P from profundal sediments to range from 6.2 to 8.3 mg P/m^2-day. Mass balance calculations led Larsen et al. (1980) to calculate a mean annual release of 10.2 mg P/m^2-day from these same sediments. Although not identical, the similarity of these estimates suggests that simulations can be a useful source of information on actual P release rates from lake sediments. Larsen et al. also calculated that the upper 10 cm of profundal sediments in the lake contained 15-25 times the calculated annual internal P loading in the form of NaOH-P. This internal loading has been the cause of the relatively slow response of this lake to restoration by reduction of P inputs (Larsen et al. 1975). Other whole-lake P balances also have frequently revealed quite high internal loadings of P from sediments, especially in response to decreased P loading from surface sources. Allan and Williams (1978) reviewed some of these studies, and cite rates ranging from 7 to 50 mg P/m^2-day, with their eutrophic Canadian prairie lakes falling into the range of 10-12 mg P/m^2-day.

We have conducted SRP release simulations similar to those reported here on several other Intermountain reservoirs, and the results are compared to those from the Deer Creek studies in Table 4. Deer Creek can be seen to be second only to Flaming Gorge Reservoir in SRP release rates. Actually, the mean anaerobic SRP release rate from Deer Creek is probably significantly higher, because the Flaming Gorge cores were incubated at 22-24°C, but no data were collected with which to perform a temperature correction. Flaming Gorge Reservoir, in the riverine reach where the cores were collected, also develops heavy late summer blooms of blue-green algae. The anoxic SRP release rates observed for Deer Creek Reservoir thus represent rates that have been seen to cause problems in other surface waters, although they are far below rates reported for many culturally eutrophic lakes of Europe (e.g., 20-50 mg/m^2-day), which have received heavy inputs of wastewater P for centuries.

The actual impact of release rates of the magnitude represented in Table 4 depends on the areal extent of each sediment type, the length of anoxia, and the effectiveness with which SRP is transported across the thermocline under stratified conditions. However, in a worst case scenario, if P transport to the euphotic zone were 100 percent efficient, then the average release rates for all of the anaerobic cores, 4.6 mg/m^2-day, would be able to support the production of approximately 230 $\mu g/m^3$ of chlorophyll a-day (Messer et al. 1983a), over the average depth of the reservoir (20 m). In other words, in the absence of surface P sources, zooplankton grazing, and algal senescence, approximately 10 mg chlorophyll a/m^3 could be produced over a 45-day period of anoxic release, an amount sufficient in itself to produce eutrophic conditions. However, because transport is not very efficient across the thermocline, and because some phosphorus is returned to the sediment by sinking detritus, the actual contribution of the sediments is certainly lower. The release rate from aerobic sediments would have a virtually negligible impact.

Paleolimnology

It was stated above that the absolute concentrations of NaOH-P or NAI-P were not useful in predicting differences in trophic states between lakes because of basic differences in the iron chemistry of different lake watersheds. However, paleolimnological studies have shown that cultural eutrophication of lakes is often accompanied by a sharp increase in the NAI-P or NaOH-P concentrations in the sediments. Allan and Williams (1978) demonstrated an increase in NAI-P from 69 to 268 mg/kg in 6 cores from Lake Erie between pre- and post-settlement horizons (1850). Allan et al. (1980) also demonstrated an increase from 306 to 528 mg/kg NAI-P with the onset of agriculture in nine Canadian prairie lake watersheds. Messer and Ihnat (1983a) showed that an increase in NaOH-P concentrations in the sediment profile from a reservoir in southern Utah corresponded to construction of the original dam which inundated a natural lake, and to rotenoning of the reservoir to remove trash fish. In each case, peaks in NaOH-P were associated with major changes in the dominant diatom flora preserved in the lake sediments. Thus, vertical profiles often can be useful in understanding time trends in the eutrophication of lakes and reservoirs.

Figures 11a-c represent a sediment profile (core 18) at a site approximately in the center of the reservoir, offshore from the State Park. In Figure 11a, the percent dry weight (dry weight wet weight) is seen to increase with depth in the sediment core as the result of compression. The bottom section contained fragments of woody plants, and thus marks the original riparian zone flooded when the dam was closed in 1941. A constant sedimentation rate model (Berner 1980) allows an estimate to be made of the corresponding date represented by each sediment section, and some example dates are shown in Figure 11a. These dates are in agreement with the observed peak of cesium-137 in the core, which corresponds to fallout from atmospheric nuclear testing in 1964. Figure 11b shows a gradual increase in the extractable Fe concentration toward the sediment surface, and very little differentiation of Mn with depth in the core, apparently indicating that the redox potential at the time the core was collected was low enough to release manganese, but not a great deal of iron.

