

Nitrogen & Phosphorus Dynamics below Glen Canyon Dam

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ABSTRACT

Nitrogen (N) and phosphorus (P) dynamics in the Colorado River below Glen Canyon Dam have important implications for primary productivity, aquatic food webs, and overall water quality. Typical phytoplankton N:P is 16 (Redfield, 1958), but this value varies with algal adaptations and riverine features. My literature and data syntheses work to understand historical and current factors influencing Colorado River N:P. USGS data from 1979-2013 reveals years of very high peak N:P events at Lees Ferry and Diamond Creek: 1990-1991 (500 and 200), 1999 (127 and 72), 2006 (no data and 180), and 2012 (197 and no data). These high N:P events are likely due to dam operations influencing sediment-bound phosphate. I suggest that P influences have been particularly under-studied in this system. As climate data and dam management point toward altered flows, N:P ratios need to be more actively included in water quality evaluations.

GOALS OF THE PAPER

1. Evaluate primary productivity pre- and post- Glen Canyon Dam and connection to N,P.
 2. Determine historical and current N & P status of the Colorado River reach between Lees Ferry and Diamond Creek. Evaluate changes in the nutrient sources for the river system.
 3. Evaluate nutrient sinks and interactions linked to climate change and dam management.
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LITERATURE SYNTHESIS

1. Increases in algae-based food webs

1.1 Primary productivity and sunlight

The introduction of Glen Canyon Dam dramatically changed aquatic foodwebs along the Colorado River downstream – a reach which currently travels through the Grand Canyon National Park and empties into Lake Mead. Prior to dam installation, the river's high sediment load blocked sunlight from photosynthesizers, leading to low plant and algal growth, or Gross Primary Productivity (GPP) (Lovich and Melis, 2007). The dam was completed in 1963, creating the Lake Powell reservoir behind the concrete walls and emptying cold, clear waters immediately below for what would soon evolve into a blue ribbon trout fishery (Shannon et al., 2001; Lovich and Melis, 2007). New low-sediment waters allowed sunlight to increase GPP, which higher trophic levels then consumed.

The increase in algal primary production immediately below the dam did not come without drawbacks, such as invasive species effects. *Cladophora glomerata* was one of the few algae species which could thrive under the unstable conditions since the dam introduction (Benenati et al., 2002). This alga is a vital resource for many native invertebrates that feed native fishes, but it is also a preferred habitat and food source for invasive species such as the New Zealand Mudsail (*Potamopyrgus antipodarum*) (Cross et al., 2010). The clear, sunlight-rich waters beneath the dam are therefore an important site for fishing recreation as well as a site for close monitoring of algae-based food webs.

Light is not the only limiting factor for primary productivity. Modern isotope tracer studies confirm a largely algae-based foodweb immediately below Glen Canyon Dam near Lees Ferry, but these same studies find more particulate organic matter-based foodwebs further from the dam (Benenati et al., 2002). Light limitation alone could account for these differences. Additionally there are concentrated areas of GPP noted on rocks and shaded cliff walls near rapids (Odum, 1956; Shaver et al., 1997; Benenati et al., 1998; Hall Jr., 2012), even if there is no explicit link to Colorado River foodwebs. Besides optimal growing conditions (light, pH, temperature), plants further require carbon and nutrients – particularly nitrogen and phosphorus.

1.2 Primary productivity and nitrogen, phosphorus

Primary productivity is inextricably linked to nitrogen (N) and phosphorus (P) dynamics. Plant growth requires N, because it is part of proteins and amino acids. All life processes require P, because it is in adenosine triphosphate (ATP, for cell energy) and nucleic acids (DNA). In systems low in available N, P-rich ATP molecules help certain plants/microorganisms to “fix” useable forms of N from abundant atmospheric reservoirs (Howard and Rees, 1996). Likewise, in P deficient ecosystems, N-rich phosphatase enzymes allow for P recycling within organisms and for acquisition of previously unavailable P (Colvan et al., 2001; Marklein and Houlton, 2012). Together, N and P constrain biological functions and plant growth.

