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Reconnaissance of Sediment-Phosphorus Relationships in Some Utah Reservoirs

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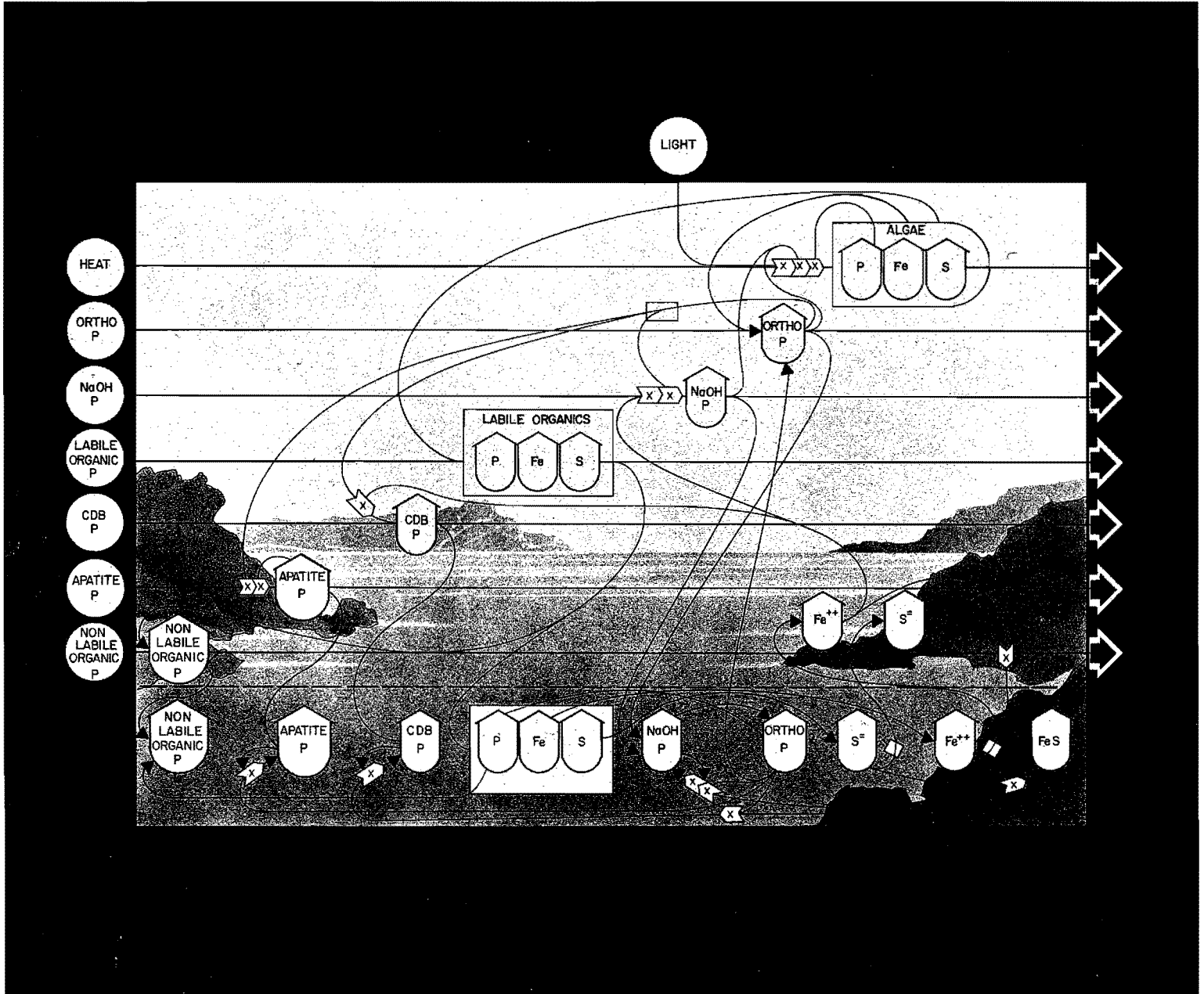
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RECONNAISSANCE OF SEDIMENT-PHOSPHORUS RELATIONSHIPS IN SOME UTAH RESERVOIRS

Jay J. Messer and Jean M. Ihnat



Utah Water Research Laboratory
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 Logan, Utah 84322

WATER QUALITY SERIES
 UWRL/Q-83/03

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TABLE OF CONTENTS

	Page
INTRODUCTION	1
METHODS	3
RESULTS AND DISCUSSION	7
SUMMARY AND CONCLUSIONS	21
REFERENCES	23

LIST OF FIGURES

Figure		Page
1	Coring sites and locations of study reservoirs . . .	4
2	P release from Core 17, Deer Creek Reservoir (November 1982), and Core PLO-1 Panguitch Reservoir (December 1982) under oxic and anoxic conditions in laboratory incubations	12
3	Chemical constituent profiles in Core PLO-1, Panguitch Reservoir, December 1982	15
4	NaOH-P concentrations and corresponding sediment dates in Core PLO-1, Panguitch Reservoir, December 1982	17
5	Chemical constituent profiles in Core 18, Deer Creek Reservoir, November 1982	19

LIST OF TABLES

Table		Page
1	Summary of chemical analyses based on the extraction procedure "D" of Williams et al. (1971) and P release rates for sediment cores taken from several reservoirs in the Intermountain West	8
2	Comparison of P fractions and CDB-Fe in some reser- voir sediment cores based on the extraction technique of Hieltjes and Lijklema (1980)	11

INTRODUCTION

Phosphorus inputs to lakes and reservoirs from tributary streams and non-point sources are well-known contributors to nuisance algal growths that degrade water quality for potable and recreational uses in lakes and reservoirs. However, phosphorus inputs to the euphotic zone may also occur 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 these 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). A series of studies on sediments in several reservoirs in the Intermountain West is being conducted at the Utah Water Research Laboratory, Utah State University, in order to further our understanding of important sediment-water interactions in the phosphorus cycles of such reservoirs. The data reported here represent preliminary results from the first field season of these studies. They relate to the phosphorus chemistry of the sediments themselves, and to P 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 several reservoirs, and to suggest some implications of these results regarding the potential for further eutrophication or the potential for recovery of the reservoirs under study. Because the inferences are drawn from preliminary data, the conclusions should be regarded as tentative. Messer et al. (1983) have provided a review of the pertinent literature, and Stauffer (1981) has presented a rationale for relating such sediment release data to the impact on the overlying water column.

METHODS

Sediment cores were collected from three stations in Panguitch Reservoir in October 1982, at four stations in Deer Creek Reservoir in November 1982, and at one site in Scofield Reservoir in December 1982 (Figure 1). The cores were collected using a gravity corer equipped with an acrylic core liner with an internal diameter of 44-47 mm (Tapp Plastic Co., Salt Lake City). The cores were returned to the laboratory within 3 days after collection, and placed in a 4°C cold room in the dark.

On the following day, the cores were extruded and sectioned into 2 cm slices, except for the top 2 cm, which was sectioned into 2, 1 cm slices. The entire top 13 cm of the Scofield core was homogenized, rather than being sectioned. Wet weights were determined on each section, before drying to constant temperature in a 105°C oven. Dry weights also were measured, thus allowing fractional dry weight to be calculated.

Phosphorus and metal analyses were performed on aliquots of the dried sediments following scheme "D" of Williams et al. (1971) as modified by Mayer and Williams (1981). A 60 mg aliquot of sediment was extracted first in 30 ml cold 0.1 N NaOH/1 N NaCl solution for 18 hr on a reciprocating shaker table. The resulting suspension was centrifuged and filtered through a Whatman GFC filter, and ortho-P 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 N NaHCO₃ for 15 min in an 85°C water bath. 0.6 gram of Na-dithionite was then added, and the solution was incubated for an additional 15 min. Orthophosphate was determined on the CDB extracts using the colorimetric finish of Weaver (1974). 0.6 ml of 1 M FeCl₃ was added to each extract and the solution was bubbled with wet air for 4 hr 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 ortho-P 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 1.0 N HCl at room temperature on a shaker table for 18 hr. The supernatant was centrifuged and filtered, and ortho-P 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. (1980) to be comprised of Ca-bound P species.

