Phosphorus Distribution in Reservoir Sediments: Implications for Groundwater Transport

Gustavious P. Williams[1,2] MASCE, Warren Casbeer, E. James Nelson[1] MASCE, and Brett Borup[1], MASCE

[1]368 Clyde Building, Department of Civil and Environmental Engineering, Brigham Young University, 84602.

[2]Corresponding author: phone (801) 422-7810, e-mail gus.williams@byu.edu.

Phosphorus (P) impairs reservoir water quality and managers impose limits on external P loading to address this problem. Even with P reductions, restoration has taken longer than expected at many reservoirs. Researchers attribute this to internal P sources, such as the interactions between the reservoir water column and sediment pore water. Subsurface nutrients and groundwater/surface water interactions seem to dominate many of these reservoirs. Data sets to characterize sediment P distribution are rare, but critical, as studies show that P types and amounts vary spatially. Deer Creek Reservoir (DCR), Utah exhibits on-going degradation even after significant reduction in external P loading. A recent DCR construction drawdown provided a unique opportunity to study delta sediments and determine the potential amounts, geochemical sources, and spatial distribution of P. Traditional reservoir studies are limited by the ability to take large numbers of core samples. We were able to obtain samples and data in higher resolution than in previous studies. We took 91 sediment samples in six transects to define the spatial distribution and geochemical form of P over an approximate 750,000 m^2 (185 acre) area. In addition to surface samples, at selected sites we took samples to characterize vertical P distribution. We analyzed all samples for water soluble P, and 19 samples for four other P forms. Water soluble P ranged from 2.28E-03 to 9.81E-03, KCl-P from 2.53E-03 to 1.10E-02, NaOH-P from 5.30E-02 to 4.60E-01, HCl-P from 1.28E-01 to 1.34E+00, and organic (residual) P from 8.23E-01 to 3.23E+00 $mg \cdot g^{-1}$. Initial geostatistical analysis indicated spatial trends in the P distribution that follow expected sediment distribution patterns.

1. Introduction

Reservoir system eutrophication is detrimental to sustainable water supplies (Morris and Fan 1998; Smith et al. 1999). Mitigation traditionally involves limiting the amount of phosphorus (P) that enters the system from point sources such as effluents from industrial and wastewater treatment plants, as well as from non-point sources such as agricultural runoff and plant decay (Carpenter et al. 1998; Morris and Fan 1998; Sas 1989; Sigua et al. 2006; Suberkropp and Chauvet 1995). However, even with improvements, eutrophication and its accompanying effects continue to slow water quality restoration projects (Rossi and Premazzi 1991). Research has confirmed that deposited sediments contribute previously trapped P back to the reservoir water column under certain conditions (Granéli 1999; Holtan et al. 1988; Mayer et al. 1999; Nowlin et al. 2005; Rossi and Premazzi 1991; Surridge et al. 2007) resulting in continued eutrophication (Pace and Funke 1991). Reservoirs are particularly vulnerable to trapping of nutrients in sediments due to longer retention times (Gibson 1997).

Reservoir managers have not commonly used information on internal loading processes because the data and information are limited and difficult to obtain (Szmant and Forrester 1996). There are few studies on the content and distribution of P in sediments. This is most likely because of the cost in collecting adequate numbers of samples to characterize the P spatial distribution; for example, sampling within reservoirs must take longitudinal and other gradients into account (Morris and Fan 1998; Thornton et al. 1982). Many of the available data are not from the upper portion of reservoirs, where active sediment cutting and resuspension occurs (Hakanson 1981; Hakanson 1984). Fabre (1988) determined that nutrients in the upper portion of the reservoir, where the delta is exposed to drawdown and refilling, as well as river inflow, are highly susceptible to resuspension and can supply nutrients to the water column. Researchers have traditionally studied P distribution and concentration through analysis of only a few scattered core samples or by laboratory column experiments (Devine and Vanni 2002; Eckert et al. 1997; Fisher and Wood 2004; Golterman 2004; Surridge et al. 2007). Such studies have insufficient data to define spatial patterns in P distribution and physical processes for developing management plans to mitigate P cycling.

