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Seasonal and spatial variation in suspended matter, organic carbon, nitrogen, and nutrient concentrations of the Senegal River in West Africa

Mamadou L. Mbaye[a,b,*], Amadou T. Gaye[a], Alejandro Spitzy[c], Kirstin Dähnke[d], Abel Afouda[b], Birgit Gaye[c]

[a] Laboratoire de Physique de L'Atmosphére et de l'océan, Ecole Supérieure Polytechnique, 5085 Dakar-Fann, Senegal
[b] Université Abomey Calavi, Laboratoire d'Hydrologie Appliquée, WASCAL, Benin
[c] Institute for Geology, University of Hamburg, Bundesstraße 55, 20146 Hamburg, Germany
[d] Helmholtz-Zentrum Geesthacht, Zentrum für Material- und Küstenforschung GmbH, Max-Planck-Straße 1, 21502 Geesthacht, Germany

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ABSTRACT

The Senegal River is of intermediate size accommodating at present about 3.5 million inhabitants in its catchment. Its upstream tributaries flow through different climatic zones from the wet tropics in the source area in Guinea to the dry Sahel region at the border between Senegal and Mauritania. Total suspended matter, particulate and dissolved organic carbon and nitrogen as well as nutrient concentrations were determined during the dry and wet seasons at 19 locations from the up- to downstream river basin. The aims of the study were to evaluate the degree of human interference, to determine the dissolved and particulate river discharges into the coastal sea and to supply data to validate model results. Statistical analyses showed that samples from the wet and dry season are significantly different in composition and that the upstream tributaries differ mainly in their silicate and suspended matter contents. Nutrient concentrations are relatively low in the river basin, indicating low human impact. Increasing nitrate concentrations, however, show the growing agriculture in the irrigated downstream areas. Particulate organic matter is dominated by C4 plants during the wet season and by aquatic plankton during the dry season. The total suspended matter (TSM) discharge at the main gauging station Bakel was about 1.93 Tg yr^{-1} which is in the range of the only available literature data from the 1980s. The calculated annual discharges of particulate organic carbon (POC), dissolved organic carbon (DOC) and dissolved organic nitrogen (DON) are 55.8 Gg yr^{-1}, 54.1 Gg yr^{-1}, and 5.3 Gg yr^{-1}, respectively. These first estimates from the Senegal River need to be verified by further studies.

1. Introduction

Anthropogenic activities have modified quantity and quality of river discharge for about 3000 years (Anthony et al., 2014). A first amplification of human impact led to a strong increase of riverine sediment load about 1000 years ago and a second amplification started decreasing sediment load in most river basins about 100 years ago (Syvitski and Kettner, 2011). Observational data covering 1945 to 2004 document a net decrease of continental freshwater discharge which is correlated with a reduction in precipitation (Dai et al., 2009). Additional anthropogenic induced water loss has occurred in rivers with strong flow regulation and irrigation (Milliman et al., 2008). The variations in dissolved and particulate river discharge are more significant than the changes in water discharge. Many rivers experienced a significant increase of suspended matter discharge related to deforestation and land use change beginning with the early human interference. Around 1950 urbanization and dam building led to a net decrease of sediment transport (Syvitski and Kettner, 2011). This reduction of suspended matter export to estuaries and coastal seas in concert with sea level rise and ground water extraction has evoked fast drowning of deltas of which most are densely populated accommodating 500 million people worldwide (Giosan et al., 2014). Increasing nutrient concentrations as well as the release of inorganic and organic pollutants has further changed biogeochemical processes in rivers and coastal seas and is very problematic in regions where rivers are used for drinking water as well as irrigation, and industrial purposes

* Corresponding author at: Laboratoire de Physique de L'Atmosphére et de l'océan, Ecole Supérieure Polytechnique, 5085 Dakar-Fann, Senegal.
E-mail address: mamadoulamine.mbaye@ucad.edu.sn (M.L. Mbaye).

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(Mouri et al., 2011; Lipp et al., 2001; Jiménez, 2003; Maya et al., 2003; WHO, 2004). Eutrophication facilitates harmful algal blooms in many coastal areas and models predict enhanced nutrient discharges due to growing anthropogenic impact (Struijk and Kroeze, 2010; Yasin et al., 2010). Whereas water discharge data are available for many African rivers, the database of sediment discharges and especially of biogenic elements such as carbon, nitrogen, phosphorous and silica is poor (Yasin et al., 2010). Thus, base line data are missing to evaluate the degree of human interference. Moreover, data are lacking to validate model results and predict the impact of changing river discharges on coastal oceans (Beusen et al., 2005; McCrackin et al., 2014).

The Senegal River is among the 30 world's largest drainage basins (Potter et al., 2004). At present about 3.5 million people inhabit its catchment; due to rapid population growth this may double in the coming decades (OMVS, 2007). The majority of the basin's people, particularly the rural, highly rely on the exploitation of largely water-dependent natural resources (traditional agriculture, fisheries, livestock farming). In addition, most of the people living alongside the river use its water directly without treatment (e.g. domestic usage, recreation); this increases the risk of water-borne diseases. Moreover, the water is used for irrigated agriculture, hydropower generation, water navigation, drinking water industries, and foodstuffs industries.

