Chapter 1

INTRODUCTION

1.1. Motivation

Extensive manipulation of river systems is a hallmark of irrigation infrastructure in the American West. As nineteenth-century exploration of Western lands revealed substantial acreage rich in sunshine but poor in water, the United States government created several legislative incentives to spur agricultural development. The Reclamation of Act of 1902 provided interest-free loans and long payback periods to farmers with the intention of creating new, agriculturally-based communities, and financial incentives continued for the next several decades (Ingram et al. 1991). To support these new communities, extensive water projects brought water from rivers to deserts and moderated seasonal flow patterns so that crops could be irrigated consistently throughout the growing season. Development increased rapidly as water infrastructure grew, so that, for example, more than one-quarter of the land area in California is now used for agriculture (Gronberg and Kratzer 2007).

Manipulations of surface water hydrology involve several related infrastructure components. A major initial step is the damming of a river, which creates a reservoir that can be used to ensure a steady supply of water to irrigation systems. Dams are often built to satisfy several needs, such as irrigation water supply, moderation of downstream river flows, production of hydroelectricity, and recreation. To meet these needs, dam releases may be seasonally greater than or less than inflows to reservoirs, leading to an unnatural downstream hydrograph and yearly fluctuations in reservoir water level. Over several years, reservoir storage can be depleted or increased when yearly inflows differ substantially from releases required to satisfy downstream obligations. With water stored in reservoirs, nearby agricultural land can be irrigated by canals; without it, large-scale irrigation usually depends on groundwater pumping. Either way, Western irrigation adds water to the land surface during dry seasons, inducing groundwater infiltration and runoff to rivers when their flow would otherwise be low.

The construction of reservoirs is known to affect biogeochemical processes in rivers. When a river enters a reservoir, it deposits an oxygenated sediment load by gravitational settling (Friedl and Wüest 2002), and this is a probable mechanism for the spatial distribution of chemicals, which tend to associate with fine particles (Horowitz and Elrick 1987). This also changes the water clarity; a turbid river can become a clear lake, altering the carbon cycle by allowing increased primary productivity. Decaying biomass is an important source of sediment to most lakes, and the sedimentation of nutrients can substantially decrease nutrient concentrations in the river downstream of the dam (Friedl and Wüest 2002). As organic carbon in the sediment is consumed by microbial respiration, early diagenesis begins, although diagenesis at sedimentation rates as high as those observed in reservoirs has been minimally studied. Diagenesis affects the chemistry of sediment porewater, which can diffuse into surface water, sometimes leading to the release of phosphorus (Gächter and Müller 2003), methane, or mercury (Friedl and Wüest 2002) into the water column. The changing water levels of a reservoir will expose and re-wet sediment along the shoreline, possibly destroying and re-establishing subsurface redox gradients. However, this topic, while examined in the fields of floodplain ecology and soil chemistry, has not been studied previously for reservoir sediment. The long-term drawdown of reservoirs can affect primary productivity by transporting nutrient-rich bottom water to the photic zone (Baldwin et al. 2008), or perhaps by exposing the previously-submerged sediment delta to the inflowing river, which may lead to desorption of chemicals from resuspended sediment.

Releases of water from the middle of the water column of a reservoir may be lower in dissolved oxygen (Friedl and Wüest 2002), higher in methane (Guérin et al. 2006), or colder (Vernieu et al. 2005) than the pre-dam river. Both dam releases and altered surface runoff can change the flow characteristics of a river, and these can affect organic matter transport, algal growth, and nutrient transport and retention (Doyle et al. 2005). Changing flow can also perturb the exchange of surface water and groundwater across the sediment-water interface (Essaid et al. 2008). This, in turn, will alter the contact time between surface water and the sediment matrix, which is a key factor influencing biogeochemical reactions in the subsurface (Findlay 1995). However, the extent of groundwater-surface water exchange has not been quantitatively related to the resulting biogeochemical processes in a river with altered groundwater flow.

1.2. Research Topics and Brief Overview of Chapters

The research in this thesis connects two important hydrological processes that occur as a result of damming and water diversion, reservoir level fluctuation and perturbed groundwater-surface water exchange, with biogeochemical processes. The focus is on inorganic chemicals, specifically trace metals and phosphorus, and the implications of their sequestration and mobilization for water quality.

After background information is presented in Chapter 2, four research topics in three hydrologically-different field locations are considered. Chapter 3 begins a three-part study at Lake Powell, a large reservoir on the Colorado River in Utah and Arizona, with field measurements of sediment porewater geochemistry. Two sets of porewater samples were collected from submerged sediment before and after a lake level fluctuation exposed the sampling locations to air and then re-submerged them. Analyses of trace metals in porewater provide insight to the perturbation of redox gradients during unsaturation and resaturation processes. Furthermore, two shoreline locations were sampled to compare the effect of varying particle size.