Higher resolution spatial data in the appropriate locations to characterize internal cycling are difficult to obtain due to the complications in subsurface sampling. Deer Creek Reservoir (DCR), completed in 1941 (Buckley 2004), is an important domestic water source for the most populated region in Utah. A recent drawdown at DCR provided a unique opportunity for a study of internal phosphorous cycling by exposing a significant portion of the sediment delta which allowed for easier sample collection. Previous studies provided information about P chemical distribution in DCR sediments (Messer et al. 1984; Messer and Ihnat 1983); however, these results were based on analysis of cores from only 4 locations. No work has specifically looked at how DCR sediments from the deposited delta affect nutrient dynamics or tried to determine the spatial distribution of P, which appears important based on variation in P concentrations across the 4 locations sampled by Messer et al. (1984). The understanding P distributions in currently exposed delta sediments with trapped nutrients may be important to nutrient cycling in DCR and other reservoirs. A previous drawdown in 2001 exhibited significant recutting of the sediment delta which resulted in a geosmin release that caused taste and odor problems that were also accompanied by a large algal bloom (PSOMAS 2002). This implies that sediment resuspension has a major impact on reservoir water quality.

2. Methods

2.1 Sample Collection

Figure 1 displays the sample locations. The figure uses an earlier aerial photograph that shows our sample area underwater at the time of the image and illustrates the extent of drawdown during the sampling period. Points along the transects are separated by 100 m with the transects spaced 200 m apart. We took 57 surface (S) samples with locations shown as white squares at each numbered point in Figure 1; points 1-6 and 60 were not sampled because they are outside the sediment delta. At 15 locations, shown as black crosses in the white squares, we collected additional samples to characterize vertical distribution. At 11 of these locations we took samples at the surface, 6 in and 1 ft and at four locations (points 12, 20, 30, and 42) we also took a sample at 2 ft in addition to the other depths.

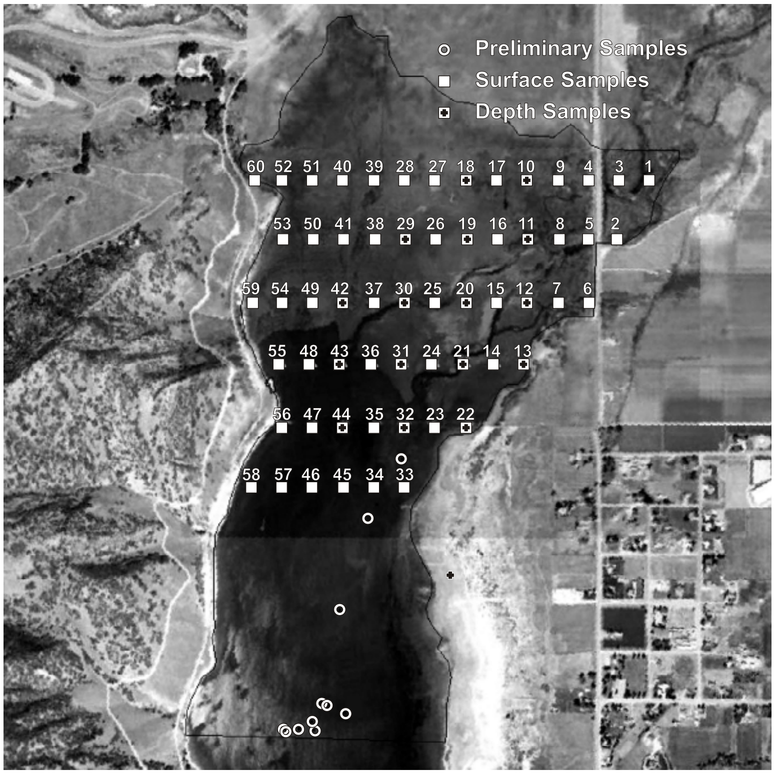

Figure 1: Delta sampling locations with sample numbers.