One core from each reservoir was also analyzed following the technique of Hieltjes and Lijklema (1980). This technique was identical to the one described

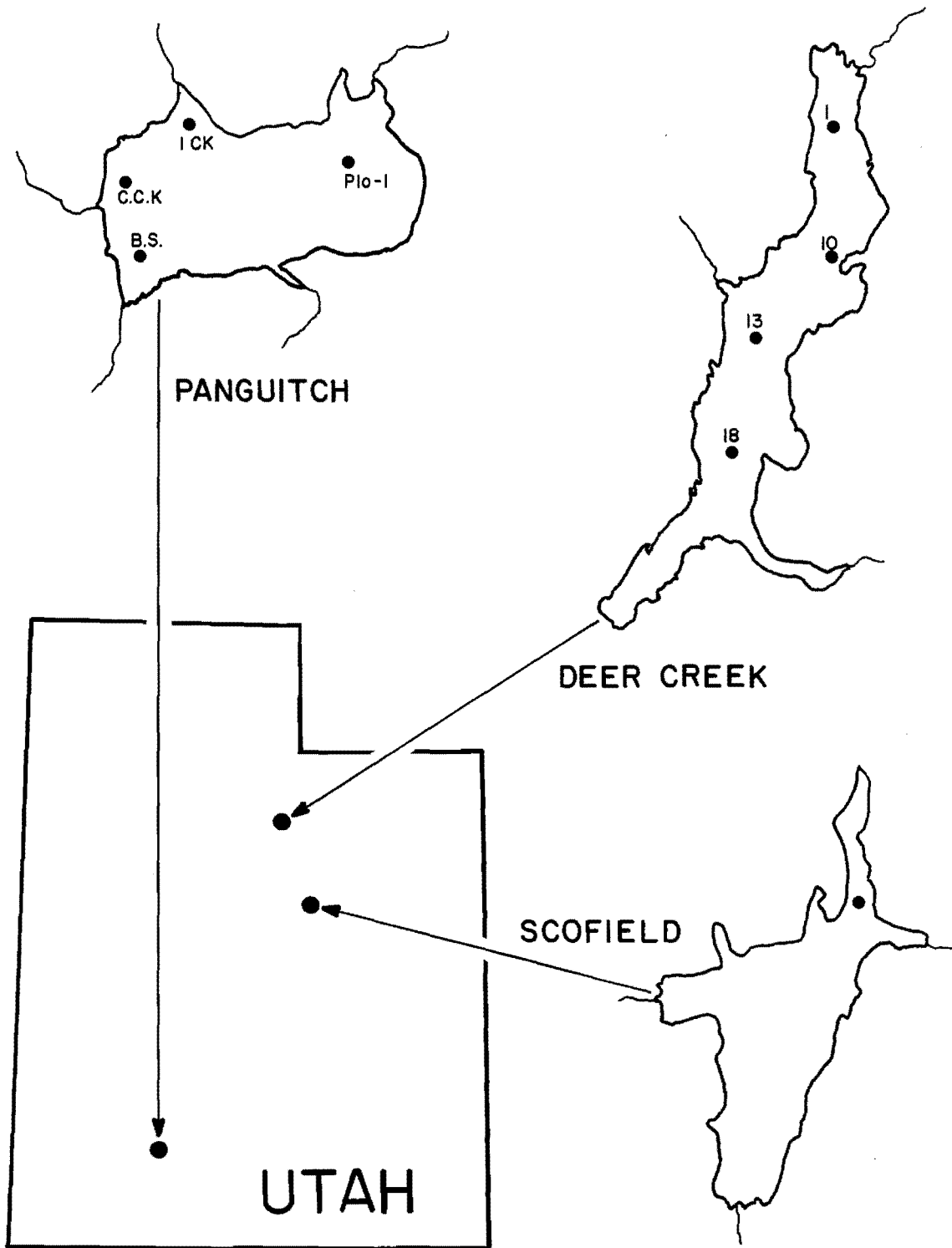


Figure 1. Coring sites and locations of study reservoirs.

above, except that the NaOH/NaCl extraction was proceeded by two sequential extractions of the sediment pellet in 30 ml of 1N NH₄Cl for 2 hr on a shaker table at room temperature. Ortho-P was determined on the combined, filtered supernatants from the two extractions using the ascorbic acid method (APHA 1981). Hieltjes and Lijklema found that the NH₄Cl was necessary in order to prevent coprecipitation of some of the Fe-P on CaCO₃ during the NaOH/NaCl extraction of some calcareous sediments.

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 HNO₃, by atomic absorption spectrophotometry on an IL Model 357 spectrophotometer. The standard curve was prepared using standards carried through the entire extraction procedure.

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, UT.

Phosphorus release studies. In order to compare aerobic and anoxic release rates of phosphate from the sediments, duplicate cores taken from various stations in Panguitch and Deer Creek Reservoirs were incubated under either aerobic or anaerobic conditions in the laboratory for 48 days. In Panguitch Reservoir, one core taken from station PLO-1 and one core from station A-4 were incubated under anoxic and aerobic conditions, respectively. In the case of Deer Creek Reservoir, duplicate cores from all sites were incubated and monitored. Prior to incubation, all cores were pushed toward the top of the core tube using the rubber stopper in the bottom as a piston, so that the sediment surface was approximately the same distance from the top of the core tube in each core. This was done to minimize differences among cores in turbulence or microbial biomass growing on the exposed surface of the core tube.

The aerobic core was incubated with an open headspace, into which was inserted a paddle attached to a jar test apparatus to provide mechanical stirring (4 rpm). The paddle was painted with an epoxy resin that has been determined to be inert to surface chemical reactions. Before each sampling, deionized water was added to the core to make up for evaporation, and after 2 min of stirring, an 8 ml aliquot of water was withdrawn into an acid washed flask containing a crop of 5 N nitric acid (inclusion of the acid acted as a control for the anaerobic cores, where 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 µm Gelman membrane filter prior to analysis for ortho-P, using the manual ascorbic acid method (APHA 1981). All aerobic incubations were carried out at at 9°C in the dark.

The anoxic core was 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, 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% purity, subsequently passed through an Alltech

gas purifier) was bubbled into the water for 4-5 min 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 5 N nitric 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 N₂ to remove any O₂ inadvertently admitted during sampling. Toward the end of the experiment, the replacement water was bubbled with N₂ to further assure anoxic conditions following sampling. However, no significant change in P release was observed as a result of this added precaution. Anaerobic incubations were carried out in the dark at two different temperatures, 6°C and 9.5°C.

RESULTS AND DISCUSSION

Sediment chemistry. The results of the sediment analyses based on extraction procedure "D" of Williams et al. (1971) are shown in Table 1, along with some results obtained from Flaming Gorge Reservoir for purposes of comparison. The values represent the surface 13 cm of sediment. This depth was arbitrarily chosen to allow a comparison to be made with the Flaming Gorge data, but it also corresponds to the relatively active diagenetic zone of most of the sediments (e.g., Allan and Williams 1978).

NaOH-P concentrations were highest in the core from the middle of Panguitch Reservoir, intermediate in most of the cores taken from Deer Creek and near Blue Spring Creek in Panguitch Reservoir, and quite low in the cores taken near Clear Creek in Panguitch and the upper middle of Deer Creek Reservoir. The low values in the latter two cores probably resulted from differences in physical composition between these cores and the others. The low-P cores were coarse-grained and heavy-textured, relative to the soft, dark-colored sediments typical of deep-water sediments.