Algae and river nutrient dynamics can help assess Colorado River’s sensitivity to change. One concern is algal blooms, which can lead to eutrophication in large rivers and lakes. Blooms do occur in spring and summer seasons, due to changes in temperature and nutrients (Power, 1992). However, large algal blooms can hurt fish populations and food webs. First the blooms block light from subaquatic plants; then plant/algae deaths lead to decomposition, which depletes oxygen and suffocates fish (Smith et al., 1999). Sustaining healthy fish populations and benign algae food webs within the Colorado River has ecological, economic, and intrinsic benefits. Thus, identifying the system’s nutrient dynamics is a key step to improve river management.

A useful tool in evaluating environmental nutrient limitations is N:P ratios. Per Redfield (1958) the typical N:P in marine phytoplankton is 16:1, or 16. The Redfield Ratio is widely accepted as a starting point to analyze algal bloom potentials in water bodies, because deviations downward are associated with blooms. This pattern is not straight-cut in riverine systems, as shorter water residence times tend to reduce algal response (Soballe and Kimmel, 1987; Ekholm, 2008). Despite overall shorter residence times than standing bodies such as lakes, river flows are dynamic (Mount, 1995) and biochemically complex (Odum, 1956) enough to merit further study. The effects of dam operations on downstream N:P may be better understood by studying resulting changes in downstream nutrient balances – inputs and outputs. I examine nutrient complexities in the Colorado River below Glen Canyon Dam and through the Grand Canyon.

2. Change in nutrient inputs

2.1 Terrestrial to mixed nutrient sources

Before the introduction of Glen Canyon Dam, nutrients were derived from upstream drift and natural rock weathering processes above the Colorado River and its tributaries. Sediment inhibited sunlight for GPP (Lovich and Melis, 2007), but there is little data detailing the extent to which GPP was limited pre-dam. Pre-dam USGS data reveals that nitrate – one biologically available form of N – fluctuated with the natural hydrograph in the Grand Canyon (Paulson and

Baker, 1980). There is limited nutrient data for the river itself, but upstream reservoir data reveals that most nutrients are bound to smaller particle sizes (Wildman, 2009), P tightly bound to either calcium or aluminum. The P is mostly from calcite and biogenic apatite, washed in from further upstream, and is largely biologically unavailable. More data is available post-dam.

N and P sources shifted from primarily terrestrial sources to a mix of sources. Upstream nutrients are now released from Lake Powell's hypolimnion – the deep, cold water region which tends to be nutrient enriched. A decade post-dam, Grand Canyon nitrate concentrations had decreased (Paulson and Baker, 1980), perhaps due to hypolimnetic N cycling and discharges of other forms of N. That same year, dissolved P from the lake outflow was 72% lower than that of the inflow (Gloss, 1977). This effect was due in part to biological uptake in Lake Powell's surface waters (Gloss et al., 1980). Most sediment-bound P was now settled at the bottom of the reservoir and blocked by the dam. Overall, Lake Powell inputs depend on hypolimnetic N cycling and any finer P-bound sediments being incorporated into the discharged water.

Other sources of N and P include wind-blown, or aeolian, dust sources and tributaries, like the Little Colorado River. Aeolian sources existed prior to the dam, but in the absence of fluvial sediment sources became more important. Flow experiments led to the build-up of beaches in some areas, increasing the exposed debris that could be wind-carried (Draut, 2012). Rare high flow experiments (HFEs) in 1996, 2005, and 2008 scattered sediment, creating sand bars and aeolian dunes that could host new riparian vegetation (A. Simler and B. Lane 2014, this volume). Lower artificial floods can have a stabilizing effect, leading to biological soil crusts which can “fix” atmospheric N into biologically available forms in upland riparian landscapes (Draut, 2012). This is one mechanism for riverside N inputs. In any event, for either high/low flows the prerequisite for aeolian dunes is some fluvial sediment source: tributaries.

