Chapter 7

CONCLUSIONS

7.1. Summary of Research Findings

This Ph.D. thesis explored the effects of two hydrologic consequences of irrigation, changing reservoir surface elevation and perturbed groundwater-surface water exchange, on biogeochemical processes in sediment, surface water, and groundwater. Reducing conditions in porewater of submerged sediment located at the shoreline of Lake Powell were assessed before and after changing water level exposed that sediment to air and then resubmerged it. The sedimentation of chemicals in the Colorado River delta of Lake Powell was described quantitatively and its implications for primary productivity in the reservoir were discussed. In combination with required minimum dam releases, the ongoing drought in the Colorado River Basin has lowered the surface elevation of Lake Powell substantially, and this process has induced the erosion and resuspension of the Colorado River delta. The possibility of release of phosphorus, the limiting nutrient in Lake Powell, from resuspended sediment was assessed in a combined field and laboratory study. At the Merced River, a chemical analysis of groundwater samples collected from the riverbed was used to compare the relative influence of hydrologic processes and biogeochemistry on the transport and sequestration of trace solutes. The findings from each of these projects will be summarized in the following subsections, and their implications and significance will be discussed in the second section of this chapter.

7.1.1. Water Level Fluctuations at the Shoreline of Lake Powell

Lake Powell is long and narrow, and many fingers, known as “side canyons”, extend away from the mainstem of the reservoir and receive sediment from small creeks. Porewater sampled from shoreline sediment deposited at the edge of two side canyons, Farley Canyon and White Canyon, was analyzed for the dissolved concentrations of several chemical constituents including manganese (Mn) and uranium (U). These elements provide information about the redox state of the system. In both sampling locations, reduction and mobilization of solid-phase Mn occurs < 10 cm below the sediment-water interface, suggesting that the intermittently rapid sedimentation in these locations deposits sufficient organic carbon to consume dissolved oxygen a very short distance into the sediment. This is notably different than previous studies at the bottom of lakes or marine basins, because, where oxygenated bottom waters have been observed, dissolved oxygen diffuses into the sediment and dissolved Mn is not generally produced at such shallow depths.

Decreasing water level at Lake Powell exposes shoreline sediment to air. Three weeks of exposure appeared to be sufficient to create oxidizing conditions in the exposed sediment, as indicated by higher concentrations of porewater U after resubmergence. Samples collected 3.5 days after the sediment-water interface had been resubmerged show that reducing conditions returned quickly in Farley Canyon, with the shape of the dissolved Mn profile resembling that collected before the water level fluctuation. However, U does not appear to respond to reducing conditions nearly as quickly as Mn: whereas the 3.5 days appears to be enough to remobilize Mn, the U curve did not resemble its previous shape even after a deeper portion of the sediment column had been resubmerged for ~12 days. This *in situ* relationship between Mn and U has not been previously observed at high resolution in sediment porewater or groundwater, and these temporal constraints for the reestablishment of metal reduction in groundwater are new.

In White Canyon, the subsurface gradients of Mn measured after the lake level fluctuation do not resemble those measured before it. Rather, dissolved Mn increases at a much greater depth, and regions of increase or steady concentrations with depth are not distinct from one other. This suggests that, 3.5 days after resubmergence of the sediment-water interface, sediment porewater at this site is not as reducing as it was before the lake-level fluctuation. The difference between White Canyon and Farley Canyon may be related to the local topography around the sampling sites; an ~8 m hill near the Farley Canyon sampling location may have supplied groundwater discharge to the sediment above the reservoir water level, preventing air from infiltrating and oxidizing reduced Mn. Conversely, the sediment bank adjacent to the White Canyon sampling location was only ~1 m high and appeared dry when samples were collected, suggesting that air may have infiltrated and delayed the onset of reducing conditions relative to Farley Canyon. Thus, physical characteristics of sediment may play an important role in the rate of reestablishment of Mn reduction in sediment on the shoreline of Lake Powell.

In White Canyon, U concentrations are much higher than in Farley Canyon, possibly because of the mining history of this watershed. There is not a clear relationship between Mn and U as in Farley Canyon, suggesting that different geochemical processes or microbial communities are present in the two canyons. Still, exposure to air greatly increases dissolved U concentrations after resubmergence, suggesting that reservoir level fluctuations may significantly affect the cycling of this contaminant.