The concentration profiles of the various phosphorus fractions are shown in Figure 11c. Each profile represents the cumulative values of the fractions thus far included, and the incremental contribution of each fraction is represented by the distance between two successive profiles. These sediments were analyzed using the older Mayer and Williams (1981) extraction technique, and hence cannot be compared to the values in Table 1. They are typical, however, of results using the newer Hieltjes and Lijklema technique on other cores, which have not yet been dated, in that there is no indication of a long-term trend in deposition of either NaOH-P or NAI-P. The observed increase in the NaOH-P concentration in the surface 6-8 cm is typical of most sediment cores, and results from a combination of trapping of iron-P at the sediment-water interface and the incomplete mineralization of organic detritus in the surface microzone. It is not likely to represent a recent increase in P loading to the reservoir or the sediment (e.g., Allan and Williams 1978). The reason for the NaOH-P peak at 25 cm depth is not known. It is unaccompanied by a peak in CDB-Fe (Figure 3b) and may represent an artifact.

The data used to construct Figure 3 also could be used to estimate the

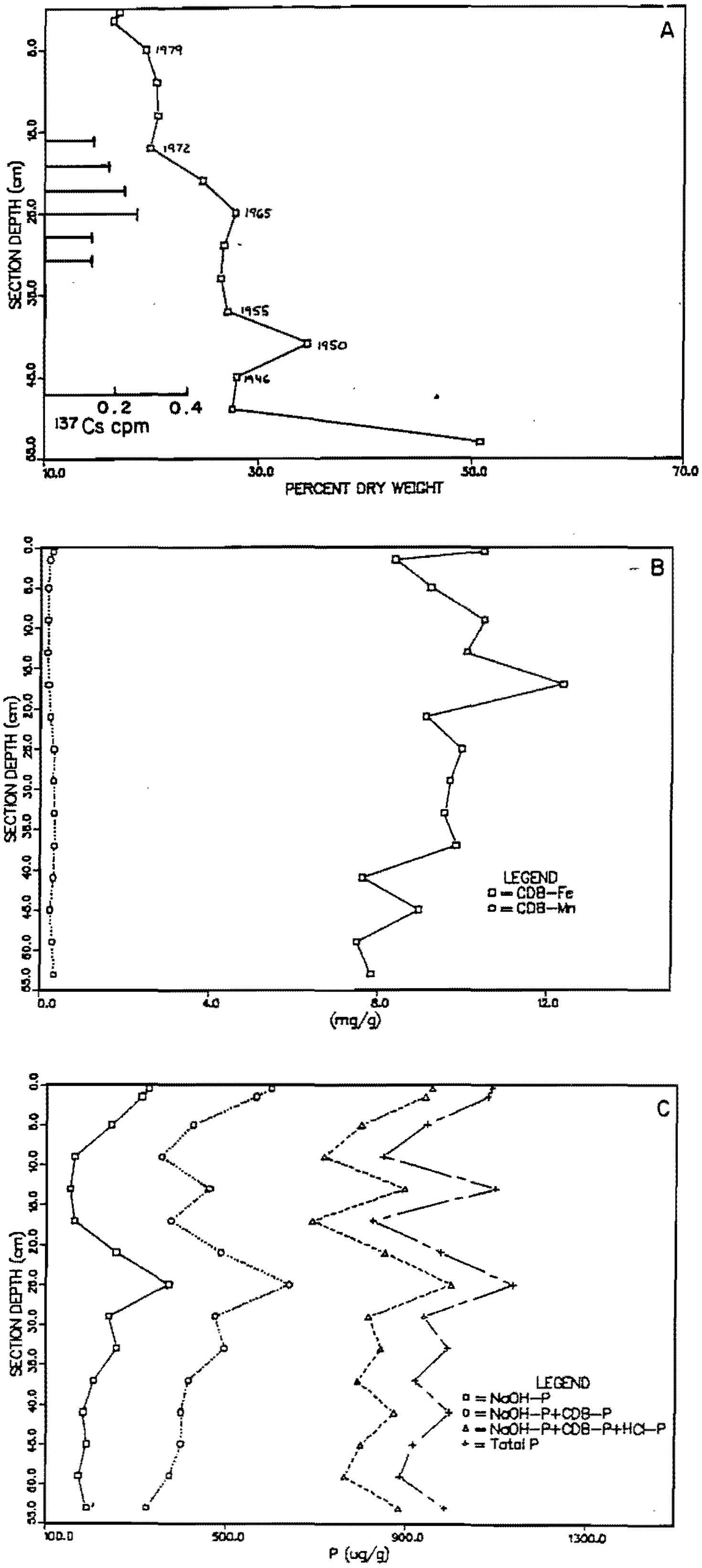

Figure 11. Chemical constituent profiles in core 18, Deer Creek Reservoir, November 1982.

