CHAPTER 6: WATER QUALITY

ALLISON OLIVER

INTRODUCTION

The Colorado River begins at the continental divide in northern Colorado, and flows approximately 2,330 km through the arid western United States before draining into the Gulf of Mexico. The watershed area for the Colorado River is approximately 640,000 km^2, comprised of seven different U.S. states, and provides key water resources for humans and ecosystems in the region, and as a consequence is one of the most highly-regulated river systems in the world, with more than 20 major dams on it's main stem and tributaries. The fragmentation of the river into a series of reservoir and river reaches not only disrupts the natural flow regime, but also alters biogeochemical processes affecting water quality. This paper will focus on the water quality issues of the Colorado River between Glen Canyon Dam and Lake Mead.

When the natural flow regime of a river is disrupted by the installation of an impoundment, changes in system linkages ultimately alter the characteristics of the river, shifting conditions away from those of a free-flowing river. The type and magnitude of the response depends on the size, location, and characteristics of the dam itself. An observed shift in parameters of water quality or ecological function is often described in terms of the Serial Discontinuity Concept (Ward and Stanford 1983). This concept describes dams as pervasive agents of change in a river system, disconnecting a river from it's flow path and thus disrupting the longitudinal and lateral processes acting within the river's normal flow regime. This concept suggests that below a dam river conditions appear to "reset" to conditions of lower order streams. Given no additional perturbations, as the distance from the dam increases the river recovers more of its natural state. The distance and extent of recovery is based on factors such as the size and location of the dam, channel geomorphology, discharge volume, and tributary inputs (Ward and Stanford 1983). Common physicochemical and hydrological changes observed in an impounded river include trapping of materials behind the dam, changes in water temperature patterns, unnatural flow regimes, armoring of the river bed, and altered patterns in nutrient loading or nutrient forms (Stevens et al. 1997). These changes can have significant effects on the biology and ecology of a river.

The Colorado River below Glen Canyon Dam is dramatically altered from pre-dam conditions. Stanford and Ward (1983) characterized the Colorado River as one of the most erosive rivers in the world, with sediment dynamics driving much of the ecology (see Gibson, Bartolomeo, this volume). The river was flood-prone, turbid, and became increasingly warmer through the summer months. In the winter, portions of the river would occasionally freeze, and flashy storm flows played a major roll in the transport of materials downstream. Before inundation by Lake Powell, sediment loads in Glen Canyon were high during winter runoff events with clearer water only during very low flows in the later summer (Woodbury et al. 1959). There is little to no information available on pre-dam algal nutrients (i.e. nitrogen, phosphorus, silica), but due to the arid nature of the southwestern United States and the high turbidity in the river during a majority of the year, it is likely that the majority of primary productivity was allochthonous (derived from sources outside of the river), with nutrients being supplemented to the system during periods of storm flow and high turbidity. At present, the major water quality issues facing the Colorado River below Glen Canyon dam include temperature, salinity, and suspended solids. In addition, it is important to understand the role of organic matter as an energy source fueling primary productivity, as this ultimately shapes the structure and function of food webs along the longitudinal gradient of the lower Colorado River (for more detail on trophic interactions affected by these resources see Gravem, this volume).

The reach of river between Glen Canyon Dam and Lake Mead is 472 km long and can be divided into three distinct reaches for the purposes of describing water quality, organic matter contributions, and primary productivity. These are defined as 1) the tailwaters reach from Glen Canyon Dam to the Paria River (26 km), 2) the variably turbid reach between the Paria River and the Little Colorado River (96 km), and 3) the usually turbid reach from below the Little Colorado River to Lake Mead (376 km) (Figure 1).

