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The influence of particles recycling on the geochemistry of sediments in a large tropical dam lake in the Amazonian region, Brazil

Rita Fonseca [a,*], Catarina Pinho [b], Manuela Oliveira [c]

[a] Department of Geosciences, Laboratory of Environmental Biogeochemistry (AmbiTerra), School of Sciences and Technology, Institute of Earth Sciences (IES), University of Évora, Apartado 94, 7002-554 Évora, Portugal
[b] Laboratory of Environmental Biogeochemistry (AmbiTerra), School of Sciences and Technology, Institute of Earth Sciences (IES), University of Évora, Apartado 94, 7002-554 Évora, Portugal
[c] Department of Mathematics and CIMA-Center for Research on Mathematics and Its Applications, University of Évora, Portugal, Apartado 94, 7002-554 Évora, Portugal

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A B S T R A C T

As a result of over-erosion of soils, the fine particles, which contain the majority of nutrients, are easily washed away from soils, which become deficient in a host of components, accumulating in lakes. On one hand, the accumulation of nutrients-rich sediments are a problem, as they affect the quality of the overlying water and decrease the water storage capacity of the system; on the other hand, sediments may constitute an important resource, as they are often extremely rich in organic and inorganic nutrients in readily available forms. In the framework of an extensive work on the use of rock related materials to enhance the fertility of impoverish soils, this study aimed to evaluate the role on the nutrients cycle, of particles recycling processes from the watershed to the bottom of a large dam reservoir, at a wet tropical region under high weathering conditions. The study focus on the mineralogical transformations that clay particles undergo from the soils of the drainage basin to their final deposition within the reservoir and their influence in terms of the geochemical characteristics of sediments. We studied the bottom sediments that accumulate in two distinct seasonal periods in Tucuruí reservoir, located in the Amazonian Basin, Brazil, and soils from its drainage basin. The surface layers of sediments in twenty sampling points with variable depths, are representative of the different morphological sections of the reservoir. Nineteen soil samples, representing the main soil classes, were collected near the margins of the reservoir. Sediments and soils were subjected to the same array of physical, mineralogical and geochemical analyses: (1) texture, (2) characterization and semi-quantification of the clay fraction mineralogy and (3) geochemical analysis of the total concentration of major elements, organic compounds (organic C and nitrogen), soluble fractions of nutrients (P and K), exchangeable fractions (cation exchange capacity, exchangeable bases and acidity) and pH(H_2O).

There is a remarkable homogeneity in the sedimentary distribution along the reservoir in terms of the texture and mineralogy of the clay fraction and of the chemistry of the total, soluble and exchangeable phases. These observations contrast with the physical, morphological and chemical heterogeneity of the soils and the setting lithology. Most of the sediments has a higher contribution of fine-grained material and the mineralogy of the clay fraction is dominated by kaolinite in soils and kaolinite and illite in sediments, followed by lesser amounts of gibbsite, goethite, and metahaloisite and by small/vestigial contents of chlorite and smectite. The sediments are mainly inherited from the watershed but there exist marked differences between the accumulated sediments and their parent materials. These differences mainly come from the selective erosion of fine-grained particles and the extreme climatic conditions which enhance complex transformations of mineralogical and chemical nature. Compared with the parental soils, the reservoir sediments show the following differences: (1) enrichment in fine-grained and less dense inorganic particles, (2) aggradative mineralogical transformations, including enrichment in clay minerals with higher cationic adsorption and exchange capacity, (3) degradation of the crystalline structure of Fe- and Al-oxides (goethite, gibbsite), (4) increase in easily leached elements (Mg, Ca, P, K, Na) and decrease in chemically less mobile elements (Si, Fe) and (5) higher contents of organic

* Corresponding author.
E-mail addresses: rfonseca@uevora.pt (R. Fonseca), c_pinho@uevora.pt (C. Pinho), mmo@uevora.pt (M. Oliveira).

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carbon, nitrogen, and soluble forms of P and K, mainly concentrated in the clay fraction. These transformations are extremely important in the nutrients cycle, denoting that sediments represent an efficient sink for nutrients from the over-erosion of soils. Mineral and organic compounds can permanently or temporarily sequester these nutrients, recycling them and enhancing their availability through the slow release of components from relatively loose crystal structures. These processes can easily explain the enrichment in soluble and exchangeable forms of elements such as P, K, Ca or Mg. This study conclude that the particles recycling in a large tropical dam reservoir which receives high fluxes of allochthonous nutrients, has an important role in the good quality of sediments for agricultural use and in the profitable use of this technology to recover depleted soils in remediation projects in regions near large hydroelectric plants.

