Journal of Hydrology 519 (2014) 164–176

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

# The upside-down river: Reservoirs, algal blooms, and tributaries affect temporal and spatial patterns in nitrogen and phosphorus in the Klamath River, USA

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ARTICLE INFO

*Article history:*
Received 29 October 2013
Received in revised form 22 April 2014
Accepted 17 June 2014
Available online 15 July 2014
This manuscript was handled by Laurent Charlet, Editor-in-Chief, with the assistance of M. Todd Walter, Associate Editor

*Keywords:*
Rivers
Biogeochemistry
Algal blooms
Dams
Nitrogen
Phosphorus

SUMMARY

The Klamath River, located in Oregon/California of the Northwestern U.S., is highly impounded and also experiences large seasonal algal blooms and impaired water quality. We investigated nitrogen (N) and phosphorus (P) constituents for one year (2010–2011) across 193 km of the Klamath River at sites above and below reservoirs and major tributaries to determine the influence of these features on longitudinal and temporal trends in concentrations, loads, and N:P ratios. In general, the headwater lake (Upper Klamath Lake) and reservoirs appeared to be the dominant influence on water quality and nutrient dynamics in the upper river, whereas tributaries appeared to exert stronger influence in the lower river. Overall, high nutrients and poor water quality at upstream sites were ameliorated downstream, however the downstream reductions in N were much greater relative to P. Seasonality appeared to play a major role in the overall appearance and magnitude of longitudinal trends. The greatest upstream–downstream differences occurred during periods of time following large algal blooms in the upper portion of the river. Overall, the amount and composition of N appeared to be strongly driven by algal blooms and biogeochemical conditions such as low oxygen, high pH and warm temperatures in the upper portion of the river, whereas P was more strongly driven by seasonal hydrology. The spatiotemporal influence of reservoirs and tributaries on nutrient flux and nutrient ratios may have significant implications for aquatic communities and ecosystem health. Nutrient objectives should be considered when designing restoration, management, and monitoring objectives for projects involving habitat suitability for anadromous fish and potential dam removal.



## 1. Introduction

Actively moving, or lotic, waters exhibit longitudinal gradients that influence aquatic ecosystem structure and function, and therefore also affect nutrient fate and transport (Vannote et al., 1980; Newbold et al., 1983). River impoundments alter longitudinal gradients by causing upstream–downstream shifts in physical, chemical, and biological processes (Ward and Stanford, 1983). Impoundments often create reservoirs that disrupt lotic connectivity and alter in-stream biogeochemical cycling (Friedl and Wüest, 2002; Humborg et al., 1997), organic matter dynamics (Miller, 2012), and downstream transport of sediments and nutrients (Kelly, 2001; Houser et al., 2009). Timing of the processing and export of materials may also be disrupted, leading to seasonal changes in downstream productivity (Ahearn et al., 2005). For example, lentic bodies are composed of still waters and are frequently viewed as annual net sinks for phosphorus and nitrogen (Harrison et al., 2009), but are also important sub-annually by influencing the export of nutrients to downstream reaches (Wurtsbaugh et al., 2005; Kendall et al., 2001). The magnitude of these effects shifts with position in the watershed and river network (Jones, 2010; Swanson et al., 1988), as well as with relative proximity to other lentic bodies (Epstein et al., 2012; Kelly, 2001). Lentic waters also affect processing within adjacent lotic reaches; comparisons between river reaches above and below lentic bodies have shown significant differences in water quality and nutrient processing (Goodman et al., 2010). Ultimately, the variety of alterations due to impoundments may have cascading effects, with consequences for water quality and aquatic communities.

In the western U.S.A., many rivers draining to the Pacific Ocean, such as the Klamath River, serve as critical habitat for anadromous

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http://dx.doi.org/10.1016/j.jhydrol.2014.06.025
0022-1694/

fish. The Klamath River emanates from Upper Klamath Lake (UKL; surface area ~250 km$^2$) in south-central Oregon and flows 402 km southwest to the Pacific Ocean (Fig. 1). Although UKL is a naturally occurring lake, for the past century the water level has been regulated by a dam as part of the Klamath Reclamation Project. In the ~94 km below UKL, the Klamath River is further regulated by five dams for the management of flow, storage, and hydropower. These dams create a series of reservoir and river reaches within the river's upper longitudinal gradient. Below the lowest dam (Iron Gate) the river flows 306 km uninhibited to the Pacific Ocean. In contrast to many large river systems in the western U.S., the Klamath River begins as a low gradient system within a wide basin and transitions downstream to a higher gradient system within a narrower basin (elevation profile: Appendix B). In contrast with more pristine headwaters, the upper portions of the Klamath River include higher temperatures, higher concentrations of pelagic algae, high nutrients, and reduced water quality. Previous acknowledgment of these trends (e.g. Asarian and Kann, 2006; FERC, 2007; PacifiCorp, 2005), in addition to distinctions between watershed characteristics of the upper versus lower river basins (Mount, 1995), has led to a conceptual framework of the Klamath River as structurally and functionally "upside-down" in comparison to many other river systems (PacifiCorp, 2006).

