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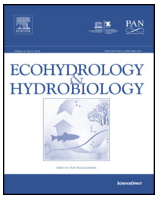

Original Research Article

Rivers in the Anthropocene: Global scale modifications of riverine nutrient fluxes by damming

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ABSTRACT

The damming of rivers represents one of the major anthropogenic disturbances of the natural cycles of water and nutrient elements on the continents. Currently, more than 50% of the world's stream and river flow crosses one or more dams before reaching the oceans. This fraction could climb up to 90% by 2030. The associated modifications of both the absolute and relative riverine fluxes of nutrients have far-reaching ecohydrological implications, from individual ecosystems to the global biogeosphere. While dam reservoirs usually act as sinks of macronutrients along the river continuum, their effects on riverine fluxes and chemical speciation differ markedly from one nutrient element to another. Dams can thus fundamentally alter nutrient limitation patterns and water quality in river-floodplain systems and receiving water bodies, including lakes and coastal marine areas. Here, we briefly review recent research addressing the impact of dams on riverine nutrient fluxes and stoichiometry, and identify some of the research challenges ahead.

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1. Introduction

Rivers and their associated riparian areas, reservoirs and floodplains sustain a plethora of ecological functions and essential ecosystem services. Rivers and streams supply water for drinking, sanitation, irrigation and industrial usage. They support inland fisheries and aquaculture, and account for a substantial fraction of the world's electricity production. Biogeochemical processes in streams and floodplains contribute to water purification, nutrient cycling and waste assimilation. Historically, trade and human settlement often followed the course of rivers, while floodplains yielded fertile lands for agriculture.

River systems are not only central to humanity's water and food security, they also harbor a wide diversity of natural habitats and biological species. The biodiversity and ecosystem functions of river systems are, in turn, closely linked to the flow regime, which regulates the timing and intensity of exchanges of water and materials between river channel, adjacent floodplains and connected aquifers (Sparks, 1995). Dissolved and suspended materials carried by rivers are ultimately delivered to lakes and sea. The outflow of rivers therefore contributes to maintaining the biological productivity and ecological integrity of inland and coastal marine environments.

Rivers are the great integrators of the freshwater cycle. The flow regime and chemical composition of river water inform us about hydrological connectivity and storage, terrestrial–aquatic interactions, and landscape disturbances in watersheds. Rivers and streams record changes in regional climate, land and water use, and pollutant loadings. Modifications of the natural flow regime and increased inputs of nutrients are among the

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most significant human drivers of change of riverine ecosystems and connected water bodies (Harrison et al., 2005).

Humans have been building dams for at least 7000 years. The systematic damming of rivers, however, began in earnest after the 1930s. By the end of the 20th century, more than half of the world's surface water was passing through dams prior to reaching the oceans (Vörösmarty et al., 1997). Since then, a new wave of dam construction has started, with the number of large hydroelectric dams projected to nearly double by 2030 (Zarfl et al., 2015). Within the next decades, dams will moderately to severely impact flow conditions in almost all major rivers on earth (Grill et al., 2015). The global scale effects of river damming, however, have received relatively little attention compared to those of other drivers of environmental change, such as energy use, agricultural intensification and urbanization.

River damming generates both risks and opportunities for integrated watershed management. In many of the major grain producing areas of the world, the water storage capacity created by the construction of dams has enabled spectacular advances in food production, while the ability to control flow conditions in river systems may help to reduce the societal costs of droughts and catastrophic flooding events. The disruption of the natural flow regime by dams, however, has been linked to the decline in biodiversity of river systems (Poff et al., 2007). Furthermore, the construction of dams not only changes the flow of water, but also the associated material flows, in particular those of nutrients. Nutrient fluxes directly affect the trophic state and water quality of rivers and their receiving water bodies.