The NaOH-P concentrations in all but the two low-P cores were higher than the cores taken from the lower Green River arm and below the confluence in Flaming Gorge Reservoir. Also, they fall within the range of values typical of eutrophic lakes studied by Allan and Williams (1978). Although it is not possible to categorize the trophic state of a lake or reservoir based on the sediment P concentration alone, NaOH-P has been shown to be highly correlated with anaerobic P release rates from sediment cores taken from upper Flaming Gorge and incubated in the laboratory (Messer et al. 1983). Therefore, the NaOH-P concentration may provide a useful indicator of the potential for P release into an anoxic hypolimnion. 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, on the basis of their NaOH-P contents, most of the Panguitch, Deer Creek, and Scofield Reservoir sediments would be expected to release significant amounts of P if their hypolimnia became anaerobic.

NAI-P concentrations tended to be highest in the lower Flaming Gorge sediments and in the central basin of Panguitch Reservoir, and lowest in the low-NaOH-P sediments described above. In most cases, NAI-P appears to increase in a downstream direction in the reservoirs, perhaps indicating mobilization from upstream sediments followed by deposition in deeper water. Such a pattern may result from anoxic conditions in the upstream reaches being followed by typically oxygenated conditions downstream in a reservoir. This scenario would be consistent with conditions observed in Flaming Gorge and Deer Creek Reservoirs. Another possibility is that Fe-P may be associated with finer sediment particle sizes that would settle out farther downstream (e.g. Frink 1969). The NAI-P concentrations in most of these sediments is in the range typical of eutrophic lakes (Allan and Williams 1978).

Table 1. Summary of chemical analyses based on the extraction procedure "D" of Williams et al. (1971) and P release rates for sediment cores taken from several reservoirs in the Intermountain West.

	P Concentrations (mg/kg)				Mole Ratios		Release Rates (mg/m ² -day)	
	NaOH-P	NAI-P	Apatite-P	Total P	Fe:NAI-P	Fe:S	Aerobic	Anoxic
Deer Creek Reservoir								
Upper (1) ¹	224	355	507	934	9	2.1	1.2 (0.3) ²	9.9 (4.0)
Upper Middle (10)	18	208	337	782	2	0.8	1.5 (0.3)	5.7 (2.3)
Lower Middle (13)	212	418	429	912	11	2.2	3.7 (0.9)	7.7 (3.1)
Lower (18)	211	444	385	874	13	1.6	2.8 (0.6)	13.7 (5.5)
Flaming Gorge Reservoir								
Lower Blacks Fork (14)	43	359	510	901	6	2.5	0.5	1.7
Upper Green River (4)	86	319	498	843	13	5.6	0.2	1.8
Lower Green River (9)	169	520	464	1090	7	2.4	2.1	11.1
Below Confluence (19)	113	472	506	1038	7	1.8	1.2	8.2
Panguitch Reservoir								
Middle (PLO-1) ³	283	543	176	726	6	2.2	-	3.1
Clear Creek (C.K.)	33	192	345	656	6	1.6	-	-
Blue Spring Creek (B.S.)	169	260	325	752	10	3.4	1.0	-
Scofield Reservoir	192	345	680	1160	17	5.3	-	-

¹Numbers in parentheses represent core designations.

²Corrected to 25°C; numbers in parentheses represent 9.5°C (aerobic) and 7.2°C (anoxic).

³Average for 2 cores.

Apatite-P concentrations ranged from 176 to 664 mg/kg, and were generally highest at the more shallow stations. The highest value was found in Scofield Reservoir, and the lowest value at the deep station in Panguitch Reservoir. The patterns observed are consistent with a source of suspended apatite-P in the watershed settling out preferentially at the stations nearer the tributaries. Under the ambient chemical conditions in the bottom waters of these reservoirs (i.e. neutral to high pH), any such apatite-P would remain trapped in the sediment, with little possibility of interacting with the overlying water. However, it is also possible that some of this P results from precipitation of Ca-P species in response to increases in pH brought about by phytoplankton blooms in the upstream reaches of the reservoirs (e.g. Messer et al. 1981).

If most of the HCl-P is detrital, rather than autochthonous in origin, then apatite-P may account for 15 to 47 percent of the total P in the Utah reservoir sediments. The majority of this P is included in the reservoir P loading calculations. Therefore, care must be taken when priorities are being set for reducing P loading from the various input streams, that the majority of the P loading in the streams being considered does not belong to this relatively inert fraction. By the same line of reasoning, reduction of P loading known to be of readily available form (e.g. wastewater or feedlot inputs) may exert a beneficial effect that far outweighs its fractional contribution to the total P loading.

Two other sediment chemical parameters that are useful in determining the importance of sediments in 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 anthropogenic inputs of P from the watershed. They cited a range of ratios of from 6 to 12 (mole basis) for a group of Canadian prairie lakes known to exhibit significant internal P loading, while lakes with apparently little internal P loading had values above 20. The Panguitch sediments appear to be characterized by quite low Fe:P ratios, and thus would be expected to release P readily under anoxic conditions. The Fe:P ratios in the deep-water Deer Creek sediments and the upper Green River arm of Flaming Gorge are somewhat higher, and the high Fe concentration in the Scofield sediment would appear to result in a low equilibrium solubility of Fe-P under anoxic conditions for this sediment.

The mobility of NAI-P also depends on the relative concentrations of Fe 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*. Because FeS controls the solubility of Fe in anoxic sediments, a sulfide concentration that exceeds a 1:1 molar ratio with Fe^{++} , will result in a complete breakdown of the control of P solubility by vivianite (e.g. Emerson and Widmer 1978). P will then 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, the 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 ($\text{Fe}_3(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$) and anapatite ($\text{Ca}_2\text{Fe}(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$). 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 2 cm of the reservoir sediment cores are shown in Table 1. All values are higher than 1.0, except for the core taken from the upper middle of Deer Creek Reservoir. Consequently, all of the other cores contain sufficient Fe to control P release under anoxic conditions. Also, the ratios presented represent minimum estimates, because Fe extractable in CDB may not include unreactive pyrite-Fe, while the total S measured by the Leco furnace would include pyrite-S (e.g. Stauffer 1981).

Subsequent to the sediment analyses reported in Table 1, it was discovered that NaOH-P and NAI-P were underestimated, and HCl-P was overestimated, by Williams et al. scheme "D" procedure when applied to Flaming Gorge sediments (Messer et al. 1983). Therefore, core 18 from Lower Deer Creek Reservoir, a duplicate of core PLO-1 from Panguitch Reservoir, and the Scofield sediment were re-extracted using the procedure of Hieltjes and Lijklema (1980), which employs extraction with NH_4Cl prior to NaOH extraction, in order to avoid coprecipitation of P in the NaOH step on CaCO_3 precipitated at the high pH of the NaOH extractant. The corresponding results are shown in Table 2, along with low- and high-P cores from Flaming Gorge for comparison.

Exchangeable (NH_4Cl)-P was quite high in the Panguitch core, relative to the other sediments studied, although all NH_4Cl -P concentrations were much lower than those in the NaOH-P fractions. NaOH-P concentrations were higher than the values obtained using scheme D (Table 1), especially when the latter values should equal the sum (Σ) of the NH_4Cl -P and NaOH-P fractions. The ordinal magnitudes are similar using either method, however, CDB-P was generally low, and the resulting NAI-P concentrations were similar in the Deer Creek and Panguitch cores using either method. NAI-P was underestimated in the Scofield sediment (344 versus 465) by scheme D, as was the case for the Flaming Gorge sediments. HCl-P concentrations were high in Scofield and similar to the values in Flaming Gorge, but were much lower in the Deer Creek and Panguitch sediments. Organic P accounts for a much larger fraction of the total P in the latter sediments. Fe concentrations were similar using either extraction procedure, and the resulting Fe:NAI-P ratios (except for the Scofield sediment) are not much different than the values in Table 1.