1. Introduction

Nowadays, land degradation for agricultural purposes is occurring in all parts of the world. The geochemistry and mineralogy of global soils are critical in estimating their capacity for sustainable organic productivity (Fyfe, 1989, 1997), which poses a major threat to farmers from less-developed countries. Given this world conflict, which has been described by the Worldwatch Institute as "the quiet crisis in the world economy"(Fyfe, 2000), and the great diversity of issues and challenges to improve this fundamental life-supporting resource, geologists from different parts of the world have developed studies on the use of rocks (e.g., Leonardos et al., 1987, 2000; Fyfe et al., 1983; Van Straaten, 2007, 2009), rock-related materials that accumulate in dam reservoirs (e.g., Fonseca et al., 1993, 1998, 2003, 2007a, 2009) and wastes such as coal ash (e.g., Shen et al., 2001; Bi et al., 2003; Hytönen, 2003; Lee et al., 2006), to enhance the fertility of soils.

The sediments that accumulate behind dams often come from the over-erosion of soils. The eroded material, which would naturally proceed downstream with the river, is trapped behind dams, becoming accumulated in lakes. Dam reservoirs are typical sites where sediments accumulation is favoured because they 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 (Fonseca et al., 1993, 1998, 2003, 2009; Friedl and Wüest, 2002; Zhao et al., 2013; Frémion et al., 2016). Many studies have been done about the correlation between the soil erosion in the basin, the sediment yields and the reservoirs sedimentation (Abedini et al., 2012; Romero-Díaz et al., 2012; Zhao et al., 2013, 2016). Soil erosion and the consequent loss of nutrients and organic matter have both direct and indirect effects, ranging from diminishing the productivity and profitability of the soils, to the physical and chemical contamination of water resources (Romero-Díaz et al., 2012).

One of the key consequences of erosion, both for its environmental and economic repercussions, is the loss of soil fertility. The finer particles, mainly clays, which contain the majority of nutrients, much needed for sustainable organic productivity, are easily washed away from soils, which become deficient in a host of components, coarse-textured and less fertile. These eroded fine materials after accumulating in the lakes contribute to the reduction of water quality because they can represent a source of a large number of organic and inorganic nutrients in readily available forms. Sediment—water interfaces play key roles in the biogeochemical cycling of nutrients because physical, chemical and biological reactions can occur; these reactions regulate the chemistry of the overlying water, often increasing the nutrients concentration and thus modulating the severity of eutrophication regardless of the level of external forcing (Fonseca et al., 1993, 1998, 2003, 2009, 2011; Van der Perk et al., 2006; Nürnberg, 2009; Smith et al., 2011; McCulloch et al., 2013; Svanbäck et al., 2014). These reactions include dissolution and deposition, sorption and desorption, migration and transformation, oxidation and reduction, enzymatic hydrolysis and bacterial biochemical processes (Zhu et al., 2016). Mobilisation and transport of nutrients from terrestrial systems to streams, rivers and lakes, excessive and unbalanced nutrient concentrations in surface waters, deterioration of water quality and eutrophication problems were first recognised in the mid-20th century (Svanbäck et al., 2014).

The accumulation of the sediments in the reservoirs is a problem, as they affect the quality of the overlying water and decrease the water storage capacity of the system; however, sediments may constitute an important resource, as they are often extremely rich in nutrients in chemical forms easily available for plants. In the framework of an extensive study on the use of rock related materials to enhance the fertility of impoverish soils, in the last two decades we have studied the characteristics of sediments accumulated in various dam reservoirs, developed under distinct climatic conditions and we have successfully developed an innovative and sustainable concept for the use of these sediments as soil additives or artificial soils. The addition of reservoir sediments to soil increases (1) the capacity to hold water, which reduces the need for irrigation; (2) the microbiological activity, which is often essential in bridging soil plant root systems; and (3) the levels of a large range of nutrients that are critical to plant development. These factors turn a classical problem in the world, namely, the excessive silting of reservoirs, into a valuable resource with ample environmental benefits (Fyfe, 2000; Fonseca et al., 1993, 1998, 2003, 2007a, 2009; Theodoro et al., 2007; Leonardos et al., 2009).

In the likeness of soils, the nature and quality of dam sediments for agricultural use are conditioned by the whole mineralogical composition, which represents a mineral reserve. However, plants can only take up chemical elements under easily available forms, and only elements in soluble or exchangeable phases are directly used by plants; such labile phases represent the most direct measure of the fertility level of a soil or sediment. The sediment components that have greater influence on the retention and release of elements into water or plants due to the large surface area and surface properties are (1) clay minerals and (2) organic compounds (e.g., Hillier, 1995; Righi and Meunier, 1995; Sparks, 1995; Velde, 1995).

(1) In tropical regions secondary minerals are dominated by layer aluminum silicates and Fe/Al oxides (e.g., Berkowitz et al., 2008) which usually occur as fine-grained and poorly crystalline materials. Depending on the type and structure of the mineral, they can sorb and desorb nutrients and metals, according to the local conditions, and form complex solid solutions that incorporate nutrients and metals (Hammarstrom and Smith, 2004). Because of their low size