The Little Colorado River intersects the Colorado River ~62 river miles downstream from Glen Canyon Dam. This tributary supplies enough sediment & nutrients to support a significant humpback chub (*Gila cypha*) population as well as diverse algal- and detritus-based food webs (USGS, 2013). The Little Colorado Watershed's high-P sediment comes from eroded sandstone and limestone, with scattered sources of weathered igneous rocks. Human activities which contribute to stream water quality include forestry (increased erosion), open grazing (increased erosion, N and P from manure), and mining (increased erosion, chemical mining wastes) (ADEQ, 2010). Nutrient-rich human wastes from local tribal lands are not directly assessed. The Little Colorado is one of several tributaries to the Colorado River but embodies the complexities involved when considering collective nutrient inputs. There is no current estimate of N and P fluxes from total mixed sources – tributary or other – into the larger river, perhaps due to too many variables such as seasonality and system responses to change.

2.2 Glen Canyon Dam operations on N:P (USGS Data Synthesis)

To see the long-term changes in N:P due to dam operations, I synthesized USGS water data from 1979-2013 collected just below Glen Canyon Dam at Lees Ferry, AZ, and just above the Diamond Creek inflow near Peach Springs, AZ (**Figure 1**, See supplemental notes at end).

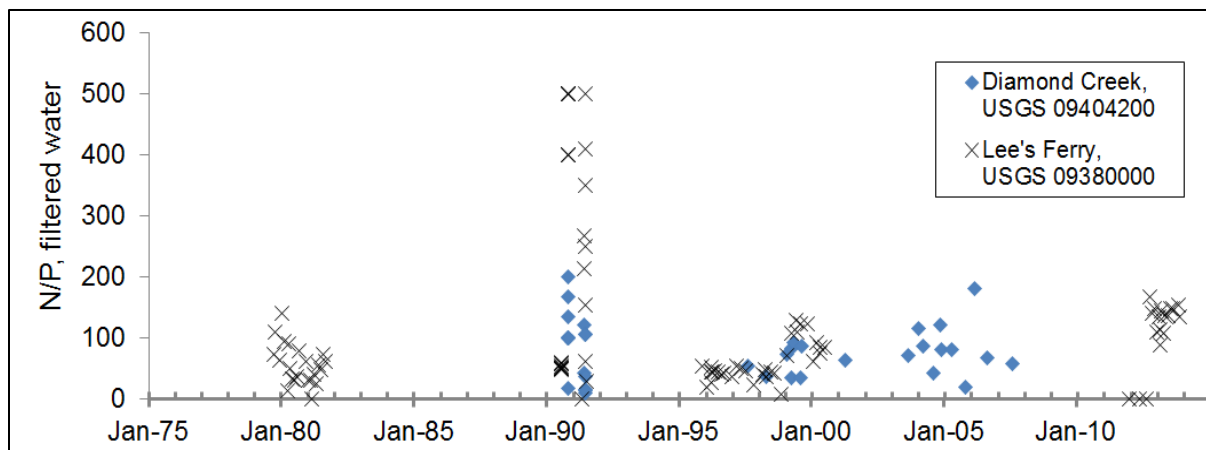


Figure 1 – Colorado River N:P at Lees Ferry and Diamond Creek (1979-2013). Ratios integrated from public U.S.G.S. water quality data for filtered water total N and P. Lees Ferry is 16 river miles and Diamond Creek is 242 river miles from Glen Canyon Dam. Flows pre-1991 ranged from 1,000-25,000cfs daily; interim flows ranged from 5,000-20,000cfs; and high flow experiments took place in March 1996, November 2005, and March 2008 (Mellis et al., 2001; Draut, 2012).