Table 2. Comparison of P fractions and CDB-Fe in some reservoir sediment cores based on the extraction technique of Hieltjes and Lijklema (1980).

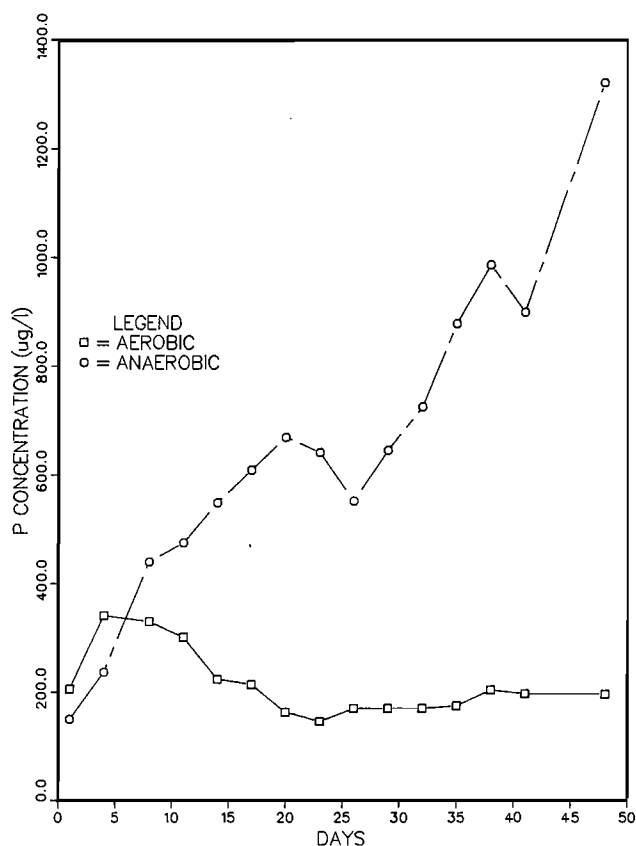
P-fraction	Deer Creek (18)	Panguitch (PLO-1)	Scofield	Flaming Gorge	
				(UBF)	(BC)
NH ₄ Cl-P	34	144	59	32	65
NaOH-P	373	277	302	204	325
Σ	407	421	361	236	390
CDB-P	69	59	104	68	82
NAI-P	476	480	465	303	472
HCl-P	258	137	543	454	506
Organic-P	250	295	161	180	60
Total-P	984	912	1,160	937	1,083
CDB-Fe	8,800	4,700	9,100	4,300	6,000
Fe:NAI-P	10	5	11	8	7

In conclusion, the core chemistry studies suggest that Fe-P available for release from anoxic sediments represents somewhat less than half of the total P in the reservoir sediments studied, and that the concentrations in Deer Creek and the central basin of Panguitch Reservoir are in the range that have been shown to result in significant internal P loading problems in other lakes and reservoirs. Fe is not overly abundant in these, sediments, and watershed P inputs appear to have stressed the P-assimilative capacities of all of the reservoir sediments. The concentrations of sulfur in these sediments, except for one site in Deer Creek Reservoir, is sufficiently low not to interfere with the control of P solubility by vivianite in anoxic sediments.

P-release rates. P release rates determined on the basis of laboratory incubations of some reservoir sediment cores are also compared in Table 1. The results of two P-release experiments are shown in Figure 2. In Deer Creek core 17 (a replicate of core 18 in Table 1), aerobic release peaked during the first 2 days and subsequently leveled off (because each water sample was replaced with deionized water containing no P, a flat curve indicates a low, constant release rather than no release). In contrast to the aerobic core, the anaerobic core continued to release P at a substantial rate during the entire experiment. The increase in the release rate following day 24 corresponded to an increase in the incubation temperature from 5.7° to 9.5°C.

In the Panguitch cores, aerobic release peaked during the first 2 days and subsequently leveled off, rising slightly near the end of the incubation. The anoxic core released P at a substantial rate during the first few days of the incubation, and subsequently maintained a 300 µg/l ortho-P concentration with a relatively slow constant release rate. This pattern is typical of a lake sediment exhibiting an "equilibrium" concentration of phosphate (Mayer and Gloss 1980), and is in contrast to the behavior of P in the anoxic incubations of the Deer Creek

P RELEASE DEER CREEK



P RELEASE PANGUITCH

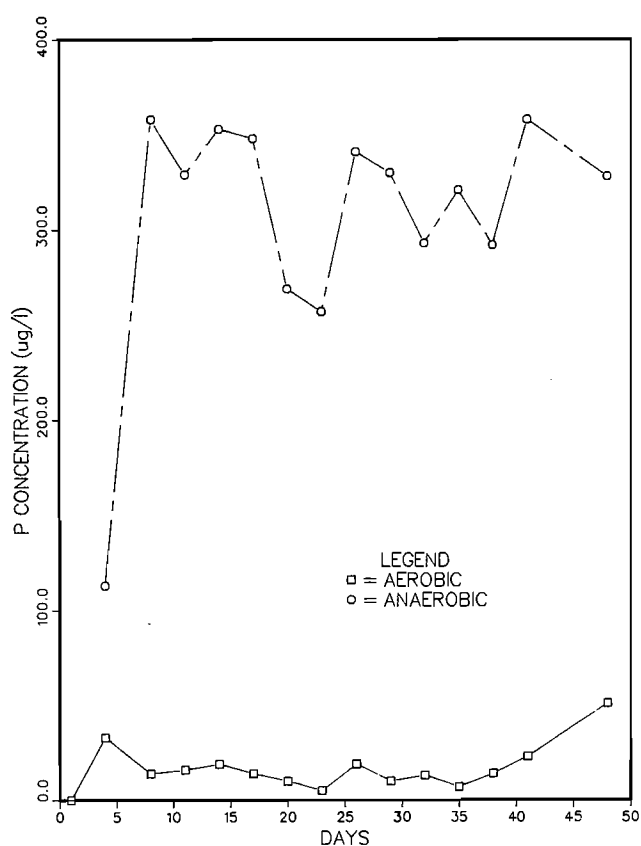


Figure 2. P release from Core 17, Deer Creek Reservoir (November 1982), and Core PLO-1 Panguitch Reservoir (December 1982) under oxic and anoxic conditions in laboratory incubations.

cores, which continued to rise above the range of 600-1200 $\mu\text{g/l}$ after an identical incubation period.

The release rates have been corrected to 25°C in Table 1, based on temperature-dependent P mineralization and diffusion coefficients, used by Jorgensen et al. (1982) to model P release from the sediments of a Danish Lake. This was done in order to convert the release rates to a common temperature basis (25 C) for comparison with the Flaming Gorge cores, which were incubated at the higher temperature. The actual rates, which correspond to an average temperature of 7.2°C, are shown on the table for purposes of comparison.

It can be seen from Table 1 and Figure 2 that in all of the sediment cores examined, P release was greatly enhanced by anoxic conditions, thus indicating the importance of the redox cycle of Fe in controlling P release. However, the relatively low equilibrium concentrations maintained by the Panguitch cores resulted in an unusually low P release rate, relative to the expected results based on the concentrations of NaOH-P found in the cores (Table 1). This result suggests that the factors controlling P release from the Panguitch sediments are both different and more effective than those mechanisms controlling release from

the other Intermountain reservoirs. The low P release, despite the apparently high organic P content, also suggests that the organic P present is probably composed primarily of refractory humic P (Cosgrove 1977). Additional work will be necessary to elucidate the exact nature of these species and mechanisms observed in cores from upper Flaming Gorge.

