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INVESTIGATING THE DRIVERS OF TOTAL SUSPENDED SEDIMENT REGIME IN THE SENEGAL RIVER BASIN USING LANDSAT 8 SATELLITE IMAGES

Cheikh Faye[1]*, Manuela Grippa[2], Laurent Kergoat[2], Elodie Robert[3]

[1]Department of Geography, U.F.R. Sciences and Technologies, UASZ, Laboratoire de Géomatique et d'Environnement, BP 523 Ziguinchor, Senegal
[2]Geosciences Environnement Toulouse, University of Toulouse III, Route de Narbonne, 31330 Toulouse, France
[3]CNRS, University of Nantes, UMR LETG, Campus du Tertre BP 81227, 44312 Nantes Cedex 3, France
*Corresponding author, e-mail: cheikh.faye@univ-zig.sn

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Abstract

Because total suspended sediments (TSS) influence the penetration of light into the water column and are likely to carry pollutants and nutrients, their study is essential for understanding the functioning of African river ecosystems. If the estimation of solid transport is important in the context of hydro-agricultural developments, its quantification often poses a problem. In addition, in situ data for these areas are rare and, as a result, the environmental factors responsible for the variability of TSS can hardly be understood. This work aims to evaluate the spatiotemporal variability of TSS in the surface waters of the Senegal River using satellite data over the 2014-2018 period. The spatio-temporal dynamics of TSS is reconstructed using a relationship established on several West African sites between in situ data from TSS and satellite reflectances from Landsat 8. These data allow analyzing the relationship between TSS and factors such as rainfall and discharge. We found that the TSS peaks in Bakel coincide with the arrival of the first rains and are followed by peaks in discharge with a lag of 2 months. A time lag between TSS and discharge peaks is also observed on its tributaries like the River Falémé. Concerning the spatial variability, TSS generally increase from the river upstream to the downstream and decrease in the Senegal delta after the Diama dam. The analysis of the TSS upstream and downstream of the Manantali dam, in the upstream area, confirms the relatively low sediment deposits in the dam lake.

Keywords: water color, suspended particulate matter, Landsat image, remote sensing, Senegal River

INTRODUCTION

In the context of climate change, a recent trend in increasing daily precipitation extremes has been detected in tropical Africa (Panthou et al., 2014; Taylor et al., 2017). Increased runoff and erosion, as well as increased precipitation, suggest a possible increase in turbidity and suspended sediments (SS) in rivers. Beyond their importance to hydrology, sediments also have an impact on inland water ecology and potentially on human health. Indeed, TSS by forming a refuge and a culture medium conducive to the growth of bacteria generally promote their development while reducing their mortality by protecting them from ultraviolet rays (Palmatee et al., 1993). Thus, in environments with high turbidity, fecal bacteria have high attachment rates to particles (Rochelle-Newall et al., 2015). In addition, Troussellier et al. (2004) noted good bacterial survival after a long residence time in the water (4-5 days) of the Senegal River. Some of these bacteria or viruses cause widespread diseases, such as diarrhoea, which is one of the leading causes of death among children under five in developing countries (Troeger et al., 2017).

Due to the scarcity of in situ monitoring in the Sahel, the development of methods for monitoring turbidity and suspended solids in the Senegal River catchment area is therefore essential. Indeed, the distribution and dynamics of TSS in the Senegal River catchment area (TSS level, seasonal cycles and interannual variability) are not always well known. However, the study of water colour by remote sensing can be used to monitor water turbidity and TSS. Indeed, suspended particles absorb and scatter light affecting the spectral response of surface waters, particularly in the visible and near infrared (NIR), which varies according to concentration, mineralogical composition, organic content and particle size distribution (Reynolds et al. 2010). Although the use of remote sensing in Sub-Saharan Africa is confronted with specificities such as high aerosol content, very high turbidity and TSS values, recent studies have shown that satellite data are effective in monitoring the variability of turbidity and TSS in continental waters in these regions. Kaba et al. (2014) studied the temporal dynamics of an Ethiopian lake using Landsat images. Robert et al. (2016, 2017) used MODIS and Landsat data to document TSS and turbidity in the Bagré reservoir in Burkina Faso (Robert et al., 2016), and in the Gourma region of Mali (Robert et al., 2017).