phosphorus retention coefficient for the reservoir, providing a sufficiently large number of cores were available. For example, the total sediment loading represented by core 18 is 155 mg/m^2. Based on a mean total P concentration of 987 mg/kg (Table 1), the total P loading would be 153 g/m^2. If this loading were distributed over the 41 years since the dam was closed, the resulting P retention rate represented by the core has averaged 3.7 g/m^2-yr. This value is much larger than the calculated present day loading of 2.4 g/m^2-yr, especially for a calculated P retention coefficient of 0.17. A similar calculation based on a core from the upper middle of the reservoir gives a similar value. The minimum sedimentation rate calculated for a core from the upper end of the reservoir is 325 kg/m^2, which would considerably increase the retention estimate. Apparently, either very low sedimentation rates are characteristic of other parts of the reservoir, sediment focusing concentrates phosphorus in holes where sediment cores can be successfully collected, or a substantial amount of phosphorus enters the reservoir in the tributary bedload, which is not sampled in the normal course of monitoring. More sampling is needed to shed further light on this problem. Much of this phosphorus is probably large-grained detrital material (e.g., HCl-P) of low bioavailability.

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APPENDIX A

Concentration of various constituents on successive days of anaerobic incubated cores. Fe, Mn, Mg, Ca, and TIC are in mg/l, phosphorus is in μg/l, and temperature in °C.

Table A1. Upper station; October 4, 1983.

Day	Fe	Mn	Mg	Ca	PO_4-P	pH	Eh	TIC	Temp
0	0.80	0.26	12.6	60	396	6.9	79	0.046	10
3	----	----	----	--	338	7.1	42	0.046	11
6	----	----	----	--	211	7.2	21	0.046	17
9	0.74	0.38	11.8	67	291	7.2	-180	0.053	11
12	0.58	0.39	11.2	66	294	7.1	-192	0.051	11
15	0.24	0.36	10.7	65	155	7.2	-171	0.051	13
18	0.18	0.35	10.6	65	127	7.2	-118	0.051	11
21	0.25	0.38	10.3	66	178	7.4	-120	0.053	12
24	0.58	0.41	11.3	76	355	7.5	-143	0.053	12
27	1.23	0.42	10.0	68	715	7.3	-113	0.057	10
30	2.22	0.44	10.5	68	1220	7.0	-80	0.059	12
33	2.15	0.48	10.4	68	890	7.1	-81	0.059	11
36	1.96	0.47	9.9	66	679	7.2	-60	0.059	10
39	0.96	0.46	9.7	66	274	7.3	37	0.059	11
42	0.65	0.47	10.0	67	202	7.3	-36	0.055	10
45	0.36	0.47	9.6	71	167	7.5	-44	0.055	11
48	0.51	0.47	9.6	72	210	7.3	-84	0.057	10
51	0.60	0.45	8.8	70	253	7.4	-78	0.057	12
54	2.15	0.48	8.7	70	477	7.4	-141	0.058	12
57	3.82	0.49	8.5	71	695	7.4	-169	0.056	12
60	4.23	0.52	8.5	73	722	---	-194	0.058	12
63	5.12	0.51	8.2	72	966	---	----	-----	11

Table A2. Upper station; October 4, 1983.