If core 10 is excluded from the Deer Creek cores, the high anoxic P release rates are consistent with the high NaOH-P concentrations, as observed in the Flaming Gorge sediments, although the NaOH-P concentrations do not account for the variations in P release rates among the Deer Creek cores themselves. Also, the highest P release rate corresponds to the highest Fe:NAI-P ratio, which is counter to the expectations outlined above. A probable explanation for these discrepancies is that the variation in core chemistry between cores taken at the same site is as high as the variation between sites, which was not the case in Flaming Gorge. The high rate of P release from the core collected in the upper middle of the reservoir, relative to the low NaOH-P concentration, may be the result of the low Fe:P and Fe:S ratios, as suggested above. Because the Scofield core was homogenized during shipment, no release experiments were conducted.

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 1 with results obtained in similar studies helps to put the release rates into context. Holdren and Armstrong (1980) observed release rates during 2-27 day incubation periods ranging from 0.02 to 83 mg P/m²-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 their epilimnetic sediments. Redox potential was more important in regulating release from non-calcareous sediments, while temperature was more important in calcareous sediments. It is also noteworthy that they observed high release rates from cores collected during the summer, when phytoplankton were abundant. Rates were often 5-100 times lower from cores collected from the same lake during the winter. These results suggest that labile organic P pools from senescent phytoplankton or macrophyte detritus may be a significant source of P release from epilimnetic lake sediments. The cores from both Panguitch and Deer Creek Reservoirs were collected during senescing blue-green algal blooms, which may have provided such a pool of labile phosphorus in the sediments.

The results of in situ P release studies by Sonzogni et al. (1977) on the eutrophic, non-calcareous Shagawa Lake, Minnesota, are especially interesting in light of the confirmatory P budget calculations of Larsen et al. (1981). 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/m²-day. Mass balance calculations led Larsen et al. (1981) to calculate a mean annual release of 10.2 mg P/m²-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).

Although not always accompanied by sediment studies, whole-lake P balances frequently reveal 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/m²-day, with their Canadian prairie lakes falling into the range of 10-12 mg P/m²-day. The values for Deer Creek Reservoir reported in Table 1 thus represent rates that have been seen to cause problems in some lakes. Conversely, release rates from the Panguitch sediments are quite low compared to the culturally eutrophic lakes of Europe (e.g. 20-50 mg/m²-day), which have received heavy inputs of wastewater P for centuries.

It is likely that the importance of sediment P release in Deer Creek stems from the geography of the reservoir. Labile P is most likely sedimented out at the upper end of the reservoir, either by reaction with oxidized Fe in the water column, or through algal uptake and subsequent transport to the sediment, either as senescent algal biomass or in zooplankton fecal pellets. When senescent phytoplankton blooms render the sediment-water interface anoxic at the upper end of the reservoir, P is released to the water column where it exacerbates the phytoplankton bloom. When phytoplankton subsequently are rafted toward the dam by wind or currents, any biomass P transported to the downstream sediments is likely to be more or less permanently trapped at the oxygenated sediment-water interface.

The scenario outlined above is supported by the extractable manganese concentrations in the surficial sediments, which increase in a downstream direction in the reservoir from 0.08 to 0.19 mg/kg, thus indicating mobilization in the upper reservoir and deposition in the middle and lower ends. The scenario also would be consistent with the observed Fe:P ratios and release rates in Table 1, if one were to reason that the high Fe:P ratios represent a combination of high P loading and Fe migration from anoxic sediments. The high release rates from the more downstream sediments may result from the fact that these sediments had relatively little chance to release P during the year because the overlying water never was anaerobic. The possible importance of P release rates of the magnitudes observed in the laboratory simulations is presently being determined by adding the corresponding P loadings to the input of the WQRRS model, and determining the resulting effects on water column P concentrations (D. Wegner, U.S. Bureau of Reclamation, Salt Lake City, personal communication).

Paleolimnology. Although absolute concentrations of NaOH-P or NAI-P are not always useful in predicting differences in trophic states between lakes because of basic differences in the Fe chemistry of their watersheds, paleolimnological studies have shown that cultural eutrophication of lakes is often accompanied by a sharp increase in the NAI-P concentrations in the sediments of a particular lake. 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, corresponding to the onset of agriculture in nine Canadian prairie lake watersheds. Thus, vertical profiles can be useful in understanding time trends in the eutrophication of lakes and reservoirs.

Figures 3a-c represent a sediment profile (core PLO-1) at a site approximately in the center of Panguitch Reservoir near the dam. In Figure 3a, the percent dry weight is seen to increase with depth in the sediment core above

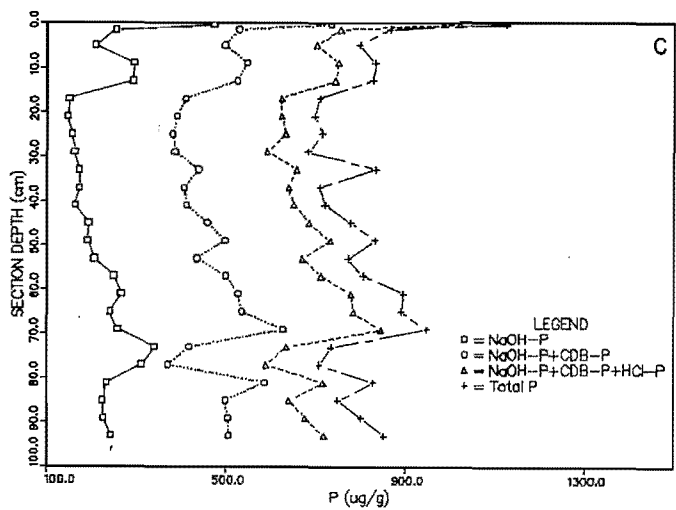
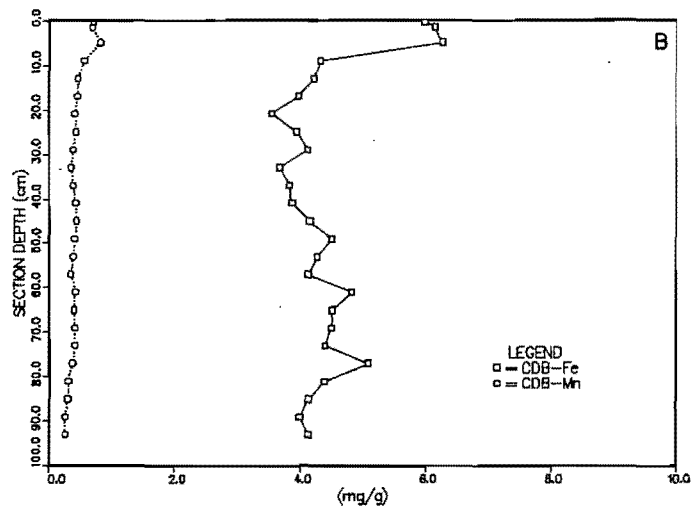
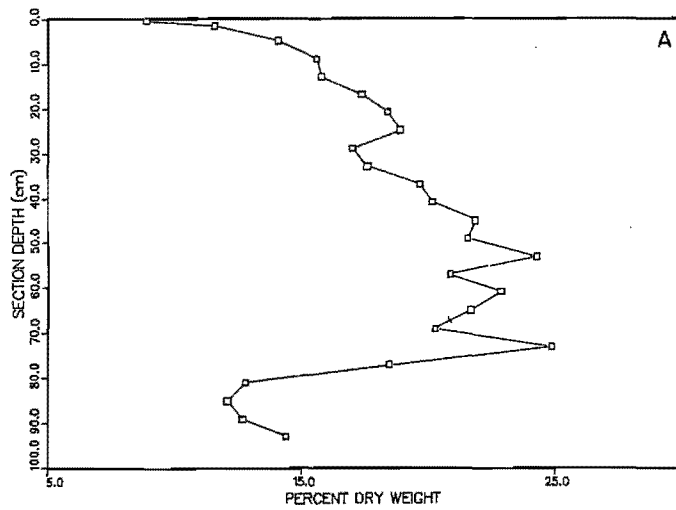


Figure 3. Chemical constituent profiles in Core PLO-1, Panguitch Reservoir, December 1982.

