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Influence of dams on sediment continuity: A study case of a natural metallic contamination

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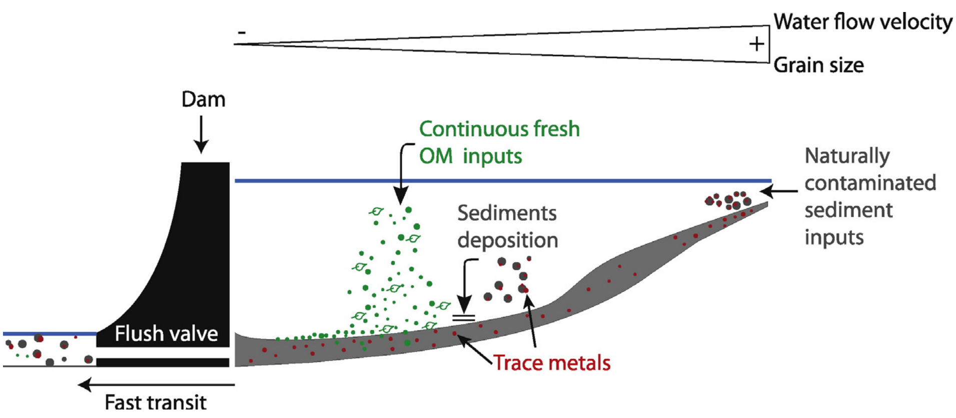
HIGHLIGHTS

- Dams presence significantly affects the sediments continuity;
- Cr-Ni from natural origin show higher concentrations than for human-affected areas;
- Statistical tests show no relationships between trace elements and organic fraction;
- Continuous inputs of fresh OM minimize the effective metallic contamination.

GRAPHICAL ABSTRACT



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ABSTRACT

Sediments play an important role on the quality of aquatic ecosystems, notably in the reservoir areas where they can either be a sink or a source of contaminants, depending on the management and hydrological conditions. The physicochemical properties of 25 surface sediments samples of a reservoir catchment (Vaussaire, Cantal, France) were studied. Results show a strong influence of dam presence, notably on the grain size and organic matter (OM) contents. The concentrations of trace metals and metalloids (As, Cd, Cr, Cu, Ni, Pb and Zn) were also measured and compared with worldwide reservoir concentrations and international sediment quality guideline levels in order to assess the intensity of the metallic contamination. Cr and Ni are the trace elements presenting the significantly highest values at the catchment scale. Enrichment Factors (EF), calculated using both local and national backgrounds, show that metals have mainly a natural origin, explaining especially the Cr and Ni values, linked with the composition of parental rocks. Unexpectedly, all the observed metal concentrations are lower in the reservoir than upstream and downstream, which might be related to the high fresh OM inputs in the reservoir, diluting the global metallic contamination. Multivariate statistical analyses, carried out in order to identify the relationship between the studied metals and sediment characteristics, tend to support this hypothesis, confirming the unusually low influence of such poorly-degraded OM on trace element accumulation in the reservoir.

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1. Introduction

Sediments play a fundamental but complex role in terrestrial and aquatic ecosystems (Ellis, 1936; Groffman and Bohlen, 1999) and act as a sink for organic and inorganic contaminants. In the hydrological cycle, it has been demonstrated that over 90% of inorganic pollutants can be trapped in sediments (Salomons and Stigliani, 1995; Viers et al., 2009). Whereas organic pollutants can be partly degraded by microorganisms, the inorganic contaminants, such as metallic elements, are persistent, creating permanent environmental pressure on aquatic media. Their presence is linked to both natural and anthropogenic sources due to rocks weathering, atmospheric inputs, and human activities (Accornero et al., 2008; Beck et al., 2013). The diversity of metallic sources as well as the persistence of these elements explain their occurrence in waters and biota in spite of the settlement of environmental legislation (Water Framework Directive, 2013/39/EU) and the decrease of industrial inputs for the last decades.

Dam reservoirs are typical sites where sediments accumulation is favored, which may alter the quality of the concerned areas (Vrhovnik et al., 2013; Zhao et al., 2013). Indeed, dams are physical barriers limiting the natural transfer of water, leading to a decrease in water flow velocity and consequently an increase in sediment residence time, allowing their deposition (Friedl and Wüest, 2002). As long as the physicochemical conditions remain stable, metals mobility and bioavailability are limited due to their natural tendency to be associated with sediments. They are sequestrated (essentially adsorption or coprecipitation) with host phases, notably with those presenting high surface specific area (Evans, 1989; Horowitz and Elrick, 1987), such as clay minerals, sulfides, iron and manganese oxyhydroxides, or organic matter (Cappuyns and Swennen, 2006; Du Laing et al., 2009; Eggleton and Thomas, 2004; Grosbois et al., 2011; Hochella and White, 1990).