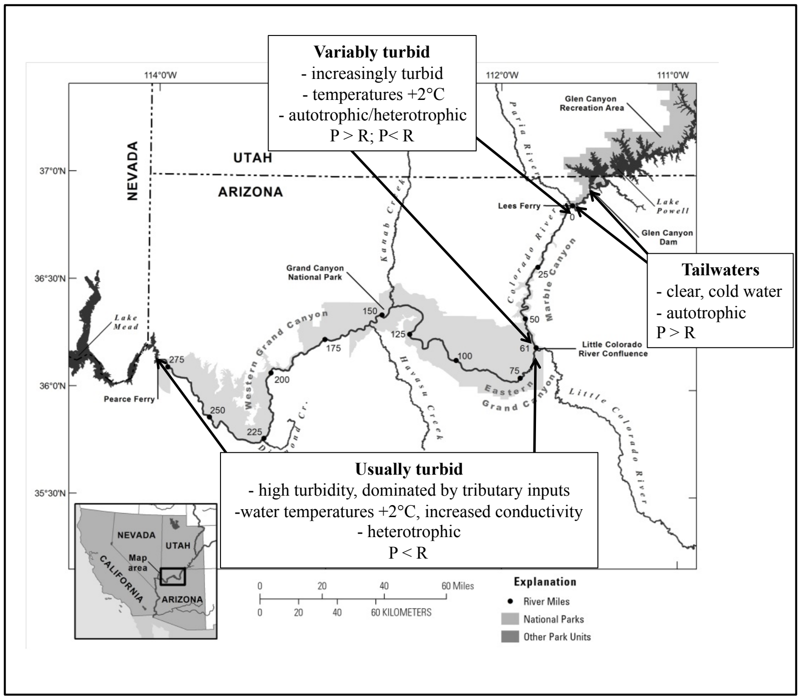

Figure 1: Reach of the Colorado River between Glen Canyon and Lake Mead showing the three distinct regions of varying water quality condition.

TAILWATERS

Water quality conditions in the tailwaters directly below Glen Canyon Dam are tightly linked to the limnology of Lake Powell. Lake Powell is a mostly oligotrophic (low in nutrients and productivity) although it may occasionally become mesotrophic (moderate levels of productivity). The lake is intensely stratified throughout most of the year, and on average mixes once per year during the winter cool down, although mixing rarely extends to the bottom (Stanford and Ward, 1990). Glen Canyon Dam releases water from the lower zone of Lake Powell. This water is colder (average 7°C) and contains approximately 50% more dissolved solids then the upper zone. Pre-dam temperatures ranged from 0 to 29.4°C, with the river warming significantly in the summer months, while post-dam river temperatures are colder and exhibit a narrower range (6.5-17°C). The summer temperature range was approximately 1/3 of the pre-dam range at Lee's Ferry, located 24 km downstream of the dam (Stevens et al. 1997).

Although there can be a significant amount of dissolved solids released from Lake Powell into the tailwaters, because the average residence time of water in the reservoir is 2 years, the majority of particulate material that enters the reservoir from upstream settles out to the reservoir bed. As a result of this sediment trapping occurring within Lake Powell, the water entering the Colorado River from Glen Canyon Dam is optically clear.

Salinity is another major water quality issue in the Colorado River. High salinity loads are a result of runoff from natural sources (e.g. saline springs, geologic formations), human sources (e.g. agriculture, municipal, industrial), as well as high rates of evaporation resulting from the arid climate. To deal with water quality problems related to high salinity, in 1974 the U.S. Congress enacted the Colorado Salinity Control Act, which resulted in the development of numerous control structures aimed at reducing salt loading though out the Colorado River basin. The amount of total salt loading can fluctuate widely depending on the size of water year. Under select climate conditions, the conductivity of discharges from Glen Canyon Dam can vary by 50% over short periods of time (Blinn et al. 1998). Over the long term, conductivity values have decreased below Lake Powell, possibly as a result of stricter enforcement and treatment facilities upstream. In addition, Lake Powell's large storage capacity and regulated, more uniform release of water from Lake Powell has reduced the variability in salt loading by buffering the effect of a flashy hydrologic regime (Mueller and Leibermann 1988).