75 cm as the result of compression. Figure 3b shows an approximately constant extractable Fe concentration with depth in the core, with a sharp increase in the surficial 6-7 cm. Extractable Mn shows a similar trend. Such profiles are indicative of present day diagenesis of Fe and Mn at the sediment surface (Allan and Williams 1978), and suggest mobility of the reduced metals in the anoxic zone below the sediment-water interface.

The concentration profiles of the various phosphorus fractions are shown in Figure 3c. 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. The profiles, indicate a sharp increase in the NaOH-P and a corresponding decrease in CDB-P between 76 and 70 cm depth, and a gradual decrease in the NaOH-P, until a sharp peak occurs at approximately 10 cm depth. Little change occurs in the apatite-P or organic P fractions with depth in the core. The increase in the NaOH-P concentration in the surface 2 cm is probably related to the process of reaching diagenetic equilibrium in the surface microzone, rather than a recent increase in P loading to the reservoir or the sediment (e.g. Allan and Williams 1978).

The sharp decrease in the percent dry weight below 75 cm (Figure 3a) was observed to be accompanied by sharp changes in the phosphorus, iron, and sulfur chemistry of the sediments. It therefore seemed reasonable to assume that the zone between 76 and 78 cm depth marked the filling of the reservoir in 1876. The sediment below this depth thus would represent the sediment present in the original lake. A constant sedimentation rate model (Berner 1980) allowed an initial estimate to be made of the corresponding date represented by each sediment section. Some example dates are plotted on a more detailed NaOH-P profile in Figure 4. These dates subsequently were confirmed to a reasonable approximation using the cesium-137 dating technique (left margin, Figure 4), which depends on the fact that the deposition of this radionuclide was significantly higher in 1964 and the few years following because of increased atmospheric nuclear weapons testing during the period immediately prior (Ritchie et al. 1973).

The higher resolution in Figure 4 emphasizes peaks that are assumed to be associated with closing of the original dam and with some event that occurred in the early 1970s. The peak at 73 cm could have resulted from a change in the original trophic state of the lake to a new, higher trophic state, perhaps triggered by the increased residence time and consequent slower washout of P in response to closing of the dam. The reservoir apparently not only reverted toward its original trophic state with time, but actually improved beyond the original conditions in the lake. The reasons for this behavior are not absolutely clear, but probably relate to differences in the hydrologic and morphometric regimes between the original lake and the reservoir (e.g. Smith and Shapiro 1981). The peak in NaOH-P tentatively associated with the 1970s may be the result of a Rotenone treatment of the reservoir in 1972, in which the poisoned fish in the reservoir were not subsequently removed. This practice could again have triggered intensive P recycling as a result of oxygen depletion in the water column.

It should be noted that, while this reconstruction of the trophic history of the reservoir remains speculative, the proposed trophic changes in the reservoir were accompanied by major shifts in the diatom flora preserved in the reservoir sediment (M. Cox and S. Rushforth, Dept. of Botany and Range Science, Brigham Young Univ., personal communication). The increase in NaOH-P at 76-78 cm

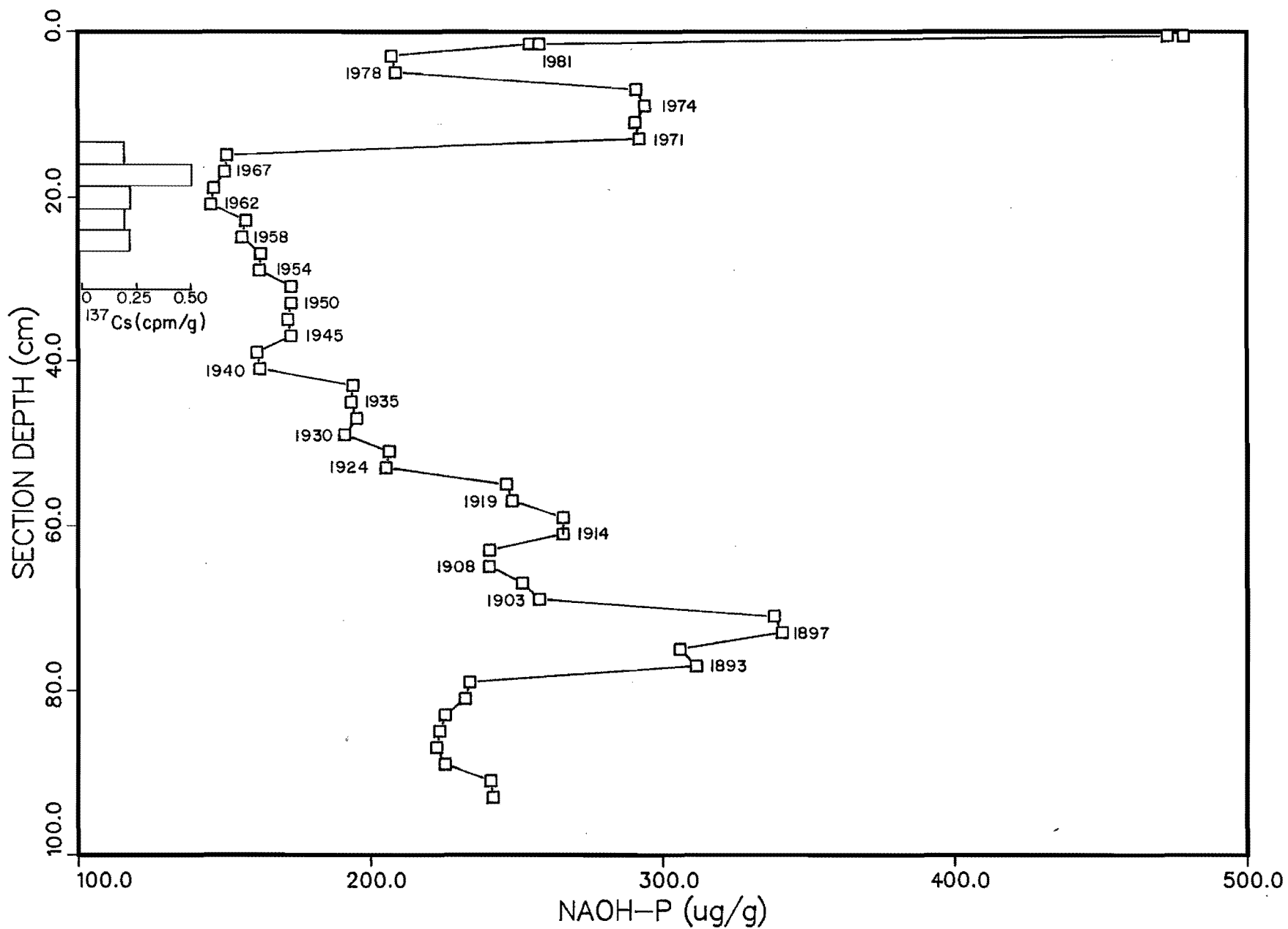


Figure 4. NaOH-P concentrations and corresponding sediment dates in Core PLO-1, Panguitch Reservoir, December 1982.

corresponds to a replacement of Melosira by Stephanodiscus sp., an indicator of eutrophic conditions. The 1970s peak corresponds with another major species shift to Cyclotella compta, another eutrophic indicator.

Similar sediment core data are presented for core 18 from Deer Creek Reservoir in Figure 5. In Figure 5a, the percent dry weight is seen to increase with depth in the sediment core, again as the result of compression. The bottom section of this core 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 again showed close agreement with cesium-137 dates (Figure 5a). Figure 5b shows a gradual increase in the extractable Fe concentration toward the sediment surface, but very little differentiation of Mn with depth in the core.