Most data aligns with electricity-centered flows before 1991, interim flows in 1991, and HFEs in March 1996, November 2005, and March 2008 (Mellis et al., 2011; Draut, 2012; B. Lane, this volume). More N:P datapoints are needed to compare to control flow events, but results were still striking. During interim flows, Colorado River N:P at Lees Ferry and Diamond Creek peaked near 500 and 200 respectively and then quickly dropped to <10 (**Figure 1**). These values are substantially different from the Redfield ratio 16 N:P. The data suggest that the river is on average extremely P limited, more-so in the tailwaters, and that dam operations affect N:P ratios.

I hypothesize that N:P increases were due to more N released from Lake Powell’s hypolimnion compared to sediment-bound P during extreme flows, both high and low. I further postulate that N:P decreases are due to two interactions: (1) High flows scattering sediment and physically releasing P through turbulence, a temporary and small spatial-scale phenomenon; and (2) Biological uptake of N and/or adaptations to low P throughout the river. To evaluate these explanations, I consider nutrient sinks/outputs and other interactions.

3. Changes in nutrient outputs and other interactions

3.1 P limitation and increased nutrient uptake

Pre-dam plants may have been slower to uptake P than those in the current system. The Redfield Ratio concept has inherent assumptions which natural bodies of water and algae may stray from, especially when in P deficient bodies of water. Several studies in the 1970s demonstrated that algal cultures in P deficient environments can physiologically adapt to assimilate phosphate more efficiently (Sicko-Goad and Jensen, 1976; Sakshaug and Holm-Hansen, 1977; Droop, 1977). Algal cultures in P limited environments may shift N:P ratios from the typical Redfield 16 to about 100, and then upon exposure to phosphate N:P drops substantially to below 10 (Sakshaug and Holm-Hansen, 1977). This phosphate “overplus phenomenon” is due to algal cells requiring an absolute minimum P per cell (Correll, 1998).

These adaptation dynamics may persist in the current P-limited Colorado River. That is, seemingly minimal deviations in P may in fact yield large responses in primary productivity.

Both whitewater and calm areas of the river can increase algal nutrient uptake. Turbulent flows may increase GPP by physically breaking bonds between phosphate and the metals in the sediment. Data from Lakes Powell and Mead shows that brief periods of hydrologic disturbance may temporarily desorb N and P from sediments (Prentki et al., 1980; Wildman, 2009). These hydrologic effects may be seen in the actual river. Intense flows – near the dam outflow, in areas after rapids, and after tributary flows – may temporarily resuspend sediments, kicking N and P off and making these nutrients available for GPP. The response (r) of algal cell abundance to total P also depends on residence time (r=0.7) and water depth (r=0.6) (Soballe and Kimmel, 1987). Thus, algal biomass in relatively still segments along the river such as deep pools – after riffles – or in side channels may respond to these induced increases in total P.

3.2 Continuous Colorado River N:P, March 2014 (New Research)

Dahlgren (2014, unpublished) observed biogeochemical changes continuously along 225 River Miles (RM) from the dam. The data confirms discussed input dynamics: low P at RM0 due to low sediment load (turbidity); low nitrate at RM0 due to hypolimnion cycling; and a sharp increase in turbidity and total P at RM63, just after the Little Colorado River inflows (**Figure 2**). Arguably the new P was largely due to the tributary sediments (**Figure 4**), possibly turbulence as well. Nutrient sinks and other interactions discussed are supported. High N:P (>>16 Redfield ratio) in the algae-rich dam tailwaters (**Figure 3**) supports low-P adaptations for fast nutrient uptake. The total N decrease near the Little Colorado River (**Figure 2**) suggests that some forms of N were lost through either a cycling or uptake mechanism. N:P<16 near this tributary seemed localized, as N:P increased by RM100 and oscillated near 50 for the remainder of the reach. If P-limited waters suddenly decrease in N:P, GPP may spike and deplete the river of P, locally. This local uptake might then cause high N:P downstream and maintain an overall P-limited system. The overall river system is potentially set up for high local algal blooms.