Primary productivity in Lake Powell tends to be limited by phosphorus (P) the majority of the year (Standford and Ward 1990). Interestingly, while the total P load entering Lake Powell is quite high due to high suspended sediment loads with P sorbed to inorganic particles, this P is not in a soluble form and therefore not readily available. In addition, calcite precipitation scavenges dissolved nutrients from the water column, further reducing concentrations (Mayer and Gloss 1980). The deeper, denser water stratum of Lake Powell (also known as the monimolimnion) remains aerobic during much of the year, so anaerobic conditions leading to bed-release of nutrients is rare. As a result of these factors, primary productivity in Lake Powell tends to be P-limited and seasonally dependent on nutrient inputs via spring flow within the river turbidity plume entering the reservoir (Gloss et al. 1980). Nitrogen (N) also enters in significant amounts, and productivity in the lake regenerates some of this N in either inorganic or organic forms throughout the year. Overall, the ratio and amount of N to P leaving Lake Powell is sufficient to support a tailwater reach with high primary productivity during the majority of the year (Ayers and McKinney 1995). Most of the organic matter (a source of carbon) supplied in this reach is autochthonous (originating within the river), derived from filamentous chlorophyte algae with associated aquatic plants as well as some contribution of reservoir inputs (Angradi 1994). The fate and importance of algal organic matter in this portion of the Colorado river is not well understood, but Stevens et al. (1997) estimated that over 70% of total algal biomass in the downstream 472 km river corridor is produced in the upper 26 km clear tailwater reach.

VARIABLY TURBID REACH: PARIA RIVER TO LOWER COLORADO RIVER

Downstream from Lee's Ferry, tributaries begin to enter the river and exert regional or "biome" effects by contributing suspended load and thermal variability that are often reduced in the tailwaters of large dams. These tributaries contribute to the recovery of the system from tailwater conditions towards a more natural, pre-dam state (Minshall et al. 1983, Corkum 1991, Johnson et al. 1995). There are more than 490 ephemeral and 40 perennial tributaries, but only 6 perennial tributaries have mean flows of $1m^3*s^{-1}$. There are a number of spring-fed tributaries that originate within the Grand Canyon, which tend to have very different physicochemical properties then non-spring fed systems (Covich 1988); however their mean flows are so low that their contribution to water chemistry during base flow is not significant (Oberlin et al. 1999). The tributaries in this reach are temporally flashy systems, and so while mean flows may be low, during runoff events they can contribute large and significant amounts of sediment and organic matter (Blinn et al. 1995, Shannon et al. 1996). A reconnaissance of 36 tributaries of the Colorado River indicated that debris flows are the major process by which sediment and organic material is transported to the Colorado River in the region of Grand Canyon National Park (Webb et al. 1989). Debris flows are slurries of sediment, organic materials, and water comprised of less than 40% water by volume. A historical account of tributary environments described one of them as:

> "…a lo[a]thesome little stream, so filthy and muddy that it fairly stinks. It is only 30 to 50 [yards] wide now and in many places a man can cross it on the rocks without going on to his knees ... [The Little Colorado was] as disgusting a stream as there is on the continent ... half of its volume and 2/3 of its weight is mud and silt. [It was little but] slime and salt ... a miserably lonely place indeed, with no signs of life but lizards, bats and scorpions. It seemed like the first gates of hell. One almost expected to see Cerberus poke his ugly head out of some dismal hole and growl his disapproval of all who had not Charon's pass."
>
> - George Bradley and Jack Sumner, August 1869

While early explorers in the region may have loathed these tributary environments, tributary inputs provide important contributions to the main stem of the Colorado River. As tributary inputs increase downstream from the tailwaters, mean temperatures increase approximately 2°C (Voichick and Wright 2007), and secchi depth (as a measure of turbidity) decreases approximately 4 m (Stevens et al. 1997). Conductivity remains fairly similar to upstream concentrations, averaging 0.92 uS. Because the tributaries are temporally variable, their effect on the mainstem varies depending on the size of the water year. This results in a "variably turbid" system, where higher water years result in a longer reach of river with higher turbidity downstream from the Paria River (the first major tributary) and lower water years result in more optically clear conditions. The type and extent of productivity in this reach is largely controlled by the temporal variability in tributary inputs. Tributary organic matter has been shown to be isotopically distinct in composition from the main stem in the upper portions of the variably turbid reach, with tributary seston derived more from upland plants and riparian vegetation then from in-stream production (Angradi 1994). Overall, conditions downstream become increasingly dominated by allochthonous (externally-derived) inputs contributed by riparian and upland carbon sources, with the magnitude of the contribution dependent upon water year and tributary discharge (Blinn et al. 1998, Shannon et al. 1996). Interestingly, previous studies have found that while total detritus mass tends to be higher at Lee's Ferry, there are no differences between detrital mass between upstream and downstream sites in the more turbid reaches, indicating that the majority of new inputs are dominated by larger particulate matter rather than smaller fraction organic matter (Stevens et al. 1997). In years where tributary discharge is low, a greater proportion of this reach will be dominated by autochthonous productivity, and become increasingly autotrophic in nature. Large tributary inputs decrease the presence of benthic algal productivity in a "stair-step" fashion, with increased inputs resulting in an even greater loss of benthic algae mass (Stevens et al. 1997). As a result, when tributary contributions are large and debris flows are contributing a significant amount of material, this reach becomes increasingly turbid and more heterotrophic.

