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Invited research article

Carbon and nutrient fluxes from floodplains and reservoirs in the Zambezi basin

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ABSTRACT

Inland waters are under increasing anthropogenic stresses. In the last century, roughly two thirds of the world's wetland area disappeared, and so many dams have been constructed that currently 50% of river water passes through reservoirs before reaching the ocean. Large river systems in tropical and subtropical areas often develop extensive floodplain areas that will suffer from modifications in the flow regime as another boom in dam construction is under way. In the Zambezi catchment, we developed a comparative analysis of the biogeochemical effects of floodplains (Barotse Plains) and reservoirs (Lake Kariba) on tropical river biogeochemistry, to provide a basis to assess the net effect of eliminating wetland areas and transforming rivers into artificial lakes. To support such analyses, we propose a combination of specific sampling campaigns with sensor deployments to capture the seasonality of fluxes over large regional scales in remote areas.

Dams and reservoirs alter the riverine biogeochemistry in distinct, and often different ways. While the Barotse Plains floodplain releases particles during a flood cycle, this suspended material is effectively trapped in Kariba reservoir. Seasonal production of biomass on the floodplain binds nutrients in the form of organic matter that sustains biological productivity in downstream ecosystems. Degradation of the biomass can lead to significant greenhouse gas emissions from the floodplain. The reservoir traps particles and nutrients, but carbon burial ($120 \cdot 10^3$ t C per year) is offset by annual emissions of methane to the atmosphere with about $3000 \cdot 10^3$ t C-CO_2-equivalents. Therefore, building new dams will add permanent sinks of particles and nutrients to the land-ocean aquatic continuum, while draining riparian wetlands will disrupt their functions as temporal storage systems and source of terrestrial biomass for aquatic food chains.

1. Introduction

Over the last centuries global river systems have been subject to dramatic changes. Channels and dikes for flood protection and navigation now disconnect large fractions of the river corridors, dry up wetlands and reduce the lateral connectivity in floodplains. In his recent review, Davidson (2014) estimated that up to 87% of global wetland area has been lost over the last 300 years, with losses in the 20th century alone diminishing the area present in 1900 by 64–71%. Wetlands are hotspots of biodiversity, and their disappearance has been accelerating the dramatic decline in freshwater biodiversity worldwide (Vörösmarty et al., 2010). In addition, wetland ecosystems provide important ecosystem services such as flood mitigation, particle trapping for reducing erosion, and uptake and transformation of nutrient flows. The biogeochemical impact of disappearing riparian wetlands has not been quantitatively analyzed so far on a global scale (Gell et al., 2016 and references cited therein), but it is safe to assume that the average residence time of global runoff spent in wetland areas has been shortened in parallel to the decline of wetland area. The loss of lateral connectivity to wetlands as important parts of the river corridor now limits the biogeochemical functions of riparian wetlands as “filter” systems for nutrients (Verhoeven et al., 2006) which are then transferred in the form of organic nutrients to downstream food chains (Durisch-Kaiser et al., 2011).

Dam construction is another major driver for global change in river systems. The number of large dams started a steady increase in the 1920s, the expansion stagnated in the last two decades, but planning in many regions of Africa, South America and Asia indicates a “second wave” of dam construction (Zarfl et al., 2015). More than 3700 hydropower dams with a capacity larger than 1 MW are currently planned or under construction. At present, about 50% of river water released to the oceans is passing through dams and if current trends continue, this will increase to 90% by 2030 (Van Cappellen and Maavara, 2016). Prolonged residence time in reservoirs generally leads to stratification

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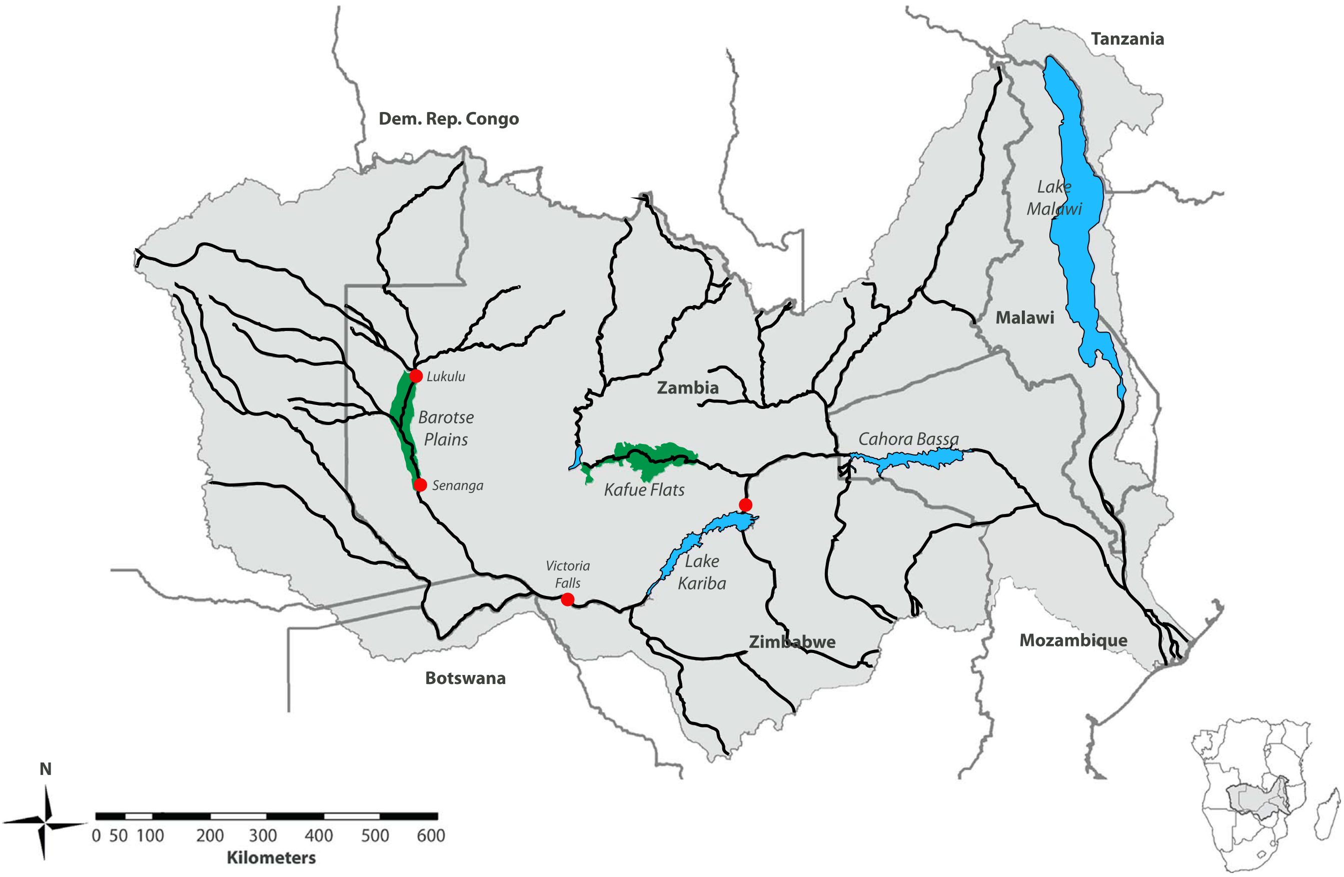