With the exception of its appendices, Chapter 3 has been submitted for publication in *Limnology and Oceanography* with coauthors Nathan Chan, Nathan Dalleska, Mark Anderson, and Janet Hering. I designed the study, led all sampling campaigns, measured 9 of 12 porewater sample sets, analyzed and interpreted data, and wrote the manuscript. Mr. Chan, a Caltech Summer Undergraduate Research Fellowship program (SURF) student whom I mentored in the summer of 2005, assisted with fieldwork, analyzed the remaining porewater sample sets, and did some preliminary sediment extractions. Dr. Dalleska fine-tuned my measurement protocols on the inductively-coupled plasma mass spectrometer, making it possible to measure many elements simultaneously. Mr. Anderson provided essential field support and expertise during an exploratory trip to Lake Powell. Dr. Hering secured funding, guided the experimental design and data interpretation, and made many important improvements to the manuscript.

The long, narrow shape of Lake Powell and the high sediment load of the Colorado River enabled an interesting study of the patterns of deposition of inorganic chemicals in the reservoir. This study, which was conducted at a second field location, the Colorado River inflow region of Lake Powell, is described in Chapter 4. Therein, spatial trends in particle size, trace element composition, and bulk mineralogy by laser diffractometry, X-ray fluorescence (XRF), elemental analysis, and X-ray diffraction (XRD) were assessed in the sediment delta. Particle size was assessed as a predictor of the other parameters, and the implications of spatial trends in the delta sediment were evaluated for their connection to observed water quality trends.

Chapter 4 will be submitted to *Environmental Science and Technology* with co-authors Michael Easler, Dennis Eberl, Lincoln Pratson, Mike DeLeon, Aurelio LaRotta, and Janet Hering. I designed the study, led some of the field expeditions and participated in others, measured all samples for particle size and elemental composition, processed and analyzed data, and wrote the manuscript. Mr. Easler, a SURF student whom I mentored in 2006, joined me on two of the field trips, processed many samples, and made preliminary measurements of solid-phase carbon. Dr. Eberl made all XRD measurements and processed those data into mineralogical concentrations. Dr. Pratson helped me understand sedimentation processes in Lake Powell and will contribute side-scan sonar figures to the appendices of the manuscript. Dr. DeLeon and Dr. LaRotta helped me design a sample preparation protocol for XRF analysis and taught me how to interpret XRF data. Dr. Hering secured funding for the project, guided data collection, and evaluated the manuscript.

Since 2000, Lake Powell has been drawn down by a combination of a serious drought in the headwaters of the Colorado River and an obligation to release water to downstream users. This has led to exposure of ~50 km of sediment delta and subsequent resuspension as the river flows through the sediment to the smaller reservoir. A third project (Chapter 5) examines the release of phosphorus (P), the limiting nutrient in Lake

Powell, by this sediment resuspension. Field measurements of dissolved P and laboratory measurements of P in sediments were conducted. The probability that this new source of P supports increasing primary productivity is discussed on the basis of the results of this study. These data will also support a detailed reservoir circulation model of Lake Powell in development by the United States Bureau of Reclamation by improving the calibrations of the biomass growth and subsequent dissolved oxygen consumption.

Chapter 5 will be submitted for publication in *Water Research* with co-author Janet Hering. The same sediment samples as mentioned in Chapter 4 were used. I designed the study, collected water samples, made all dissolved P measurements, and did all laboratory work for the sediment measurements. Dr. Hering secured funding for the project, guided data collection, and evaluated the manuscript.

At a third field location, the Merced River in the Central Valley of California, the effect of irrigation on the transport of solutes in groundwater was examined. In this setting, water is moved via canal to an almond orchard that is irrigated with the equivalent of a 7.5-cm rainstorm every two weeks. As a result, the local water table rises during the growing season (summer) and groundwater is generally discharged to the Merced River; little river water infiltrates into the riverbed. In this setting, groundwater samples beneath the Merced River were collected and analyzed for a suite of trace solutes, allowing for a statistical assessment of the relative importance of hydrologic processes and biogeochemistry for the transport and sequestration of trace solutes. This research, presented in Chapter 6, was done in conjunction with a detailed study on the transport of agricultural chemicals at this site conducted by the United States Geological Survey as part of its National Water Quality Assessment program, Phase II.

Chapter 6 has been accepted for publication in *Journal of Environmental Quality* after being written with co-authors Joseph Domagalski and Janet Hering. In this study, I collected most samples, analyzed all samples for trace solutes, statistically analyzed data, and wrote the manuscript. Dr. Domagalski enabled and guided sample collection, collected some samples, and provided supporting data sets of field parameters and dissolved organic carbon. Dr. Hering secured funding for the project, assisted with data interpretation, and made many important improvements to the manuscript.

Finally, in Chapter 7, the major results of this research are summarized and wider implications are discussed.

1.3. References

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