Many sensors have been developed for various water color applications, including water turbidity assessments, sensors such as AVHRR, SeaWiFS, MODIS, IKONOS, Landsat TM and ETM +. Variations in temporal and spectral resolutions, data availability, calibration issues and temporal coverage are some of the most important factors determining the selection of the best instrument for a particular study (Li and Li, 2004). Although the application of water color algorithms to estimate water constituents is generally limited by site-specific factors (Hellweger et al., 2004), and the absence of a uniform model of remote sensing to estimate the TSS (Wang et al., 2004), satellite images can be effectively employed to recover water quality parameters. In this context, the objectives of this article are as follows: (i) analyse the seasonal cycle and interannual variability of TSS in the Senegal River basin using Landsat images; (ii) study the links between TSS variability and precipitation and discharges; (iii) explore the variability of TSS in the Senegal River basin, including the Manantali Dam and major tributaries.

STUDY AREA

The Senegal River, some 1700 km long, drains a 300,000 km^2 basin straddling four countries: Guinea, Mali, Senegal and Mauritania (Fig. 1). It ranges from 10°20' to 17° N and 7° to 12°20' W and is made up of several tributaries, the main ones being the Bafing, Bakoye and Falémé rivers that originate in Guinea and form the upper basin (OMVS, 2008) (Fig. 1). The Senegal River, formed by the junction between the Bafing and Bakoye rivers, receives the Kolimbiné and Karokoro rivers on the right and Falémé on the left, 50 km upstream from Bakel. In the southern part of the basin, the density of the surface drainage system reflects the impermeable nature of the land (Rochette, 1974).

The basin is generally divided into three entities: the upper basin, the valley and the delta, which differ greatly in their topographical and climatological conditions. The upper basin extends from the sources of the river (Fouta Djalon) to the confluence of the Senegal River and the Falémé River (downstream of Kayes and upstream of Bakel). It is mainly composed of the Guinean and Malian parts of the river basin and provides almost all of the water inputs (more than 80% of the inputs) of the river to Bakel (OMVS, 2008). The analysis of the hydrological system of the Senegal River basin reveals four hierarchical levels: (1) the natural (uncontrolled) reaches of the Bafing upstream of the dam (Falémé and Bakoye), (2) the reach of the Bafing downstream of the dam (controlled), (3) the reach after the confluence of the Bafing and the Bakoye (at Kayes), (4) the reach after the confluence of the Falémé and the semi-artificialized Bafing-Bakoye subsystem (at Bakel).

From a hydrological point of view, at Bakel, which is often considered the reference station of the Senegal River, the average annual discharge of the river is about 676 m^3/s, corresponding to an annual input of about 21 billion cubic metres. Mean monthly discharges range from extreme values of 3,320 m^3 /s in September to 9 m^3/s in May (Ndiaye, 2003). For the distribution of hydrological inputs from the main rivers in the basin, 50% come from the Bafing (which is the main tributary), 25% from the Falémé, 20%