Fig. 1. Map of the Zambezi catchment, with largest floodplain systems shown in green and most important sampling locations as red circles.

and distinctly different biogeochemical processes than in the main stem river. These processes not only alter the quantity of material transported downstream, but also their characteristics. In addition, the flow regulation can alter the timing of carbon and nutrient delivery to downstream ecosystems (Van Cappellen and Maavara, 2016). It has been estimated that 12% of the global river phosphorus load was trapped in reservoirs in 2000, with this number likely increasing to 17% by 2030 due to the increasing damming of the world's rivers (Maavara et al., 2015). From a biogeochemical perspective, the transformation of running waters into lakes adds a new reactor system to the aquatic continuum with sediments as semi-permanent deposits of both terrestrial as well as aquatic particles (Vörösmarty et al., 2003). Under high nutrient loads, aquatic photosynthesis might enhance carbon storage in sediments. On the other hand, reservoir sediments with high carbon accumulation rates will develop methanogenic conditions that release methane to the atmosphere (Barros et al., 2011). The process often occurs via direct ebullition in the form of gas bubbles (Delsontro et al., 2010), and has now been estimated to represent a significant contribution of 0.5–1.2 Pg C equivalents per year to the anthropogenic greenhouse gas emissions (Deemer et al., 2016).

Large tropical and subtropical rivers are often characterized by their strong connection with extensive riparian wetlands (e.g., Abril et al., 2014; Kummu et al., 2014; Melack et al., 2009). In many regions, the strong seasonality in rainfall favors the formation of extensive floodplain systems with seasonal inundation dynamics. The ongoing and planned expansion of hydropower production will have profound impacts on the structure and function of these tropical wetlands (Zarfl et al., 2015). A biogeochemical assessment of such massive alteration of tropical river systems should be based on comparative studies of the biogeochemical function of both wetlands and dams. Quantifying the transformation, burial and emissions rates of carbon and nutrients by wetlands and dams in similar hydro-climatic environments provides a basis to assess the net effect of eliminating wetland areas and transforming rivers into artificial lakes.

A recent report documents, however, that Africa has only 0.02 measurement stations for water quality per 10,000 km^2 (UNEP, 2016). This density is two orders of magnitude lower than in Europe or North America. Laboratory analyses based on water sampling will not close this gap in the near future. Proxy measurements by recording instruments using in-situ sensing techniques could therefore provide valuable information on processes and drivers affecting water quality in many tropical river basins. We have shown previously (Zuijdgeest et al., 2016) how sensor-derived biogeochemical data can provide high-resolution time-series of processes such as aquatic carbon turnover in remote areas. In the present study, we illustrate how high-resolution sensor data and conventional spot measurements can be combined in order to derive biogeochemical budgets for data-sparse regions.

In this context, our study follows one main objective. We use the Zambezi River basin as a test site to develop a comparative analysis of the biogeochemical effects of the Barotse Plains and Lake Kariba, a hydroelectric reservoir, on carbon and nutrient fluxes. In order to achieve this goal, we provide a synthesis of different studies conducted over the last years. The set of available date includes discrete chemical analyses of water and sediments and sensor deployments that cope with the significant seasonality of fluxes over large regional scales in remote areas. In our biogeochemical analysis we specifically address the questions how large wetlands and hydropower reservoirs change the seasonality and overall availability of nutrients to downstream ecosystems. We develop and present specific budgets and fluxes for carbon and nutrients concentrations, and their ratios for the pristine Barotse Plains and the Lake Kariba reservoir, and compare the results with field studies from other tropical and subtropical sites.