7.1.2. Sedimentation of Inorganic Chemicals in Lake Powell

As the Colorado River enters Lake Powell, coarse particles are deposited first, followed by fine particles. High-resolution particle size measurements of sediment samples collected from the lakebed in the inflow region show a trend of decreasing particle size away from the river inflow, but the trend is not strong due to a small range of particle sizes measured. This implies that these samples were collected too close together to represent the full range of sediment deposition in the delta. Since visual observations of these samples during collection indicated that they were of small particle size, yet sampling further upstream was not possible due to the low level of Lake Powell, a series of stacked sediment cores was collected from a shoreline location. This sediment included coarse, sandy layers that must have been deposited when this location was at the upper edge of the reservoir as well as fine, clayey layers that must have been deposited when the reservoir was higher and this location was far from the river inflow. Trace element, mineral, and carbon data from these sample sets indicates that particle size is a strong predictor of chemical parameters. Small particles are higher in carbon, trace elements, and clay minerals, whereas coarse particles are higher in quartz and zirconium.

These findings contribute to a conceptual understanding of the broad spatial distributions of chemicals in the Colorado River delta of Lake Powell. While trends over ~10 km are slight, major trends exist over the > 100 km delta, with sediment further from the dam lower in inorganic chemicals than sediment closer to the dam. This is significant because it may help explain an increase in summertime surface water chlorophyll measured in the upper region of the reservoir during a recent period of low water level. Monitoring data collected by the U.S. Geological Survey show that chlorophyll did not increase in the first three years of reservoir drawdown, and then it increased dramatically. This may suggest that, during the initial decrease of the reservoir level, resuspension of the sediment delta by the Colorado River only disturbed coarse sediment with low chemical concentrations. However, there may be a water level threshold that led to resuspension of fine sediment rich in phosphorus (P), the limiting nutrient for primary productivity in the reservoir. The initiation of resuspension of fine sediment may have caused the increase in surface water chlorophyll. This is significant because it suggests that manipulation of reservoir level can change the quality of the water stored.

Sediment collected from shoreline locations is derived from the sedimentary rock formations surrounding Lake Powell. This sediment was sandy and low in most trace elements. If the type of rock formation surrounding a shoreline region (i.e., sandstone or shale) influences particle size of the shoreline, too few samples were collected to demonstrate a significant trend.

7.1.3. The Effect of Sediment Resuspension on Dissolved Phosphorus in Lake Powell

During low water levels, the Colorado River has been observed to resuspend the portion of its delta in Lake Powell that is exposed above water. Field measurements indicate that sediment resuspension buffers the concentration of dissolved P in the river as it flows through the exposed sediment delta. Consequently, low dissolved P concentration at base flow is increased during sediment resuspension, whereas high dissolved P concentration during the spring flood is decreased. Once in the reservoir, seasonal advective density currents determine whether P enters the photic zone or passes beneath it. Spring sampling captured base flow and an underflow density current, a scenario that implies release of P by sediment resuspension and subsequent transport to the bottom waters of the reservoir. Conversely, sampling in the early summer during snowmelt runoff and an overflow density current captured a scenario of P uptake by sediment resuspension and transport to the photic zone by an overflow current. Neither of these scenarios would seem to add P to the photic zone, yet primary productivity has increased during low reservoir levels (see section 7.1.2 and Chapter 4). This suggests that a specific hydrologic scenario of low river flow and an overflow or interflow current may occur in the late spring, and this scenario adds P to the reservoir at a depth where it can stimulate primary productivity.

These field measurements were supported by sequential extractions and sorption experiments conducted in the laboratory. Sequential extractions indicated that most of the sediment-associated P in the Lake Powell delta is extracted by a chemical treatment targeting P bound to calcite and biogenic hydroxyapatite. This implies that, despite observed inhibition of calcite precipitation in the upper region of Lake Powell by organic carbon compounds, the calcite precipitation that does occur effectively scavenges P from the water column. The step targeting easily exchangeable P, the most likely P to desorb during sediment resuspension, extracted ~10% of the total extractable P. Sorption experiments indicate that P has a much higher affinity for fine sediment than for coarse sediment. Equilibrium phosphorus concentrations calculated from Freundlich isotherms fit to the laboratory data are higher than the concentration of P entering Lake Powell, suggesting that experimental conditions did not adequately match those in the field. The amount of P desorbed from sediment resuspensions with no P added was much lower than the putative exchangeable P measured during the sequential extraction.