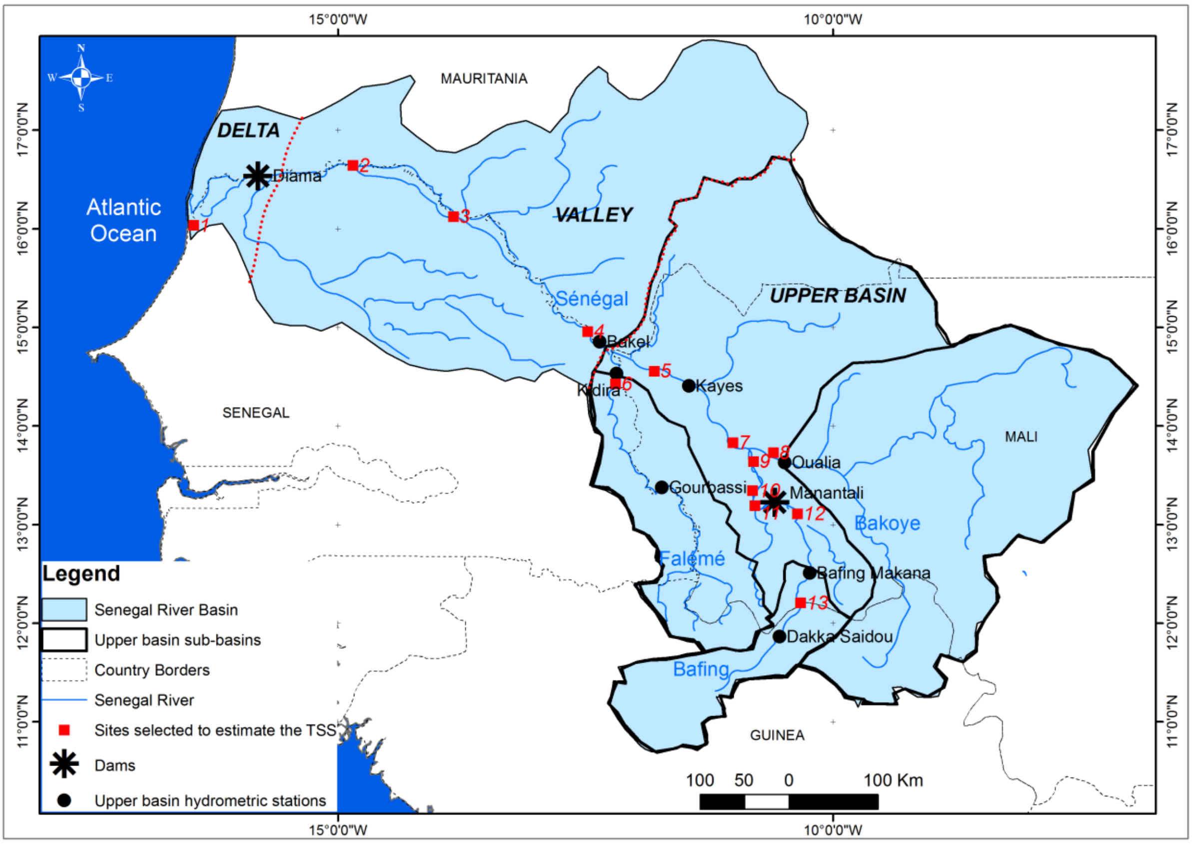

Fig. 1 Location of the Senegal River Basin and sites for estimating TSS. 1: Senegal River site in Saint Louis ; 2: Senegal River site in Podor ; 3: Senegal River site in Matam ; 4: Senegal river site after Faleme ; 5:Faleme River site in Kidira ; 6: Senegal river site before Faleme ; 7: Senegal river site after Bakoye ; 8: Bakoye River site in Oualia ; 9: Senegal river site before Bakoye ; 10: Bafing site after Manantali ; 11: Site downstream of the Manantali Dam : 12: Site upstream of the Manantali Dam ; 13: Bafing site before Manantali

from the Bakoye and the remaining 5% transit from the other tributaries of the Senegal River (OMVS, 2012).

Various studies in this basin have highlighted climate change and changes in its hydrological regime since the 1970s (Faye et al., 2015; Wilcox et al., 2018). Indeed, faced with a very strong drop in precipitation, which installed the Senegal River basin in a succession of deficit years. the average discharge module at Bakel thus decreased by more than half and went from 1374 m^3/s over the period 1903-1950 to 597 m^3/s over the period 1951-2002; and from an average of 840 m^3 / s over the period 1950-1972 to only 419 m^3/s over the period 1973 (OMVS, 2012). The width of the Senegal river is variable, it is on average 450 m, a width which decreases to reach 400 m only between Guinea and Mali. At the level of the Bakoye, the average width is 250 m. At the level of the valley, the river surrounds a large arm 600 m wide, 12 m deep and a small arm 200 m wide at Saint-Louis.