USUALLY TURBID REACH: LITTLE COLORADO RIVER TO LAKE MEAD

The reach of the Colorado River below the Little Colorado River (124 km from Glen Canyon Dam) is defined as “usually turbid” due to the cumulative effect of tributary inputs that result in low water clarity. The effect of tributaries accumulates downstream so that this reach is continuously dominated by high turbidity and allochthonous inputs year-round. The depth of light penetration at Lower Granite Gorge (above Diamond Creek, 388 km from Glen Canyon Dam) is approximately 1/5 of the depth from above the Little Colorado River. Mean water temperatures continue to increase downstream from the Little Colorado River, approximately another 2°C as a result of warmer tributary water inputs as well as increased solar radiation as a result of increased residence time in the canyon (Voichick and Wright 2007).

In addition to water temperature, mean conductivity also increases in this reach (Stevens et al. 1997), probably as an effect of tributaries that drain larger watersheds sourced outside of the Grand Canyon that tend to have higher conductivities with greater variability. Examples include the Little Colorado River and Kanab Creek, which have some of the highest measures of conductivity of the Grand Canyon tributaries and can carry large amounts of total dissolved solids (Oberlin et al. 1999).

Many of the larger tributaries located in the lower portion of the river have little direct external input aside from scouring, debris flows that occur during large runoff events. As a result, those tributaries that receive adequate light input are dominated by the in-stream productivity of cyanobacteria and diatoms. However, due to chronic low light availability, the main stem of the Colorado River between the Little Colorado River and Lake Mead is heterotrophic. While algal nutrients are sporadically replenished by allochthonous inputs derived primarily from tributaries, the lack of light and unstable substrates on the river bed limits primary productivity.

MANAGEMENT OF WATER QUALITY ISSUES

Management of water quality in the lower Colorado River between Glen Canyon Dam and Lake Mead primarily concerns sediments, temperature, and salinity, as well as the ecological significance of nutrient availability and primary productivity. For more discussion on issues surrounding sediments, please see previous chapters (Burley, Gibson, and Bartolomeo, this volume). Addressing the issues of temperature and salinity are complex and require management of water resources in upstream portions of the river within the context of multiple interests and uses such as non-native fisheries (Lusardi and Steele, this volume), agriculture, and industrial/municipal purposes. While tactics such as HFE’s (Burley, this volume) may be potential tools for addressing sediment issues, the HFE’s have had minimal effects on in-stream water quality parameters. For example, during the 1996 HFE, the only detectable change in water quality parameters was variation in the range of penetrable light intensity within the main channel due to variation in turbidity during the flood and post-flood (Stevens et al. 1997). There were however, some interesting temporary effects of the 1996 HFE on productivity. This event scoured detritus and senescent plant material from periphyton in the tailwaters reach, resulting in increased post-flood primary productivity and a doubling of in-stream metabolism (Stevens et al. 1997). The HFE may have also contributed to a seasonal increase in N, P, and C concentrations in downstream backwater habitats, as floods buried organic matter that was subsequently mineralized to available nutrient forms (Parnell et al. 1999). Despite observed changes, these effects were not long-lasting and are not likely to sustain long term change in current ecosystem-wide processes.