7.1.4. Hydrological Processes and Biogeochemistry in Groundwater beneath the Merced River

During the growing season, irrigation of agricultural fields surrounding the study reach of the Merced River raises the water table and induces groundwater discharge to the river. However, increases in river stage can reverse this exchange, pushing surface water back into the riverbed. Concentrations of bromine (Br) and Mn in groundwater samples collected from the riverbed reflect this complicated hydrology. Correlation analysis and analysis of the residuals from a linear model using Br as the predictor variable show that there is no statistical relationship between Br and Mn. Thus, Br, which can be interpreted as a conservative tracer of hydrologic processes, and Mn, which reflects the redox state of groundwater, can be used to represent these two separate influences on the transport of trace solutes.

Principal component analysis performed on a data set that included Mn, Br, strontium (Sr), barium (Ba), U, and P in groundwater suggest that hydrological processes accounted for > 50% of the variability, whereas 35-42% of the variability can be explained by trends in redox chemistry. Transport of Sr appears to be mainly by hydrological processes. Trends of Ba and U vary in two transects located ~100 m apart, but hydrological processes are generally more important for these two elements. Where P concentrations are high, P appears to follow hydrologic trends, whereas, where concentrations are lower, it appears to be controlled by redox chemistry.

7.2. Wider Implications and Significance

7.2.1. Interdisciplinary Significance of Research Topics

The broad aim of this Ph.D. thesis has been to connect variations in physical hydrology with biogeochemical processes that control the partitioning of inorganic chemicals between the solid and dissolved phases. The four research topics have attempted to extend areas of scientific understanding outside their traditional disciplines. In Chapter 3, the sampling methods and theory of early diagenesis, a process that has been studied nearly exclusively in deep lacustrine and marine basins with a steady sedimentation rate, were applied to the shoreline of a reservoir, an area with rapid, intermittent sedimentation. The results obtained there provide important knowledge about how subsurface redox gradients recover after a hydrological disturbance. Additionally, the application of high-resolution porewater sampling to the shoreline of a reservoir can also pertain to other environments that experience unsaturated conditions, such as floodplains and soils. Perhaps the most useful way to follow this research would be to study chemical transformations during unsaturation explicitly. This would give a clearer picture of trace metal mobility *during* a fluctuation in water level, since the current project sampled only *before* and *after* water level fluctuation.

The results of Chapter 4 bring basic concepts of sedimentation to bear on reservoir water quality and management. The sharp increase of primary productivity observed after three years of decreasing water level of Lake Powell suggests that a certain lake surface elevation was reached below which resuspension of the sediment delta may have supplied nutrients to the water column. This implies that, if reservoir managers wish to avoid major perturbations to the reservoir ecosystem, then reservoir drawdown should be halted before significant quantities of fine sediment are resuspended. However, such a management decision carries significant political implications. Additionally, the results of this project were made possible by several precise analytical measurements that have rarely (if ever) been applied to the study of a reservoir delta. The trends described in Chapter 4 would not have been clear without high-resolution measurements of particle size, trace element composition, and mineralogical composition.

The discussion of Chapter 5 describes a tight connection between sediment geochemistry and physical limnology, with both contributing to influence the amount of P released from Colorado River delta sediment and transported to the photic zone of Lake Powell. This implies that both natural factors, such as the volume of river flow, the timing of spring runoff, and the temperature difference between a river and a reservoir, and management decisions, such as the timing and extent of reservoir drawdown and the physical features (i.e., width and depth) of a valley flooded when a dam is built, contribute to perturbations in nutrient cycling during low water levels. This study of nutrient release in a reservoir where small changes in P cycling can be measured is important for the study of nutrient enrichment in both oligotrophic and eutrophic systems. The conclusions of this research could be enhanced by detailed field monitoring during a greater variety of lake levels and hydrologic conditions. Furthermore, a wider range of laboratory conditions are needed if sorption experiments are to adequately represent field processes.