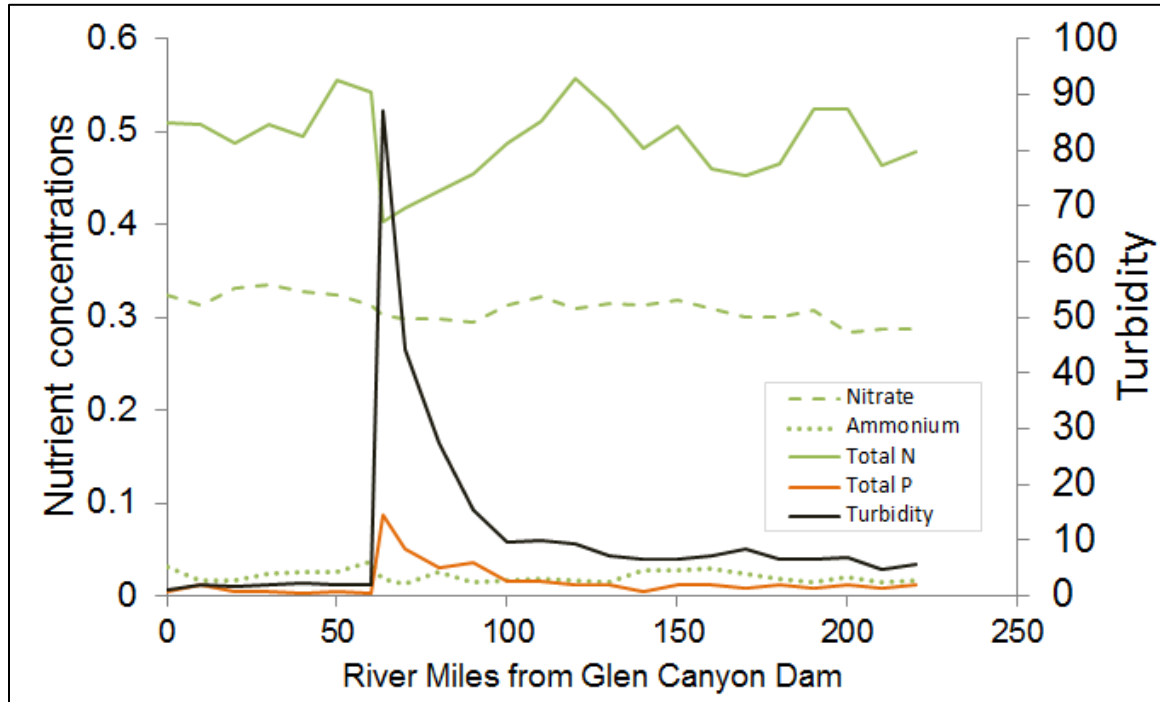


Figure 2 – Colorado River Nutrients and Turbidity (March 2014). Water quality data collected by RA Dahlgren (unpublished) from March 13-March 28, 2014, every 10 river miles. Units for concentrations are mg/L. Units for turbidity are ntu.