Day	Fe	Mn	Mg	Ca	PO_4-P	pH	Eh	TIC	Temp
0	0.49	0.27	12.4	58	294	7.4	69	0.044	10
3	----	----	----	--	572	7.0	-57	0.052	11
6	----	----	----	--	926	7.1	-119	0.048	17
9	1.84	0.44	10.9	61	1176	7.1	-249	0.053	11
12	1.90	0.45	10.5	62	1313	7.2	-245	0.050	11
15	1.94	0.45	10.0	63	1459	7.2	-263	0.052	13
18	1.97	0.46	9.5	62	1411	7.1	-176	0.052	11
21	2.00	0.47	9.4	61	1583	7.2	-195	0.051	12
24	2.00	0.49	9.6	65	1574	7.4	-201	0.050	12
27	1.68	0.47	9.0	64	1405	7.2	-126	0.054	10
30	1.95	0.49	9.2	64	1420	7.1	-78	0.055	12
33	2.23	0.51	9.2	63	1225	7.1	-43	0.055	11
36	2.33	0.51	8.8	62	1193	7.1	-75	0.056	10
39	2.32	0.51	8.6	60	1093	7.3	-19	0.054	11
42	1.92	0.52	8.6	62	834	7.3	-73	0.054	10
45	1.68	0.51	8.2	65	777	7.4	-108	0.053	11
48	1.85	0.52	8.0	66	784	7.3	-130	0.053	10
51	1.94	0.53	8.1	65	790	7.4	-118	0.055	12
54	3.32	0.54	7.9	67	921	7.3	-147	0.056	12
57	4.40	0.54	7.5	68	821	7.4	-160	0.053	12
60	4.30	0.55	7.6	68	783	---	-186	0.055	12
63	1.89	0.56	7.8	69	288	---	----	-----	11

Table A3. Upper middle; October 4, 1983.

Day	Fe	Mn	Mg	Ca	PO_4-P	pH	Eh	TIC	Temp
0	0.62	0.40	11.7	55	264	7.3	25	0.042	10
3	----	----	----	--	669	7.2	-91	0.046	11
6	----	----	----	--	955	7.0	-176	0.047	17
9	2.30	0.61	10.3	58	1192	7.1	-254	0.047	11
12	2.39	0.64	9.9	58	1287	7.3	-251	0.046	11
15	2.15	0.65	9.4	58	1459	7.5	-277	0.049	13
18	2.03	0.64	9.1	58	1772	7.2	-208	0.048	11
21	1.96	0.66	9.0	57	1591	7.4	-206	0.047	12
24	2.00	0.68	9.0	59	1526	7.4	-203	0.046	12
27	1.55	0.65	8.5	59	1290	7.2	-143	0.049	10
30	1.84	0.66	8.6	59	1316	7.4	-126	0.050	12
33	2.18	0.69	8.7	58	1153	7.2	-108	0.050	11
36	2.13	0.69	8.4	59	1008	7.2	-99	0.050	10
39	2.14	0.68	7.9	57	941	7.3	-75	0.047	11
42	1.54	0.65	7.5	56	612	7.5	-31	0.049	10
45	1.64	0.67	7.4	61	627	7.3	-68	0.048	11
48	2.03	0.69	7.3	61	628	7.4	-127	0.046	10
51	2.11	0.67	7.1	61	629	7.3	-138	0.048	12
54	3.32	0.69	7.1	61	748	7.4	-155	0.049	12
57	4.35	0.69	6.8	62	774	7.4	-180	0.047	12
60	5.15	0.68	6.6	62	929	---	-181	0.049	12
63	5.98	0.70	6.4	62	1162	---	----	-----	11

Table A4. Upper middle; October 4, 1983.

Day	Fe	Mn	Mg	Ca	PO_4-P	pH	Eh	TIC	Temp
0	0.13	0.04	11.1	54	29	7.4	103	0.038	10
3	----	----	----	--	17	7.3	-2	0.040	11
6	----	----	----	--	117	7.2	-147	0.041	17
9	2.30	0.61	10.3	58	336	7.1	-232	0.044	11
12	1.80	0.63	9.4	55	580	7.3	-231	0.042	11
15	2.10	0.66	9.1	56	831	7.2	-267	0.047	13
18	2.15	0.66	8.7	56	875	7.2	-184	0.046	11
21	2.19	0.69	8.7	56	1044	7.4	-200	0.047	12
24	2.17	0.69	8.5	58	1031	7.4	-186	0.046	12
27	1.85	0.67	8.0	57	890	7.4	-126	0.048	10
30	2.19	0.69	8.4	58	965	7.3	-131	0.046	12
33	2.54	0.69	8.1	56	845	7.2	-87	0.047	11
36	2.07	0.70	7.9	56	667	7.3	-88	0.047	10
39	2.20	0.70	7.5	55	532	7.4	9	0.046	11
42	2.19	0.70	7.4	56	500	7.5	-106	0.046	10
45	2.27	0.70	7.1	57	504	7.5	-157	0.044	11
48	2.58	0.71	7.1	59	578	7.2	-140	0.045	10
51	2.86	0.70	6.8	57	651	7.4	-131	0.046	12
54	4.17	0.73	6.9	59	698	7.4	-156	0.047	12
57	4.80	0.73	6.7	59	644	7.5	-183	0.045	12
60	5.20	0.73	6.6	60	685	---	-190	0.047	12
63	5.88	0.75	6.4	59	857	---	----	-----	11

Table A5. Lower middle; October 4, 1983.