Water discharge has been measured at the gauging station Bakel since 1903 and was found to fluctuate in accordance with the periodicity of Sahelian rainfall (Faure and Gac, 1981; Hubert et al., 2007; Kattan et al., 1987). Dam building in the late 1980s has induced studies of changes of the agricultural systems in the upstream river basin (Rasmussen et al., 1999), of the morphology of the river mouth (Barusseau et al., 1995, 1998), and of the plankton assemblage (Monteillet et al., 1993). Most chemical and biological studies were carried out in the lagoon and river mouth at Saint Louis and discussed the consequences of dam building and the artificial opening of a new river mouth in 2003 (Baklouti et al., 2011; Bouvy et al., 2006, 2010; Ka et al., 2011; Quiblier et al., 2008; Troussellier et al., 2004, 2005). There is currently a lack of data on the composition of particulate and dissolved river discharge and no database on water quality particularly in upstream tributaries (OMVS, 2007).

In this study, we attempt to supply base line information on dissolved and particulate river discharge and on water quality of the Senegal River. Samples were taken during three sampling campaigns along the river from its three major upstream tributaries to downstream stations at the river mouth. The main objectives of this work are: (i) to determine inorganic nutrients (nitrate, nitrite, ammonia, phosphate, silicate), DOC and DON concentrations as indicators of the trophic state and human interference (Seitzinger et al., 2005); (ii) to understand the major mechanisms controlling the sources and concentrations (De Brabandere et al., 2002; Paolini and Ittekkot, 1990; Voss and Struck, 1997; Coynel et al., 2005) of TSM, POC, particulate nitrogen (PN) and their stable isotopic ratios ($\delta^{13}C$, $\delta^{15}N$) during the wet and dry seasons; (iii) and finally, to give quantitative estimates of TSM, POC, PN, DOC, DON, dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorous (DIP) and dissolved silicate (DSi) fluxes at the gauging stations in order to quantify the discharge to the Atlantic. A better understanding of the seasonal and spatial variability in water quality will help to formulate effective water resource management to reduce water pollution.

2. Material and methods

2.1. Study area

The Senegal River Basin is the second major river basin in West Africa (Fig. 1). From its source in Guinea, it flows through the western Sahel region in Mali, Mauritania and Senegal and opens into the sea at Saint Louis. Its catchment has an area of about 300,000 km^2 and it has a length of 1800 km (OMVS, 2009). The basin is subject to a large north–south precipitation gradient ranging from 150 $mm\,yr^{-1}$ in the north to more than 1650 $mm\,yr^{-1}$ in the south (Fig. 2). The predominantly natural vegetation of the region follows this rainfall gradient, ranging from sub-humid forest in the south to semi-arid savannah in the north (Stisen et al., 2008). Peak discharge occurs in September with a maximum of 1700 $m^3\,s^{-1}$ at the gauging stations Bakel and Matam (Senegal River; Fig. 3). The lowest discharge values are obtained at the upstream gauging stations Kidira, Gourbassi, and Fadougou in the Faleme tributary (Fig. 3). The three main tributaries (Bafing, Bakoye and Faleme) ensure over 80% of the Senegal River's flow of which the Bafing transfers half. The gauging station Bakel after the confluence of the river Senegal and the Faleme is used in the literature as the reference station for discharge estimates (Kattan et al., 1987).

Part of the upstream Senegal River and its tributaries Bafing and Bakoye pass through Precambrian sandstone deposits, lower Cambrian schisto-dolomitic deposits, and Palaeozoic metamorphic rocks, mainly composed of schists and quartzites from a volcano-sedimentary complex and granites (Michel, 1973). Downstream the Senegal River is bordered by Holocene fluvio-deltaic deposits composed of fine sands, silts and clays, surrounded by stabilized so-called red dunes (Michel et al., 1993). Surface runoff in the region of these soft sediments has a suspended matter concentration of ~1 $g\,L^{-1}$ and is responsible for 50–80% of the riverine suspended load via slope erosion. In the river bed, this suspended load is diluted by subsurface and groundwater discharge (Kattan et al., 1987).

Human impact has increased considerably since the 1970s when the natural flooding of the banks ceased due to droughts and irrigated areas were rapidly created and replaced the natural flood receding agriculture (OMVS, 2007; Rasmussen et al., 1999). Dam building further impacted the river in the late 1980s.

The Manantali dam with a reservoir capacity of $11.5 \times 10^9\,m^3$ was functional in 1988. It was constructed to store water for irrigation during the dry season, to attenuate extreme floods and to generate hydropower (OMVS, 2009). This damming has further added to upstream discharge reduction and withdrawal of the flood receding agriculture (Rasmussen et al., 1999). The Diama dam is located 23 km from Saint Louis near the River mouth in the delta (Diene, 2012). It was functional in 1986 and was built to block seawater intrusion which had extended more than 200 km upstream in the dry season prior to dam building (Monteillet et al., 1993). Water upstream of the Diama dam can be used for irrigation which has facilitated population growth and intensified land use and has augmented eutrophication and pollution in the estuary (Troussellier et al., 2004, 2005). Further eutrophication occurred after an artificial breach of a sand bar shortened the estuary by 30 km favoring intrusion of salt water which is strongly nutrient enriched during the upwelling season (Baklouti et al., 2011). The data used in Figs. 2 and 3 are taken from OMVS (Organization in charge of the management of the Senegal River Basin).

2.2. Sampling

Dry season sampling was done during December 2012 and March 2013 and wet season sampling during July 2012 (one sample) and August 2013 from upstream to downstream (Table 1; Supplementary material). Water samples were taken at 19 locations (Fig. 1) with a syringe at midstream where maximum mixing occurs. Filters were air dried and the filtrates were stored in plastic bottles and cooled with ice during transport to the laboratory where they were deep frozen before analyses. Sediment samples were taken from the river bank at each location and were air