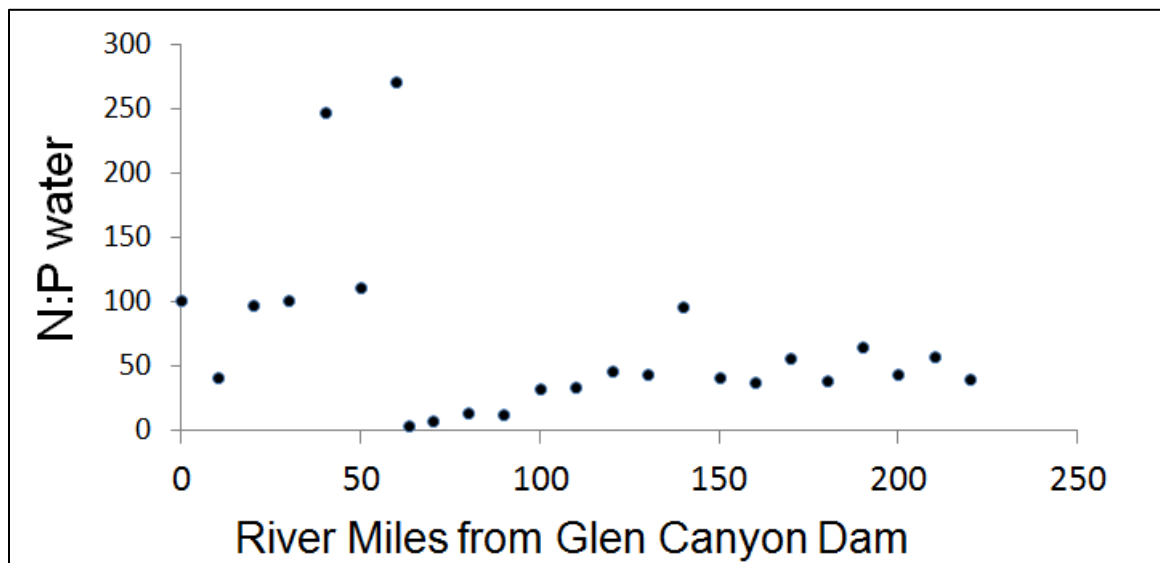


Figure 2 – Colorado River N:P (March 2014). Water quality data collected by RA Dahlgren (unpublished) from March 13-March 28, 2014, every 10 miles. N:P sharply decreases at RM63, just after the Little Colorado River intersects the Colorado River.

systems along adjacent watersheds may increase nitrates seeping into groundwater and into the Colorado River, especially closer to Lake Mead (Prentki et al., 1980), increasing eutrophication risks (Conley et al., 2009). Furthermore, changes in water supply, demand, and allocation pressures (K. Harrison 2014, this volume) may require a change in dam operations. Prior to making such changes it is vital to study N:P dynamics throughout the natural system. As discussed above, different flow intensities can affect the river sediment, morphology, riparian ecology, and a slew of nutrient interactions affecting productivity and food webs. This data supports that the Colorado River, let alone any river, should not be viewed as a uniform conduit for nutrients into lakes, but rather as a complex, sensitive system in need of further study.

CONCLUSIONS

1. Glen Canyon Dam (GCD) increased algae-based food webs below by influencing sunlight and N:P. Lake Powell's hypolimnion is rich in cycled N. However, sediment-bound P inputs have been greatly reduced. Some algae and plants may have adapted to low-P environments.
2. The Colorado River through the Grand Canyon is very P-limited. GCD shifted the system from terrestrial to mixed sources of nutrients: hypolimnetic N, aeolian sources, and tributaries. Overall, the system is now set to be responsive to any increase in P, whether through actual supply or through interactions which may lead to P desorption from sediments.
3. Nutrient outputs are primarily plant/algal uptake of N and P. There is also gaseous cycling of N, which can cause climate interactions. Environmental, climate, and tidal influences on dissolved oxygen will influence microbial N cycling. Flow regimes will affect P primarily through sediment effects. Further study is needed to confirm N:P interactions, river-wide as well as in certain segments more prone to P responses. Water management must be comprehensive and multi-faceted in the face of climate change and new water allocation pressures.

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Supplemental Notes on Figure 1

NWIS code P00666: Total P. Total dissolved, alkaline persulfate digestion, processed through 0.45um filters at collection; stored in filtered chilled container

NWIS code P00602: Total dissolved nitrogen. TDN – CAWSC SOP C1.DOM --- Merriam et al., 1996, Shimadzu TOC, high temp combustion.

Station USGS 09380000 -- Colorado River at Lees Ferry, AZ

Station USGS 09404200 – Colorado River above Diamond Creek, near Peach Springs, AZ

Data synthesis was limited to total N and total P collected at same date, time and site.