Day	Fe	Mn	Mg	Ca	PO_4-P	pH	Eh	TIC	Temp
0	0.99	1.02	11.7	56	672	7.3	-16	0.044	10
3	----	----	----	--	1148	7.0	-109	0.049	11
6	----	----	----	--	1525	7.3	-245	0.045	17
9	2.28	1.16	9.8	56	1678	7.2	-222	0.048	11
12	2.26	1.15	9.5	57	1859	7.2	-183	0.047	11
15	2.23	1.14	9.0	57	1836	7.4	-185	0.049	13
18	2.29	1.14	8.7	56	1811	7.2	-143	0.047	11
21	2.49	1.14	8.5	55	1963	7.3	-157	0.047	12
24	2.59	1.13	8.7	58	1845	7.4	-162	0.046	12
27	2.49	1.10	8.2	58	1847	7.4	-139	0.050	10
30	2.78	1.09	8.4	59	1730	7.3	-131	0.047	12
33	3.32	1.11	8.2	57	1545	7.1	-91	0.049	11
36	3.36	1.10	8.0	56	1390	7.2	-70	0.050	10
39	3.65	1.08	7.7	57	1302	7.3	-41	0.047	11
42	3.38	1.04	7.4	56	1103	7.4	-82	0.048	10
45	3.51	1.02	7.1	59	1157	7.5	-170	0.046	11
48	3.70	1.00	7.0	60	1118	7.3	-150	0.046	10
51	3.91	0.99	6.8	59	1078	7.3	-147	0.047	12
54	5.66	1.03	6.9	60	1329	7.4	-162	0.048	12
57	6.81	1.02	6.5	61	1292	7.3	-198	0.047	12
60	7.33	1.01	6.4	63	1493	---	-169	0.048	12
63	7.48	0.98	6.0	59	1328	---	----	-----	11

APPENDIX B

Concentrations of sediment phosphorus and metal fractions extracted from successive core segments from anaerobically incubated cores. All parameters except percent dry weight are in mg/kg.

		% Dry Wt	NH_4Cl	NaOH	ΣP	CDB-P	NAI-P	HCl-P	TOT-P	CDB-Fe	CDB-Mn
11-04-83	00-02	23.0	29	211	240	155	395	443	906	-----	—
LOWER	02-03	28.3	55	246	301	124	425	407	911	10400	80
	03-04	29.5	41	226	267	133	400	391	867	10800	60
	04-05	30.2	40	244	284	131	415	398	854	11300	60
	05-06	30.8	36	226	262	117	379	406	864	10800	60
	06-07	30.9	29	227	256	115	371	406	845	10900	60
	07-08	31.1	32	228	260	86	346	404	815	11000	60
	08-09	31.4	24	241	265	114	379	396	836	12000	60
	09-10	33.6	26	281	307	118	425	406	871	11700	60
	10-11	34.3	19	261	280	115	395	394	859	11300	60
	11-12	35.5	25	260	285	109	394	402	853	11400	50
06-18-83	00-02	15.3	19	517	536	168	704	511	1135	11800	170
LOWER	02-04	15.4	13	492	505	120	625	477	1089	12500	170
	04-06	18.2	14	519	533	298	831	572	1108	11100	170
	06-08	16.6	9	439	448	214	662	452	923	11100	120
	08-10	20.1	5	426	431	171	602	478	994	11700	150
	10-12	22.7	7	431	438	172	610	462	975	10400	140
06-18-83	00-02	34.5	27	140	167	168	335	625	926	7600	60
UPPER-MIDDLE	02-04	43.5	24	133	157	212	369	632	866	7600	50
	04-06	44.0	17	116	133	31	164	611	849	7600	40
	06-08	46.7	12	93	105	99	204	582	819	6700	40
	08-10	55.3	11	78	89	178	267	655	669	6200	30
	10-12	70.8	13	36	49	40	89	617	579	3400	30
07-20-83	00-02	27.6	64	215	279	120	399	455	850	9500	100
UPPER-MIDDLE	02-04	34.6	68	277	295	95	390	460	902	7700	70
	04-06	27.5	30	147	177	129	306	464	762	8500	60
	06-08	49.6	43	153	196	81	277	558	800	5300	50
	08-10	39.6	34	198	232	99	331	453	822	7900	70
	10-12	52.9	27	110	137	85	222	516	679	7600	70
07-20-83	00-02	30.8	50	179	229	124	353	438	812	7800	80
UPPER-MIDDLE	02-04	34.0	38	166	204	213	417	414	722	9500	60
	04-06	39.0	24	172	196	101	297	425	697	7800	50
	06-08	55.9	30	86	116	55	171	352	639	4800	40
	08-10	57.4	29	87	116	50	166	525	587	3900	40
	10-12	37.7	50	218	268	103	371	496	853	7700	60
07-20-83	00-02	35.9	85	163	248	66	314	445	813	8300	100
UPPER	02-04	46.7	99	103	202	218	420	465	682	5000	50
	04-06	46.1	79	91	170	84	254	436	669	4400	30
	06-08	49.9	71	82	153	78	231	405	584	4000	30
07-20-83	00-02	39.1	57	117	174	192	366	590	773	7200	70
LOWER-MIDDLE	02-04	54.2	75	153	228	127	355	474	765	6600	80
	04-06	62.7	64	165	229	159	388	422	650	7100	90
	06-08	66.8	71	160	231	30	261	357	678	7100	100