The concentration profiles of the various phosphorus fractions are shown in Figure 5c. The P profiles in core 18 were typical of all of the cores except core 10, and they indicate little change in the phosphorus deposition or cycling in the sediment over the years in which the sediment accumulated. The increase in the NaOH-P concentration in the surface 6-8 cm is probably related to diagenetic processes, as described above. The reason for the NaOH-P peak at 25 cm depth is not known. It was unaccompanied by a corresponding peak in CDB-Fe (Figure 5b), and may represent an artifact. In light of the Panguitch core data discussed above, unless the entire sediment column in core 18 has been disturbed, the absence of a pattern can be assumed to indicate a corresponding absence of P cycling efficiency or P loading historically in the reservoir.

The data used to construct Figures 3 and 5 also can be used to estimate the P retention coefficient for these reservoirs, providing the areal extent of the deposition zone is known. For example, the total sediment loading represented by core PLO-1 is 169 kg/m². Based on a mean total P concentration of 737 mg/kg, the total P loading was 125 g/m² over the central depositional basin. If this loading were distributed equally over the 96 yr since the dam was closed, the resulting P retention rate has averaged 1.3 g/m²-yr over the depositional basin. Similar calculations can be done for the two cores from Deer Creek Reservoir for which a baseline date can be established. The total sediment loading represented by core 18 is 155 kg/m². Based on a mean total P concentration of 934 mg/kg, the total P loading was 145 g/m². If this loading were distributed over the 41 yr since the dam was closed, the resulting P retention rate has averaged 3.5 g/m²-yr. Core 13 yields a similar estimate. These calculated values could be compared with present-day loading estimates for the respective reservoirs to give an estimate of the P retention coefficient, R_p.

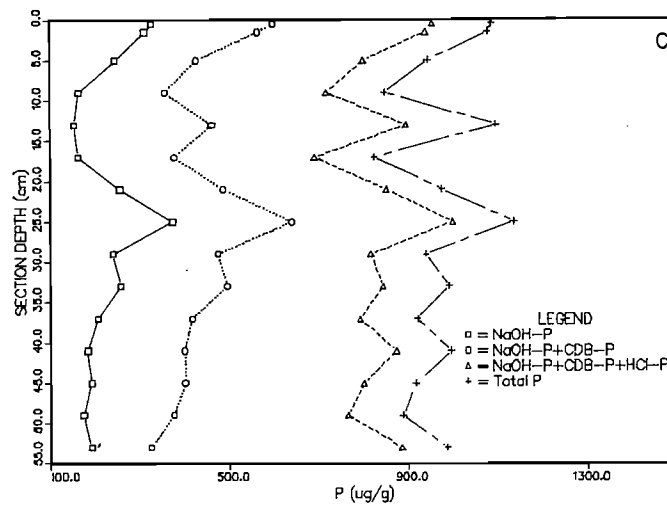
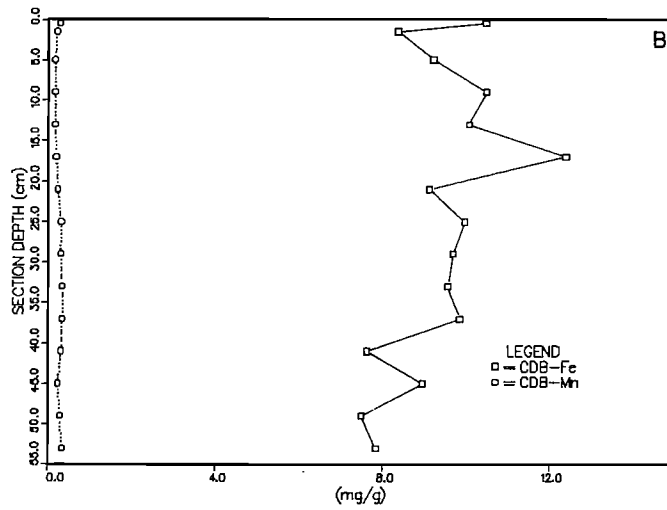
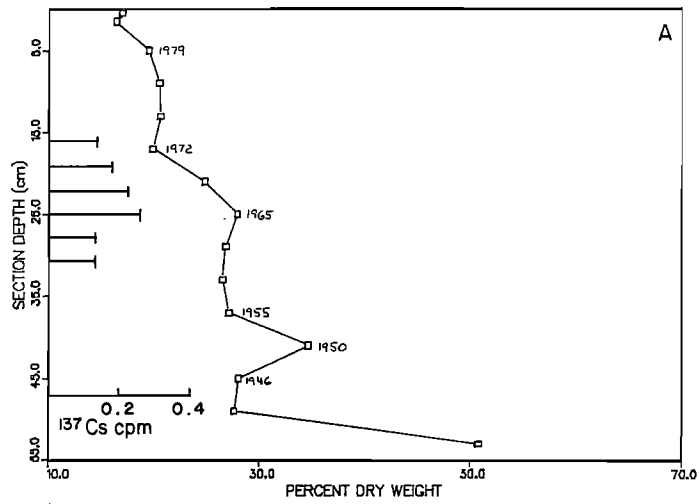


Figure 5. Chemical constituent profiles in Core 18, Deer Creek Reservoir. November 1982.

SUMMARY AND CONCLUSIONS

The sediments of Panguitch Reservoir indicate a relatively low potential for serving as a source of P for the overlying water column under anoxic conditions. This potential would be worst when periods of anoxia are interspersed with periods of mixing. This is the case because of the relatively rapid attainment of a low equilibrium concentration of P in anoxic water overlying the sediments. The redox cycle of Fe is closely associated with P release in the reservoir, and aerobic P release rates are probably insignificant in the phosphorus budget of the reservoir. Sediment profiles indicate that the trophic state of this reservoir has probably undergone two marked changes since it was first filled, the first associated with closing of the original dam in 1892, and the second with a rotenone treatment of the reservoir in the early 1970s. The trophic history of the reservoir, together with the low measured P release rates under laboratory simulation, suggest that the water quality in the reservoir would be expected to improve with reductions, or even maintenance, of historical P loading rates, provided fish are not left to decompose in the reservoir following future Rotenone treatments.

It should also be noted 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.

The sediments of Deer Creek Reservoir indicate a moderate potential for serving as a source of P for the overlying water column under anoxic conditions. This potential could account for the occurrence or exacerbation of blue-green algal blooms commonly observed 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 decreased external P loading, if the upper end of the reservoir still experiences sufficiently severe algal blooms to render the sediment-water interface anoxic. The redox cycle of Fe is also closely associated with P release in this reservoir, and aerobic P release rates are probably insignificant in the phosphorus budget of the reservoir. Sediment profiles indicate that the trophic state of the reservoir probably has 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 apatite-P fraction, and attempts at reducing P loading should take this into account.

Although very little information is available on the sediments of Scofield Reservoir, the corresponding Fe-P concentrations are similar to the values observed in Deer Creek and Panguitch Reservoirs. However, the high Fe:P and Fe:S ratios suggest that internal P loading from the sediments of this reservoir may be relatively lower in Scofield than in the other reservoirs even under anoxic conditions. This conclusion should be confirmed for other sediment locations and seasons in the reservoir.

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APPENDIX

Table A.1. Deer Creek.