Understanding how the construction of dams modifies the environmental flows of nutrients within river basins should be taken into consideration in the design and implementation of long-term, ecohydrological strategies aimed at the sustainable utilization of water resources (Zalewski, 2000; Donald et al., 2015). Unfortunately, much of the data needed to address the impacts of dams on riverine nutrient fluxes are either nonexistent or not available in the public domain. In this paper, we review recent research on river damming and its effects on the transport of macronutrients (phosphorus, nitrogen, silicon) along the river continuum. In particular, we address the question of how to scale up the limited number of available elemental budgets for individual reservoirs in order to estimate the regional, and ultimately global, effects of dams on riverine nutrient fluxes. We further highlight that, in addition to modifying the absolute fluxes of nutrients, dams may significantly alter riverine nutrient ratios. The latter finding is important because changes in both the absolute and relative delivery of nutrients by rivers affect the ecological health of receiving lakes and coastal seas.

2. Riverine nutrients

Rising inputs of nutrients are causing long-term shifts in the trophic state and ecosystem functioning of river systems (Garnier and Billen, 2007). For example, over the course of the second half of the 20th century, CO_2 saturation levels in the lower reaches of the Yangtze River (Changjiang) have systematically decreased, a trend that reflects a gradual transition from heterotrophic to autotrophic conditions (Duan et al., 2007). This transition is most likely driven by the increasing supply of anthropogenic nutrients, which stimulates in-stream primary production and, consequently, changes the balance between primary production and respiration. Large shifts in trophic state further imply an evolving role of river-floodplain ecosystems in the global carbon cycle and climate system (Raymond et al., 2013).

Much attention has been devoted to anthropogenic enrichments of rivers by nitrogen (N) and phosphorus (P). A comprehensive assessment of anthropogenic effects on riverine nutrient fluxes, however, needs to take into consideration other essential nutrient elements, such as silicon (Si), sulphur (S) and iron (Fe). Changes in nutrient stoichiometry may lead to changes in nutrient limitation patterns, foodweb structure and trophic status of aquatic environments. The competition between siliceous and non-siliceous algae, for instance, depends on the availability of Si, relative to P and N (Garnier et al., 2010). Because human activities have perturbed loadings of P and N to a greater extent than Si, riverine Si:P and Si:N nutrient ratios may serve as indicators of anthropogenic pressures at the catchment scale.

Time series water quality data for the Yangtze River compiled by Duan et al. (2007) provide a textbook example of historical changes in nutrient stoichiometry within a major river system. From 1960 to 1985, the average molar ratios of dissolved silicate to dissolved inorganic N in the middle and lower reaches of the river dropped from values around 13 to values below 2, primarily as a result of rising concentrations of inorganic N. In contrast, over the same time period, changes in the Si:N ratio within the upper reaches of the river were far less pronounced, due to fewer anthropogenic N sources. Similar trends are observed for the Si:P ratios. The existing data indicate that declining riverine Si:P and Si:N nutrient ratios are a general, worldwide phenomenon, and may be one of the reasons behind the increased incidence of non-siliceous algal blooms in lakes and coastal marine areas (Billen et al., 1991; Humborg et al., 2006; Garnier et al., 2010).

3. Nutrients and river damming

In addition to changes in nutrient loadings (Ver et al., 1999), humans are modifying riverine fluxes of nutrients by building dams. Dam closure turns the upstream stretch of a river channel into a reservoir. The longer hydraulic residence time and the accompanying lowering of flow velocity and turbidity promote primary productivity and nutrient cycling within the reservoir (Fig. 1). Through sediment accumulation, and for N also denitrification, reservoirs usually remove nutrients from the streamflow (Kõiv et al., 2011). Building a dam may thus alleviate eutrophication pressure on downstream ecosystems by reducing the riverine supply of nutrients. However, biogeochemical processes in the reservoir also alter nutrient speciation and stoichiometry, while flow regulation by the dam changes the timing of downstream nutrient delivery by the river. Damming may thus affect watershed nutrient cycles in multiple and complex ways.

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