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Nutrients, trace metals and B-vitamin composition of the Moulouya River: A major North African river discharging into the Mediterranean Sea

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ABSTRACT

We analyzed dissolved nutrient, trace metal and vitamin (B-vitamins and methionine) concentrations in the lower course of the Moulouya River (MR, Morocco) and its estuary. The flow of this African river has changed drastically (a reduction of almost 50%) in the last 50 years due to the regulation of the river flow through dams and alterations of the course constructed to satisfy population necessities and growing agricultural requirements. Consequently, it has produced a remarkable increase in nitrate concentrations (up to 270 μM) and alteration of N:P ratios within the river, as well as a reduction of overall P and Si efflux to nearby coastal waters. Despite the historical mining activities in the upper MR, concentrations of Pb, Zn and other metals in sediments and waters do not display significant contamination as compared with other Mediterranean rivers, mainly due to the retention by dams of upstream metal contamination. Mean concentrations of dissolved B-vitamins in the river showed lower levels (13–55% lower) than those in coastal waters and hence the river does not represent an important B-vitamin source.

1. Introduction

Nutrients and other life-sustaining elements delivered to the coastal zone by large river systems are a major determinant of the functioning of coastal ocean ecosystems. The arrival of terrestrial substances to the marine system depends on both natural and anthropogenic loads from rivers and groundwater, as well as on the biogeochemical transformations that occur preferentially in transitional areas such as estuarines and deltas. These compounds have a key influence on sustaining the productivity of large shelf areas that are affected by the riverine outflows (e.g. Macias et al., 2014).

Because the Mediterranean Sea is a relatively small and semi-enclosed basin where oligotrophic conditions prevail for most of the year (Bosc et al., 2004; Ludwig et al., 2009), influence of freshwater inputs in these regions, associated with major river discharges, affect the water mass balance and the chemical species in coastal waters (Bosc et al., 2004). Most of the knowledge regarding riverine outflows in the Mediterranean Sea is based in studies carried out in large rivers from Southern Europe. For example the Rhone, Ebro and Po Rivers are known to have a major effect on the productivity of the NW Mediterranean (Ludwig et al., 2009; United Nations Environment Programme and Mediterranean Action Plan, 2003). Less well known is the role of North African rivers which are considered as resources for the economic development of the countries in this region. As a result of high, steep and

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young mountains with erodible rocks, a great amount of sediments are thought to be supplied by Morocco and Algerian rivers (McNeill, 2002). In fact, pre-dam northwest African rivers discharged nearly 20% of the sediments discharged by all African rivers (Probst and Suchet, 1992).

Arguably, the most significant ecological impact on North African rivers is the outstanding reduction in the river flow caused by damming, extraction for irrigation and climate change (Margat and Treyer, 2004). Apart from the obvious hydrological changes, which mainly affect estuarine and coastal areas, the reduction in the transport of particulate material together with changes in land-use, may influence the C, N and P cycles in the river and the delivery of these elements to coastal waters. Strong reduction in river flow may lead to coastal impacts such as shoreline retreat, estuarine water salinization, loss of arable lands and soil erosion, which thereby can alter the estuary topography and coastal stability. Moreover, the continuous inputs of nutrients and metals from urban and agriculture activities may lead to river eutrophication and pollution, which are considered a global threat for ecosystems, water quality, and aquatic chemistry (Cloern, 2001; Rabalais et al., 2009; Smith, 2003). These issues are particularly critical in undeveloped countries due to inadequate treatments of domestic and industrial sewage, and the lack of efficient urban development plans. In Africa these effects could be exacerbated by societal responses to global change pressures (Kitheka et al., 2009).

Three main African rivers discharge into the Western Mediterranean: the Medjerdah (Tunisia), the Chéliff (Algeria), and the Moulouya (Morocco). The Moulouya River (MR) is the only African river with active influence in the basin of the Alboran Sea (Ludwig et al., 2009). It drains into a shallow and productive shelf area off of North Eastern Morocco, discharging particulate matter, nutrients and other compounds (Fig. 1). As a result of the damming of the MR, the Alboran Sea has experienced for a period of 20 years (from 1974 to 1994) the strongest reduction in the whole Mediterranean Sea of freshwater discharged (approximately 57%) (Ludwig et al., 2009; United Nations Environment Programme and Mediterranean Action Plan, 2003; Milliman and Farnsworth, 2011). Set in a region with strong economic development needs, the ecological conservation of the lower course and deltaic area of the MR has been absent from governmental priorities until very recently.