Core	Section	%-Dry	NaOH-P ug/g	CDB-P ug/g	HCl-P ug/g	R-P ug/g	Total-P ug/g	CDB-Fe mg/g	CDB-Mn mg/g	Total-S mg/g
1	1	43.0	219.	101.	575.	53.	947.	4.2	0.07	1.3
1	2	44.8	352.	125.	492.	41.	1009.	5.7	0.11	1.6
1	4	52.5	185.	96.	454.	86.	821.	3.8	0.05	1.0
1	6	38.6	217.	143.	529.	84.	974.	6.7	0.07	****
1	8	44.6	229.	166.	519.	84.	998.	7.3	0.13	****
1	10	52.6	194.	140.	535.	51.	920.	6.0	0.09	****
1	12	65.2	246.	157.	519.	48.	970.	5.9	0.10	****
1	14	62.9	228.	105.	520.	46.	899.	4.7	0.09	****
1	16	65.8	108.	94.	480.	38.	720.	4.1	0.06	****
1	18	59.7	202.	157.	466.	59.	884.	4.9	0.10	****
1	20	62.2	149.	107.	513.	46.	815.	4.2	0.09	****
10	1	49.9	48.	245.	355.	113.	761.	1.7	0.27	0.70
10	2	55.4	22.	245.	372.	122.	762.	0.7	0.11	0.62
10	4	55.5	14.	188.	357.	121.	680.	****	0.09	0.66
10	6	64.9	14.	197.	386.	107.	703.	****	0.07	****
10	8	57.3	13.	148.	249.	100.	511.	****	0.06	****
10	10	58.1	9.	204.	350.	116.	679.	****	0.06	****
13	1	29.4	238.	214.	435.	147.	1035.	7.8	0.21	2.0
13	2	27.9	266.	218.	438.	126.	1047.	8.0	0.26	2.0
13	4	27.6	255.	259.	444.	115.	1073.	8.2	0.23	2.3
13	6	27.3	167.	179.	446.	108.	899.	7.6	0.16	****
13	8	28.1	188.	174.	393.	112.	867.	9.4	0.15	****
13	10	31.8	176.	186.	444.	73.	879.	8.3	0.15	****
13	12	33.7	208.	186.	435.	112.	941.	9.0	0.16	****
13	14	32.4	196.	250.	423.	81.	950.	8.6	0.17	****
13	16	31.5	194.	312.	365.	125.	996.	8.8	0.16	****
13	18	31.9	184.	251.	385.	118.	937.	10.3	0.18	****
13	20	28.6	192.	186.	344.	121.	843.	10.1	0.21	****
13	22	32.8	190.	195.	450.	94.	929.	8.9	0.25	****
13	24	41.8	162.	121.	****	154.	*****	7.2	0.21	****
13	26	48.0	156.	142.	512.	144.	953.	7.9	0.37	****
13	28	57.0	141.	63.	667.	167.	1038.	6.2	0.58	****
18	1	17.0	326.	270.	357.	133.	1087.	10.5	0.28	3.3
18	2	16.4	311.	252.	375.	139.	1078.	8.4	0.22	3.3
18	4	19.5	245.	181.	373.	145.	943.	9.2	0.17	5.0
18	6	20.5	164.	191.	361.	130.	846.	10.5	0.17	6.0
18	8	20.6	153.	307.	434.	202.	1096.	10.1	0.17	5.8
18	10	19.9	163.	214.	313.	134.	824.	12.4	0.20	7.9
18	12	24.8	256.	231.	364.	125.	976.	9.1	0.24	4.4
18	14	27.9	374.	266.	360.	137.	1137.	10.0	0.32	3.5
18	16	26.8	240.	235.	341.	123.	939.	9.7	0.31	4.6
18	18	26.5	257.	238.	349.	148.	992.	9.6	0.34	3.4
18	20	27.1	206.	210.	376.	128.	921.	9.9	0.34	4.7
18	22	34.6	183.	216.	475.	122.	996.	7.6	0.31	3.1
18	24	28.0	191.	210.	400.	117.	917.	9.0	0.24	3.3
18	26	27.6	174.	201.	389.	124.	888.	7.5	0.28	3.9
18	28	50.8	191.	134.	560.	102.	988.	7.9	0.34	2.0

Table A.2. Panguitch and Scofield.

Core	Section	%-Dry	NaOH-P ug/g	CDB-P ug/g	HCl-P ug/g	R-P ug/g	Total-P ug/g	CDB-Fe mg/g	CDB-Mn mg/g	Total-S mg/g	Fe/S
1	1	8.9	473.	262.	287.	105.	1127.	6.0	0.71	1.50	4.0
1	2	11.6	255.	274.	226.	110.	865.	6.1	0.69	1.60	3.8
1	4	14.1	209.	289.	205.	95.	798.	6.3	0.82	1.40	4.5
1	6	15.6	294.	253.	204.	82.	833.	4.3	0.56	1.40	3.1
1	8	15.8	292.	232.	219.	84.	828.	4.2	0.47	1.40	3.0
1	10	17.4	150.	259.	215.	85.	708.	4.0	0.46	1.80	2.2
1	12	18.4	146.	244.	234.	74.	698.	3.5	0.41	1.50	2.4
1	14	18.9	156.	224.	252.	82.	715.	4.0	0.43	1.40	2.8
1	16	17.0	162.	224.	206.	91.	683.	4.1	0.38	1.70	2.4
1	18	17.6	173.	266.	219.	178.	836.	3.7	0.35	1.70	2.2
1	20	19.7	173.	234.	233.	70.	710.	3.8	0.38	1.90	2.0
1	22	20.2	162.	249.	240.	71.	722.	3.9	0.42	1.60	2.4
1	24	21.9	193.	265.	226.	94.	778.	4.2	0.43	1.40	3.0
1	26	21.6	191.	306.	235.	100.	832.	4.5	0.41	1.30	3.5
1	28	24.3	205.	229.	236.	102.	771.	4.3	0.39	1.40	3.1
1	30	20.9	249.	250.	213.	94.	806.	4.1	0.35	1.30	3.2
1	32	22.9	266.	260.	252.	118.	896.	4.8	0.42	1.30	3.7
1	34	21.7	241.	294.	249.	108.	891.	4.5	0.40	1.20	3.8
1	36	20.3	258.	369.	219.	103.	949.	4.5	0.41	1.50	3.0
1	38	24.9	341.	76.	218.	100.	735.	4.4	0.41	1.80	2.4
1	40	18.5	312.	59.	219.	118.	708.	5.1	0.37	1.90	2.7
1	42	12.8	232.	354.	131.	111.	828.	4.4	0.30	3.20	1.4
1	44	12.1	224.	274.	143.	109.	749.	4.1	0.30	4.60	0.9
1	46	12.7	226.	278.	173.	126.	802.	4.0	0.26	4.30	0.9
1	48	14.4	242.	264.	213.	133.	852.	4.1	0.26	4.30	1.0
2	1	35.1	73.	133.	388.	68.	662.	2.0	0.33	0.84	2.3
2	2	60.6	30.	117.	318.	65.	530.	1.7	0.24	0.52	3.3
2	3	61.0	40.	166.	283.	88.	576.	2.2	0.36	****	****
2	4	65.2	33.	164.	375.	80.	651.	2.0	0.30	0.42	4.9
2	5	67.3	30.	155.	340.	93.	618.	1.8	0.26	****	****
2	6	56.8	42.	177.	395.	116.	730.	2.2	0.30	0.56	3.9
2	7	71.7	21.	151.	312.	73.	557.	1.6	0.20	****	****
2	8	70.4	17.	178.	358.	84.	636.	1.8	0.25	0.20	8.8
2	9	71.1	13.	167.	295.	59.	535.	1.5	0.23	****	****
2	10	72.7	8.	130.	310.	51.	499.	1.7	0.22	0.28	6.1
3	1	14.9	305.	216.	261.	92.	874.	4.7	0.62	1.00	4.7
3	2	20.3	678.	115.	276.	91.	1160.	4.9	0.53	0.68	7.2
3	4	46.2	103.	74.	339.	83.	599.	4.6	0.41	0.56	8.1
3	6	46.3	102.	73.	350.	88.	613.	4.6	0.38	0.48	9.5
3	8	57.0	88.	75.	325.	71.	558.	4.7	0.34	0.38	12.3
3	10	58.0	125.	55.	347.	70.	597.	4.6	0.36	0.34	13.5
3	12	65.0	614.	53.	348.	46.	1062.	4.2	0.29	0.26	16.2

Scofield

1	1	15.9	192.	152.	680.	136.	1160.	10.3	****	1.00	10.3
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