Current water quality issues will continue to persist as long as Glen Canyon Dam continues it's current operations. Within the Glen Canyon Dam Adaptive Management Program, proposals have been made to address the issue of the cold waters released from Lake Powell. This would include installing a temperature control device that would allow managers to draw water into penstocks from various depths within the reservoir and therefore be able to ameliorate current cold water conditions, in theory making habitat more suitable for native fish in the absence of alien fishes (for more on this see Lusardi and Steele, this volume). Ultimately, it is these types of creative solutions that may need to be incorporated into dam operations and management of the river in order to address the water quality issues of the Colorado River within the Grand Canyon.

REFERENCES

Angradi T.R. 1994, Trophic linkages in the lower Colorado River: multiple stable isotope evidence. J. N. Am. Benth. Soc. 13:479-495.

Ayers A.D. and T. McKinney. 1995, Effects of different flow regimes on periphyton standing crop and organic matter and nutrient loading rates for the Glen Canyon Dam tailwater to Lee's Ferry. Draft final report. Arizona Game and Fish Department, Phoenix.

Blinn D.W., J.P. Shannon, L.E. Stevens, and J.P. Carter. 1995, Consequences of fluctuating discharge for lotic communities. J. N. Am. Benth. Soc. 14:233-248.

Blinn D.W., J.P. Shannon, P.L. Benenati, and K.P. Wilson. 1998, Algal ecology in tailwater stream communities: The Colorado River below Glen Canyon Dam, Arizona. J. Phycol. 34, 734–740

Covich A.P. 1988, Geographical and historical comparisons of neotropical streams: biotic diversity and detrital processing in highly variable habitats. J. N. Am. Benth. Soc. 7:361-386.

Stanford J.A. and J.V. Ward. 1990, Limnology of Lake Powell and the chemistry of the Colorado River, pgs 75-101 in Colorado River ecology and dam management: proceedings of a symposium. Santa Fe, New Mexico. National Research Council (U.S.). Committee to Review the Glen Canyon Environmental Studies

Mayer L.M. and S.P. Gloss. 1980, Buffering of silica and phosphate in a turbid river. Limnol. Oceanogr. 25:12-22

Mayer L.M., S.P. Gloss, and D.E. Kidd. 1980, Advective control of nutrient dynamics in the epilimnion of a large reservoir. Limnol. Oceanogr. 25:219-225.

Mueller, D.K., and T.D. Liebermann. 1988, Extension of Streamflow and Dissolved Solids Records at Selected Sites in the Colorado River Basin: Arizona, California, Colorado, Nevada, New Mexico, Utah, and Wyoming, 1940-83. U.S. Geological Survey, Water Resources Investigations Report 87-4203.

Oberlin G.E., J.P. Shannon, and D.W. Blinn. 1999, Watershed influence on the macroinvertebrate fauna of ten major tributaries of the Colorado River through Grand Canyon Arizona. The Southwestern Naturalist. 44:17-30.

Parnell R.A., J.B. Bennett, and L.E. Stevens. 1999, “Mineralization of riparian vegetation buried by the 1996 controlled flood” In The Controlled Flood in the Grand Canyon, Volume 1. Eds. R.H. Webb, J.C. Schmidt, G.R. Marzolf, R.A. Valdez, American Geophysical Union, Washington D.C

Shannon J.P., D.W. Blinn, P.L. Benenati, and K.P. Wilson. 1996, Organic drift in a regulated river. Canadian J. Fish. Aq. Sci. 53:1360-1363.

Stevens, L.E., Shannon, J.P., and Blinn, D.W., 1997, Colorado River benthic ecology in Grand Canyon, Arizona, USA—Dam, tributary, and geomorphological influences: Regulated Rivers—Research & Management, 12:129–149.

Voichick, N., and Wright, S.A., 2007, Water-temperature data for the Colorado River and tributaries between Glen Canyon Dam and Spencer Canyon, northern Arizona, 1988–2005: U.S. Geological Survey Data Series 251, 24 p.

Ward J.V. and J.A. Stanford 1983. The Serial Discontinuity Concept of River Ecosystems. *editors* T.D. Fontaine, S.M. Bartell: “Dynamics of Lotic Ecosystems”. Science Publications, Ann Arbor, MI