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Regulation causes nitrogen cycling discontinuities in Mediterranean rivers

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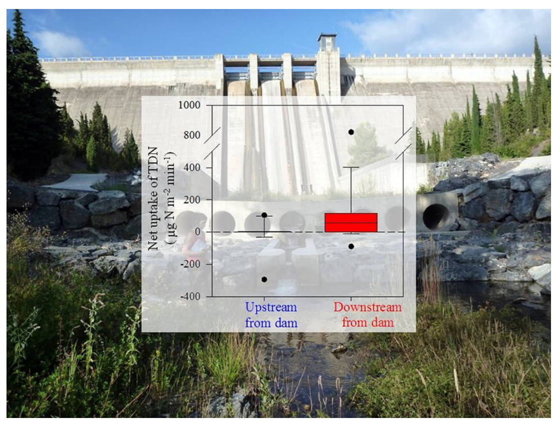
HIGHLIGHTS

- Whole-reach net uptake of dissolved nitrogen (N) increases downstream from dams.
- Hydromorphological stability and high organic matter and metabolism foster N uptake.
- River reaches below dams may constitute relevant N cycling discontinuities.

GRAPHICAL ABSTRACT



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ABSTRACT

River regulation has fundamentally altered large sections of the world's river networks. The effects of dams on the structural properties of downstream reaches are well documented, but less is known about their effect on river ecosystem processes. We investigated the effect of dams on river nutrient cycling by comparing net uptake of total dissolved nitrogen (TDN), phosphorus (TDP) and organic carbon (DOC) in river reaches located upstream and downstream from three reservoir systems in the Ebro River basin (NE Iberian Peninsula). Increased hydromorphological stability, organic matter standing stocks and ecosystem metabolism below dams enhanced the whole-reach net uptake of TDN, but not that of TDP or DOC. Upstream from dams, river reaches tended to be at biogeochemical equilibrium (uptake ≈ release) for all nutrients, whereas river reaches below dams acted as net sinks of TDN. Overall, our results suggest that flow regulation by dams may cause relevant N cycling discontinuities in rivers. Higher net N uptake capacity below dams could lead to reduced N export to downstream ecosystems. Incorporating these discontinuities could significantly improve predictive models of N cycling and transport in complex river networks.

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1. Introduction

Human needs, including drinking water supply, irrigation, flood control and hydropower, have fostered the construction of dams along river networks worldwide (Lehner et al., 2011). Today, more than 25% of the global river flow is dammed or diverted (Vörösmarty et al., 2010). Around 50,000 large dams (defined as more than 15 m in height) and over 800,000 smaller ones are in operation, and more are still being constructed (Nilsson et al., 2005; Zarfl et al., 2015). Dams have become common features in many landscapes, and have fundamentally altered large sections of the world 's river networks (Graf, 1999). The Mediterranean region is especially abundant in dams because of the high water demand and dry climatic conditions (Nilsson et al., 2005). In particular, the Iberian Peninsula hosts ~20% of the European reservoirs and has the largest number of dams per inhabitant and per land area in the world (Léonard and Crouzet, 1999).

The serial discontinuity concept (SDC) (Ward and Stanford, 1983) recognizes that dams and associated reservoirs create breaks or discontinuities in the river continuum. Dams affect structural properties of downstream reaches, reducing flood frequency (Haxton and Findlay, 2008; Poff et al., 1997), simplifying channel geomorphology (Graf, 2006; Petts and Gurnell, 2005), reducing sediment load (Tena et al., 2011; Xu et al., 2006), and altering water chemistry (Friedl and Wüest, 2002; Humborg et al., 1997) and temperature (Olden and Naiman, 2010; Preece and Jones, 2002). These changes alter community composition (Haxton and Findlay, 2008), and increase biofilm biomass below dams (Ponsatí et al., 2014). Additional impacts include changes in growth, foraging, reproduction, and migration of aquatic species (Johnson et al., 2008; Murchie et al., 2008). The impact seems to be directly related to the degree of flow alteration, which in its turn is related, among other factors, to the reservoir age and dam size as well as to the regional climate (Poff and Zimmerman, 2010).

Less is known about the effect of dams on river ecosystem processes, despite their inherent importance to ecosystem services that rivers provide (Wilson and Carpenter, 1999). Dams can affect organic matter decomposition (Arroita et al., 2015; Casas et al., 2000; Mendoza-Lera et al., 2012), ecosystem metabolism (Aristi et al., 2014; Uehlinger et al., 2003) or biofilm functioning (Munn and Brusven, 2004; Ponsatí et al., 2014). Particular attention needs to be given to nutrient cycling in rivers and how much it is affected by the presence of dams. The SDC proposes that river nutrient cycling will be strongly altered by dams, especially in low to mid-order streams (Ward and Stanford, 1983), even though empirical evidence of such a pattern is not strong. To our knowledge, no studies have specifically investigated the effect of dams on nutrient cycling in rivers. However, some studies conducted in lake outlets show that the combined effects of stable benthic habitat and lake-derived source-waters may result in high in-stream uptake of phosphorus (P) and low in-stream uptake of nitrogen (N) (Arp and Baker, 2007; Hall and Tank, 2003; Hall et al., 2002).