Historically, the Klamath River supported large runs of anadromous fish, including Chinook salmon (*Oncorhynchus tshawytscha*), Coho salmon (*O. kisutch*), and steelhead trout (*O. mykiss*). Today, the decline of the Klamath River fisheries is attributed to multiple factors, including dams, water diversions, land-use change, disease, loss of genetic diversity, fishing, forest harvest, mining, eutrophication, and climate fluctuations (Brown et al., 1994). The Klamath River is largely in equilibrium with meteorological conditions, and as a result warm temperatures are typical throughout the river from late spring through early fall (Bartholow and Henricksen, 2006; PacifiCorp, 2008). Warm warmer temperatures are seen as a major obstacle for fish recovery, particularly in regards to the possibility of dam removal, which has the potential to shift thermal regimes throughout the river (Bartholow et al., 2005).

In addition to warm seasonal temperatures, the upper portion of the Klamath River experiences large seasonal (summer and fall) algal blooms dominated by the N-fixing cyanobacteria *Aphanizomenon flos-aquae* (Eilers et al., 2004; Jacoby and Kann, 2007). Blooms contribute to multiple water quality impairments, including organic matter and nutrient enrichment, low dissolved oxygen, and high pH (ODEC, 2010). While nutrients (i.e. N and P), are important indicators of trophic status, resource availability, and water quality, they are rarely considered priority objectives in managing and restoring rivers for anadromous fish. In the Klamath River, high ammonia concentrations are considered a major stressor to endangered suckers (Bortleson and Fretwell, 1993; Martin and Saiki, 1999). Therefore, full assessment of fish habitat and resources in rivers like the Klamath requires understanding of not only temperature and flow regimes, but also spatial and seasonal nutrient dynamics, including the role of nutrients in algal blooms and the effects of algal bloom and nutrient propagation to downstream reaches.

In this study, N and P within the Klamath River were tracked for one year across a longitudinal gradient of lentic and lotic reaches to investigate how river impoundments, flow regulation, and algal blooms altered N and P dynamics across spatial and temporal scales. Results of this study may be utilized to better understand

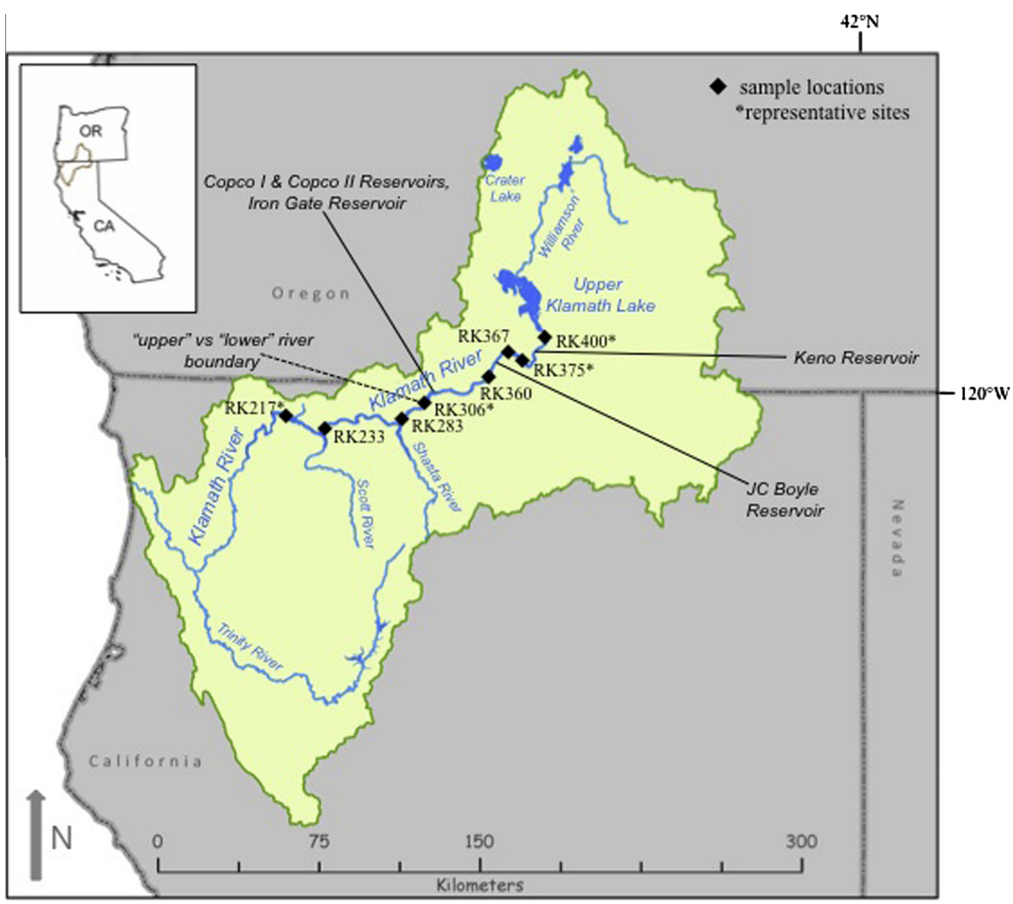


**Fig. 1.** Map of the Klamath River basin with sampling locations.