We collected samples using hand augers in 4 sampling trips spaced over 4 weeks in the summer of 2008. We refrigerated the samples soon after collection and performed analysis within one week of collection. We performed water soluble P tests for each (n=91) sample and a complete fractionation for 19 selected sediment samples. The samples with complete fractionation were (the digits before '.' indicate the sample location number in Figure 1, those after indicate sample depth): 9.S, 12.S, 12.2ft, 20.S, 20.2ft, 22.S, 22.1ft, 23.S, 24.S, 29.S, 29.1ft, 30.S, 30.2ft, 31.S, 31.1ft, 32.S, 32.1ft, 33.S, and 35.S). Full results are available in the electronic supplement to this article.

2.2 Geochemical Fractionation

P occurs in many different chemical forms, or pools in soils and sediments and depending on its form, can be more or less bioavailable and mobile in the environment (Pierzynski et al. 2005; Sims and Pierzynski 2005). Some chemical forms of P, such as apatite minerals, are highly unavailable and have little impact on reservoir processes. Other forms may become available under certain conditions and have significant impacts (Shang and Zelazny 2008).

Soil complexity makes it difficult to accurately measure P content in the soil. However, soil scientists have devised fractionation, extraction, or selective dissolution methods to selectively dissolve certain P pools from the soil into solution (Chang and Jackson 1957; Dean 1938; Kouwe and Golterman 1976; Shang and Zelazny 2008; van Eck 1982). These methods typically involve shaking or mixing sediment with an extracting solution, centrifugation, and filtration of supernatant, which is then measured for P concentration. The complete process is carried out sequentially to remove each P form from the soil sample.

Table 1: The average water soluble P sediment concentrations by sample depth.

Depth	n	$C_{P.avg}$ (mg·g^{-1})
Surface	55	5.64E-03
6 in	15	4.43E-03
12 in	13	4.06E-03
2 ft	4	3.99E-03
All	87	5.12E-03

We used the P fractionation scheme of Moore and Coale (2000) to characterize the geochemical P forms and concentrations. This scheme distinguishes five separate P forms, defined by the extracting solution used:

1. Fr.W: water soluble and interstitial water P
2. Fr.KCl: anion exchange sites, loosely sorbed P
3. Fr.NaOH: Al- and Fe-bound or adsorbed P
4. Fr.HCl: Ca-bound (apatite) P
5. Fr.$K_2S_2O_8$: residual (mostly organic) P

Step 5 involves digestion of residual sediment or a separate aliquot of sediment to obtain total P. We used persulfate digestion for this step following Standard Methods (Stieg et al. 2005). Table 1 provides method details including the extracting solution and shaking time for each step. It also compares our method with the methods used by Messer et al. (1984) in a previous DCR study. Messer et al. (1984) used an intermediate Fr.CBD step using Na-citrate, Na-bicarbonate, and Na-dithionite for determining the Fe-bound or P occluded by oxides. We did not perform this step, causing this P-pool to be included in the Fr.HCl fraction in our results.

3 Results

We collected a total of 91 sediment samples, and from these prepared 161 solutions for P analysis. We analyzed only water soluble P, Fr.W, for 72 of the sediment samples, while for the remaining 19 samples we performed a complete fractionation to determine P content in all five forms. Complete results are available in an electronic supplement to this article.