However, when facing environmental changes related to reservoir management (hydropeaking operations, dredging, flush valve opening), the physicochemical conditions may vary. This includes parameters such as pH, solid/liquid ratio, redox conditions, temperature and salinity, whose influence on the mobility and fate of sediment-bound metals has been largely reviewed (Calmano et al., 1993; Du Laing et al., 2009; Eggleton and Thomas, 2004). This can lead to the release of metals, previously associated with the sediments, in the water column through the oxidization of sulfides or the degradation of the sediments organic fraction (Caetano et al., 2003; Cantwell et al., 2002). In such cases, sediments act therefore as a source of metallic elements, affecting not only their speciation, but also their transport and bioavailability, constituting therefore a potential source of contamination for aquatic biota (Chapman et al., 1998; Colas et al., 2013b), even for communities far from the dam, due to downstream transfers.

The main objective of this study is to assess the influence of a highly exploited reservoir (Vaussaire, Cantal, France) on the distribution of sediments and their associated metallic elements contents. This site is part of a large hydroelectric complex at the watershed scale and has the particularity to be submitted to daily hydropeaking operations and large water-level range. Moreover, it is subjected to a very specific management, completed almost once every two years. It consists in flush valve opening during favorable periods, that is to say when the inflow is important, in order to evacuate the sediments in the river downstream from the dam. To this day, such management has been performed six times since 2003. As a consequence, the studied sediments are freshly deposited. Moreover, their continuity is strongly altered, notably regarding their grain size and OM content. The originality of this work also comes from the fact that the studied watershed is poorly affected by human activities and metallic contamination, if any, may be related to natural sources. Indeed, the presence and distribution of trace elements of anthropogenic origin in dam reservoirs have been quite extensively investigated in the last decade worldwide (e.g., Dhivert et al., 2015; Hamzeh et al., 2014) but few information are available on the importance of the watershed lithology.

2. Study area

2.1. Geographical and hydrological characteristics

Located in the French Massif central, the Rhue River is 56 km long and flows into the Dordogne River (Fig. 1A). The Rhue catchment represents approximately 900 km^2 of surface area. It has an oceanic climate characterized by low-flow period in August and peaks in water discharge in fall, winter and the beginning of spring.

The Vaussaire dam was constructed in 1952 over the Rhue River, 18 km upstream from its confluence with the Dordogne River. The mean annual instream flow is 19.3 m$^3 \cdot$s^{-1}. The reservoir maximum capacity is 1.5 hm^3. It serves as water reserve for covering peaks in energy demand at the Rhue hydroelectric plant located upstream the Bort-les-Orgues reservoir (Fig. 1A), for which it provides water through an 18 km pipeline. It is approximately 3 km long and characterized by the presence of a former regulating dam, located 1.6 km upstream from the actual Vaussaire dam. The former regulating dam (7 m) was constructed in 1927 and was completely covered by the waters after Vaussaire dam construction (Fig. 1B and C).

Five major tributaries (Tr1 to Tr5) flow into the Rhue River, the major one being the Tr5 (Fig. 1A and B). Downstream the Vaussaire dam, the short-circuited section over 18 km of the Rhue River's length receives the instream flow.

The Vaussaire catchment is subjected to a permanent pressure due to water management as it takes part of an important hydroelectric complex composed by more than 10 dams, notably the one of Bort-les-Orgues over the Dordogne River (Fig. 1A). Thus, water flow in Vaussaire reservoir fluctuates on a daily basis according to the natural supply, the hydropeaking operations performed on the dams of the tributaries as well as the functioning of the Rhue plant.

2.2. Geological setting

The main geological units of the catchment area are: (i) metamorphic bedrocks such as gneisses, migmatites, amphibolites, anatexites and blastomylonites, covering more than 52% of the surface area; (ii) volcanic and volcanoclastic rocks such as basalts representing more than 41% of the catchment surface (Fig. 1A); (iii) granitic rocks corresponding to 2% of the site surface; and (iv) quaternary alluvia and glacial deposits along the river covering 5% of the surface (Brousse, 1972, 1990; http://infoterre.brgm.fr).

3. Materials and methods

3.1. Sampling

Surface sediment sampling was conducted along the Rhue river (Up1, Up2, and Do1–Do4), 15 representative zones of the reservoir (Re1–Re15) as well as its feeding tributaries (Tr1–Tr3 and Tr5) in the winter 2013 (Fig. 1A, B and C). Stations Re1 and Re2 belong to the reservoir and are located upstream from the former regulating dam. The sampling locations in the reservoir were selected based on bathymetric maps (not shown) performed the day prior the sampling campaign. Within each zone, composite samples of 2 × 2 m area were selected based on the sedimentation area. Surface sediment samples of the reservoir were collected using Ponar and Eckman stainless steel grabs, just below the surface water and up to 26 m depth immediately upstream from the Vaussaire dam (Table S1). Sediments of the tributaries and downstream were collected manually using a plastic scoop. The collected composite samples were then transferred to plastic bags, sealed and stored at 4 °C before laboratory processing. They were then homogenized in pre-cleaned polyethylene boxes and dried at 40 °C for 10 days. Finally, sediments were sieved at 2 mm and 63 μm (Nylon meshes), due to the affinity of such fine fractions towards trace elements compared to coarser fraction.