Discontinuities in nutrient cycling are important to be understood, since they reflect changes in nutrient retention, removal, and transport which ultimately may affect nutrient loading and eutrophication of freshwater and coastal ecosystems (Alexander et al., 2000; Mulholland et al., 2008). Noteworthy, results from most river nutrient cycling studies are derived from estimates of gross nutrient uptake (i.e. immobilization of nutrients from the water column) which may overestimate the net influence of streams on nutrient downstream export because they do not take into account the release of immobilized nutrients to the water column (Brookshire et al., 2009; Newbold et al., 1982; Roberts and Mulholland, 2007). Release processes (e.g. mineralization, nitrification, desorption), however, can be relevant in streams, and may counterbalance to some extent nutrient immobilization processes (e.g. assimilation, denitrification, and adsorption), or even result in a net downstream release of nutrients (von Schiller et al., 2015). Therefore, measurements of net nutrient uptake provide a more accurate information on actual nutrient export from a given river reach and on the relevance of in-stream processes at catchment scale (Bernal et al., 2012).

To examine the effect of dams on river nutrient cycling, we compared net uptake of dissolved nitrogen (N), phosphorus (P) and organic carbon (DOC) between river reaches located upstream and downstream from three reservoir systems. We predicted that the net uptake of downstream reaches would be increased with respect to upstream reaches because of higher hydromorphological stability, larger organic matter standing stocks and increased biological activity below dams. In the case our prediction is true, incorporating these alterations could significantly improve predictive models of biogeochemical cycling and transport in complex river networks.

2. Materials and methods

2.1. Study sites

We sampled reaches upstream (control) and downstream (impact) from reservoirs in three rivers within the Ebro River catchment (NE Iberian Peninsula; Fig. 1). The Cinca River drains a 9000-km^2 limestone-dominated catchment in the Central Pyrenees. Precipitation averages ~800 mm and tends to be greater in winter, although discharge peaks in late spring and early summer with the thaw (Beguería et al., 2003). Two successive large reservoirs, Mediano and El Grado, with a storage capacity of 436 and 399 hm^3, respectively, separate the control and impact reaches. The Montsant River and the Siurana River drain smaller (170 and 347 km^2, respectively) limestone-dominated catchments. Their climate is strongly Mediterranean, with an average annual precipitation of ~600 mm, 80% of it falling from October to April (Candela et al., 2012). The Margalef reservoir (3 hm^3) and the Siurana reservoir (12 hm^3) separate the control and impact reaches in the Montsant River and the Siurana River, respectively.

The studied reservoirs differ in their hydrological operation. Those in the Cinca River are subject to important water abstraction, which is diverted for irrigation and hydropower, whereas no significant abstraction occurs either in the Margalef or in the Siurana reservoirs. All studied reservoirs release deep water, which depending on the period, varies from epilimnetic to hypolimnetic. All have set environmental flows, defined as 10% of the seasonal average. The regulation capacity (i.e. the ratio between river annual discharge and reservoir storage capacity) is 0.46 $year^{-1}$ in the Siurana River, 1.75 $year^{-1}$ in the Cinca River and 3.64 $year^{-1}$ in the Montsant River (Aristi et al., 2014).

The length of selected reaches ranged from 500 to 2500 m. The control and impact reaches were as close as possible to the reservoir inlet and outlet, respectively. No lateral surface-water inputs were present along the reaches. For measurements, we placed 6 equidistant transects along each reach. We performed three sampling campaigns at different hydrological periods: summer and autumn of 2011, and winter of 2012. Because the control reach of the Montsant River was dry in summer 2011, we performed the sampling campaign in May 2012, just before the summer drought.

2.2. Hydrogeomorphological characteristics

We obtained daily means of water level for the Cinca and Siurana rivers from the water agencies (Confederación Hidrográfica del Ebro, and Agència Catalana de l'Aigua, respectively). For the Montsant, we calibrated precipitation data (Servei Metereològic de Catalunya) against a pressure transducer (Levellogger LCT F100/M30 and Barologger LT F15/M5, Solinst, Georgetown, USA) installed in the river during the study. We assessed disturbance by extreme flow events on the basis of incipient movement of streambed particles (Leopold et al., 1964). Once at each site, we determined the size distribution of 150 stones collected randomly in the wet channel following the method by Wolman (1954). We established the discharge thresholds for initiation of sediment motion and for disruption of riverbed based on a comparison

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