Despite the growing concern on environmental issues in northern Africa and the increasing efforts on environmental monitoring and research, information on both river alteration and its effects on the coastal ocean is fragmented and mostly gathered in unpublished reports. The main objective of this paper is to characterize the chemical composition of waters and sediments of the lower-course and estuary of the MR. While trace metals and nutrient concentrations have been previously reported in the upper course of this river (Bouabdli et al., 2005; Chahboune et al., 2014; Iavazzo et al., 2012b; Makhoukh, 2011; Makhoukh et al., 2013) the concentrations in the lower course, below the last dam, and the contribution to the solutes in the coastal waters of the Mediterranean is uncertain. In addition to inorganic nutrients and trace metals, we have analyzed soluble B-vitamins (thiamin B_1, riboflavin B_2, pyridoxine B_6, biotin B_7 and cobalamin B_{12}) and the amino acid methionine. Vitamins are a major regulator of marine plankton metabolism but many aspects of their sources and fate remain unclear (Sañudo-Wilhelmy et al., 2014 and references therein). Because of their high bacterial activities, freshwater sources (such as rivers and groundwater) are considered important sources of vitamin B_1 and B_6 (Barada et al., 2013; Gobler et al., 2007; Okbamichael and Sañudo-Wilhelmy, 2005).

Knowledge on the biogeochemical characteristics of the lower MR and its estuary may help the understanding of past and future changes in the biogeochemical budgets of this region and the possible consequences in the Alboran Sea. This basin is a transition zone that plays a key role on the exchanges between the Atlantic Ocean and the Mediterranean Sea through the Strait of Gibraltar (Vargas-Yáñez et al., 2002).

2. Material and methods

2.1. Site description

With 54,000 km^2, the Moulouya is the largest Moroccan river basin (Snoussi, 2007) and the second largest estuarine area in the North African coast only behind the Nile Delta. The river flows northeasterly from the Grand Atlas region (2000 m height) to the Mediterranean Sea not far from the Nador Lagoon, after some 650 km (Fig. 1). The lower Moulouya basin corresponds to a vast plain through which the river meanders along ~90 km and connects with the coast through a large estuary, flanked by extensive beaches and dune fields (Fig. 1). The lithology in the middle course is primarily sandstones (Pastor et al., 2015) whereas, the lower course runs through the Guercif basin and the Triffa Plain which is mainly composed of limestone and dolomites (Boudchiche, 1994; Ouahhabi et al., 1986; Naciri, 1986).

Climate in the basin is typically Mediterranean arid to semi-arid, characterized by large variability in precipitation with yearly accumulated values ranging between 230 and 380 mm/yr (IUCN, 2010; Tekken et al., 2009). Climate in the upper course of the river is continental and rainfall exceeds 600 mm/yr. Available information on annual water discharge by the MR reveals large variations in mean flux values, most probably indebted to large climate and water use variations during the considered period of flux estimation (Snoussi, 2007).

According to the Agence du Bassin Hydraulique du Moulouya (ABHM), upstream of the Mohamed V dam, the mean annual flow is 34 m^3/s (IUCN, 2010). Maximum flow (80 m^3/s) at this site is attained during the spring, especially in April, and it coincides with the melting of snow in the High and Middle Atlas. Downstream, the flow is reduced to 5 m^3/s and sometimes less (IUCN, 2010). In this lower section, the Moulouya receives on its southern banks the waters of Wadi Sharaa, whose tributary Wadi Zegzel drains the limestone mountains of Beni Snassen. The latter has a mean annual flow of 135 Mm^3/s, which corresponds in its majority to flashfloods because the base flow barely exceeds 0.1 m^3/s (Snoussi, 2007). Also in this area, land drainage from irrigation and from aquifer seeps is estimated to contribute 2–3 m^3/s to the total flow (IUCN, 2010). Further south, the Wadi Cherraa, that runs through the city of Berkane, is derived for irrigation and is often dry before joining the main course of the Moulouya. The water is accumulated in 5 reservoirs with a total storage capacity of 11,000 m^3 (CID, 2012). The city of Berkane, also dumps some 0.024 m^3/s of treated waste water to the Moulouya (through a sewage treatment plant 'SWTP' located in the city) as well as some 0.110 m^3/s that are discharged untreated (CID, 2012). According to Snoussi et al. (2002) the construction of dams and changes in rainfall have reduced the annual flow and sediment fluxes in the MR up to 47% and 93%, respectively. This supply of sediment is not entirely prevented since high sediment discharges to the sea may occur when water from the dam is released following most heavy rains (Fig. S1).

The economy of the Moulouya basin depends mainly on agriculture and cattle, but also on industrial activities concentrated in the urban centers, and some incipient tourism activities on the coast (Kitheka et al., 2009). Lead mining in the upper river was an important activity until 1985 when the main mines, already depleted, were abandoned (Iavazzo et al., 2012b). Lead and Zn have been identified among the main metallic contaminants resulting from this activity (Iavazzo et al., 2012a). River damming together