		% Dry Wt	NH_4Cl	NaOH	ΣP	CDB-P	NAI-P	HCl-P	TOT-P	CDB-Fe	CDB-Mn
07-20-83 LOWER	00-02	14.1	55	272	327	96	423	454	967	11100	110
	02-04	16.2	52	295	347	90	437	437	956	10700	120
	04-06	18.8	39	286	325	41	366	432	917	11500	120
	06-08	19.3	26	279	305	223	528	532	873	11300	120
07-20-83 LOWER	00-02	13.5	51	325	376	62	438	434	993	11700	110
	02-04	17.0	64	303	367	147	514	472	960	11000	130
	04-06	18.6	34	304	338	8	346	407	903	12100	130
	06-08	19.1	29	290	319	44	363	401	733	12300	120
07-20-83 LOWER-MIDDLE	00-02	50.2	99	157	256	56	312	459	753	---	--
	02-04	66.4	102	143	245	171	416	422	694	---	--
	04-06	73.0	141	165	306	26	332	369	696	---	--
	06-08	75.2	151	160	311	193	504	408	739	---	--
08-04-83 UPPER	00-02	32.7	60	202	262	---	---	---	---	---	--
	02-04	36.5	59	183	242	---	---	---	---	---	--
	04-06	39.6	65	219	284	---	---	---	---	---	--
	06-08	46.7	60	161	221	---	---	---	---	---	--
08-04-83 UPPER	00-02	33.3	45	210	255	158	413	552	906	7200	82
	02-04	39.9	61	264	325	188	513	554	967	8600	98
	04-06	46.0	54	158	212	104	316	550	880	5900	75
	06-08	45.3	50	165	215	213	428	647	946	5900	66
	08-10	48.5	54	165	219	169	388	568	842	5500	33
	10-12	48.9	57	172	229	177	406	574	877	5300	33
08-04-83 UPPER-MIDDLE	00-02	52.3	39	97	136	---	---	---	---	---	--
	02-04	58.1	39	98	137	---	---	---	---	---	--
	04-06	60.0	43	103	146	---	---	---	---	---	--
	06-08	60.8	43	111	154	---	---	---	---	---	--
08-04-83 UPPER-MIDDLE	00-02	48.0	26	141	167	117	284	358	521	5100	83
	02-04	56.4	37	130	167	147	314	346	512	4400	90
	04-06	65.8	57	190	247	145	392	376	539	5400	101
	06-08	70.9	72	157	229	180	409	734	338	4000	107
	08-10	63.5	59	127	186	133	319	293	583	3600	91
08-04-83 LOWER-MIDDLE	00-02	20.0	23	258	281	191	472	408	727	8600	83
	02-04	22.8	30	235	265	128	393	380	684	8600	82
	04-06	23.6	9	234	243	145	388	392	646	9700	75
	06-08	25.3	11	208	219	129	348	399	626	9300	74
	08-10	29.9	12	200	212	126	338	406	605	8300	74
	10-12	32.3	13	180	193	9	202	353	569	8700	67
11-18-8?	00-02	16.7	72	541	613	83	696	271	---	12600	340
	02-04	14.0	60	516	576	83	659	261	---	10000	260
	04-06	19.5	35	359	394	66	460	259	---	11100	200