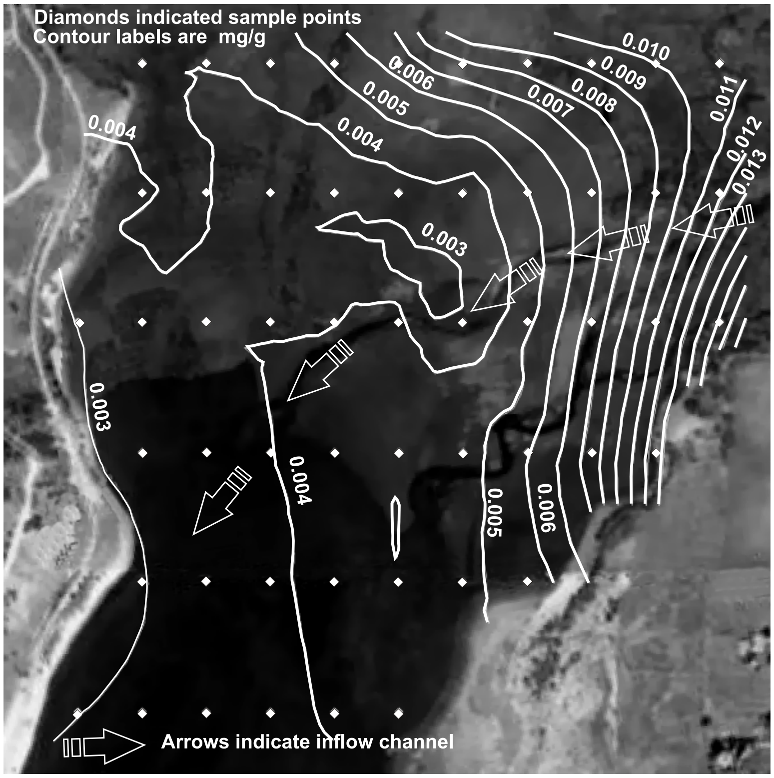

Figure 2: Contours display preliminary geostatistical analysis of water soluble P variation for surface samples across the delta. Notice the lateral variation, with higher concentrations apparent on the right side (looking upstream) of the delta.

3.1 Water Soluble (Fr.W) Results

In the 72 samples analyzed only for Fr.W, the average P concentration was 5.19E-03 mg·g^{-1} dry sediment with a standard deviation σ equal to 3.95E-03 (~76% of average). The standard deviation is relatively high, possibly indicating that P concentrations exhibited spatial trends or anisotropy across the delta. The Fr.W P average for all 91 samples was 5.12E-03 mg·g^{-1}.

Tables 1 presents directional P concentration variations by depth with data from the surface at depths of 6 in, 1 ft, and 2 ft and by observation shows a decreasing trend in concentration with increasing depth.

Data analysis showed that P concentrations exhibit trends in with depth, laterally, and longitudinally. The change in concentration with depth might be attributable to decreasing water content with depth or greater quantities of organic matter with depth. The longitudinal trend might be due to the fact that sediments further away from the reservoir or most upstream on the delta have been uncovered for longer periods or due to changes in soil grain size distributions. The lateral variation might be influenced by the distance from the river entrance where higher column numbers are generally further away from the river.

To further explore P spatial variation across the delta we performed an initial geostatistical analysis using the Groundwater Modeling System (GMS) (Aquaveo 2008). We used the water soluble P concentrations from the 55 surface samples to interpolate a surface using kriging. This surface is shown in Figure 2 as contour data.

The longitudinal and lateral trends in P concentration are evident in Figure 2. In general, the concentration profiles follow the river channel. Geostatistical analysis of the other P pools with significantly smaller sample numbers also displayed variation, though slightly different.

4 Conclusions

The data show that Fr.W P concentrations display spatial trends across the delta and with depth. Though there were only sparse data for other fractions of P, it is assumed that these concentrations also vary across the delta in similar spatial patterns (Borgnino et al. 2006) and the cursory geostatistical analysis appeared to verify this. These initial results, which demonstrate trends in P concentration across the delta, may be useful in understanding how various processes could release P back into the water column. This unique data set may provide insights into spatial deposition and resuspension trends that have implications for reservoir management, such as to how reservoir drawdown and refilling activities could affect nutrient concentrations.

This work confirms past studies that found apatite-P in large quantities in DCR sediments while extending this finding to exposed delta sediments. However, these initial results suggest that there is more apatite-P in the exposed delta sediments than in sediments that had been deposited in the reservoir when comparing our results with those of Messer et al. (1984). This could have repercussions on refilling the reservoir, as some of the apatite-P found in delta sediments might be of authigenic (precipitated in area previously covered by water) instead of detrital origin. This could be exacerbated by the extended droughts of recent years in the Western United States. This P might more easily become available as the reservoir is refilled.

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