Taken together, Chapters 4 and 5 show the significance of dam releases that do not correspond to natural river flows. This has already been clearly described for river reaches below dams, but it has been studied infrequently for the water quality of reservoirs. Engineers who operate dams are asked to optimize a variety of parameters, such as the generation of electricity, ecological health of downstream rivers, water supply to downstream communities, flood control, the water quality of rivers, the aesthetic value of a water body, and the water quality of reservoirs. The last of these is not usually a high priority, and this research gives an indication of how it can be affected when dam release schedules are designed to prioritize other factors.

Whereas many studies have examined groundwater flow patterns beneath rivers, and others have addressed the release or sequestration of trace solutes by redox processes in the subsurface, the study reported in Chapter 6 quantitatively compares these processes in the same setting. Its results indicate that increased groundwater flow induced by summertime irrigation and subsequent groundwater infiltration may be more important for trace element mobility than redox processes. These results, which may be applicable to a wide range of agricultural areas, contribute to scientific understanding of how trace chemicals respond to major hydrologic and chemical trends. An ideal complement to this study would be a similar measurement campaign in a reach of the Merced River that is not characterized by irrigation-induced groundwater flow.

Taken together, the four projects in this thesis make a contribution to understanding the effects of water infrastructure on the quality of the water being managed. The extensive construction of new water infrastructure is frequently cited as a means towards economic revival in developed countries and economic development in primitive ones. Furthermore, as water stress increases across the American West due to rising population and climate change, the effective management of water infrastructure is sure to grow in importance during the 21st century. In each of these cases, a detailed scientific understanding of the coupling between natural and engineered systems is crucial to supply clean water and protect environmental health.

7.2.2. Broader Impacts of this Research

In addition to producing the results discussed in previous chapters, this Ph.D. thesis has supported the education of two undergraduate students and a high school student. Caltech Summer Undergraduate Research Fellows Nathan Chan and Michael Easler both provided important field and laboratory help, and they will be included as co-authors on publications resulting from this research. Nathan also did his senior research project under the supervision of Dr. Hering and myself. Each has found direction in his young career, with Nathan completing a master's program in public policy and Mike transferring to the University of Minnesota to pursue an avid interest in Landscape Architecture.

In addition to these in-depth research experiences, research at Lake Powell introduced a Caltech undergraduate, Andrew Kositsky, and a junior graduate student, Claire Farnsworth, to field-based research.

This research also served as the basis for an outreach effort at the Environmental Charter High School. Located in Lawndale, California, this school serves low-income, low-ambition students from ethnicities rarely found in academia. The outreach program began as a series of guest lectures by other Caltech graduate students and me, and it evolved into a year-long elective class called Science and Society. During my frequent visits to the school while co-teaching this class, I identified a student, Fabian Ponciano, with an interest in a research career in the fields of geology and natural hazards. Fabian spent a summer working with me on a literature survey about Lake Powell, and later graduated with honors and now attends the University of California, Santa Cruz.

Finally, this work has also developed my understanding of a diverse set of fields outside of my immediate areas of specialization. My projects are tangentially related to river restoration, soil science, climate change, and water resource management. I have had an initial exposure to complicated social issues surrounding the flooding of a productive river valley and the development of a natural resource in a region populated by disadvantaged people (the Navajo and Hopi Indian tribes) who do not benefit from that development.

I first learned of Glen Canyon and Lake Powell from Edward Abbey's book *Desert Solitaire*, in which he campaigns for an appreciation of the wild places of the American West and vilifies the U.S. Bureau of Reclamation for building Glen Canyon Dam. However, after working with scientists from many different government agencies, reading the work of a few non-governmental organizations, and working at Lake Powell myself, I have come to understand that the use of natural resources in the American West is not easily described in absolute terms. Should my career involve an opportunity to manage natural resources, I will approach such a responsibility with both a healthy respect for the many various demands placed on a river system and a conviction that optimal use and appreciation is crucially reliant upon sound scientific knowledge.