Faced with the effects of climate change and changes in the hydrological regime, a series of developments (Diama and Manantali dams) were initiated, totally transforming the hydrological dynamics of the Senegal River basin. The Diama dam, located on the Senegal river 27 km upstream of Saint-Louis, was put in water in 1986. Besides its function of blocking the ascent of salt water, it ensures the availability of fresh water while throughout the year for all uses, the development of an irrigable potential of 120,000 ha, the improvement of the filling of lakes (Guiers in Senegal, Rkiz in Mauritania). The Manantali dam, built between 1982 and 1988, is located on the Bafing river, the main tributary of the Senegal river, 90 km upstream of Bafoulabé. At the filling level of 208 meters IGN, its reservoir has a capacity of 11.3 billion m^3 and covers an area of 477 km². The Manantali dam regulates the flow of the Senegal river and irrigates a potential of 255,000 ha of land and, in the long term, should make it possible to navigate the river for approximately 800 km from its mouth (OMVS, 2012; Faye, 2018). The Manantali dam was built to guarantee a maximum flow of less than 4,500 m^3/s at Bakel (Thiam, 2016), causing sediment retention at the level of sn lake.

DATA AND METHODS

Satellite data

For this study, we used the surface reflectances of the Landsat 8 OLI satellite available since 2013. These data, corrected by atmospheric effects, are provided by the United States Geological Survey. They were analyzed from Google Earth Engine (and partially downloaded from Earth Explorer). Landsat 8 has several spectral bands in the visible, near infrared and mid-infrared, with a spatial resolution of 30 m and acquires the data with a temporal repetitiveness of 16 days. For this work, we used the blue, green and red bands (2, 3 and 4 at 482 nm, 561.5 nm and 654.5 nm respectively), the near infrared band (5 to 865 nm) and the SWIR bands (6 and 7 at 1613.5 nm and 2202 nm). Data were extracted from 13 sites located along the Senegal River (Fig. 1).

Landsat 8 was chosen for this study because it allows monitoring small rivers such as the tributaries of the Senegal River (spatial resolution of 30 m) using consistent time series since 2014. MODIS satellite data were not retained because their spatial resolution (250 m) does not allow monitoring the dynamics of TSS in small rivers. Sentinel-2 data could provide complementary information to Landsat data, and work in ongoing to evaluate their potential to retrieve TSS over West Africa, and particularly the effect of sunlight, that given the smaller angle of the image acquisition could be more important than for Landsat. Moreover, the first Sentinel-2 images date back to December 2015 and over the study area, at the time of this study, full times series of level 2 products (atmospheric corrected images) were not yet provided.

Cloud images and images with high aerosol levels over the study sites were discarded based on the quality indices provided with the Landsat satellite data (clouds, adjacent clouds, cloud shadows, aerosols, cirrus clouds). TSS were estimated only for open water pixels. Pixels that were not already masked by clouds, aerosols or cloud shadows were classified as open water using a threshold on the MNDWI index (Robert et al. (2017). For this study area a threshold of 0.1 was applied.

Rainfall and discharge data

Rainfall and daily discharge data are also used in this study. The rainfall data come from the database of the National Civil Aviation and Meteorology Agency. These are daily rainfall data from the stations of Kédougou, Podor, Matam and Saint Louis from 2014 to 2018. Hydrological data are daily discharges from the stations of Bakel on the Senegal River and Kidira on the Falémé River from 2014 to 2018. These data come from the database of the Organization for the Development of the Senegal River.

Estimation of TSS

TSS measurements acquired at different sites in West Africa were used to evaluate different satellite indices proposed in the literature, which use visible and infrared bands. Only images acquired within three days of the in situ sampling dates were selected for this analysis. A total of 49 images were used for this study. For the comparison of in situ data and satellite reflectances, the open water pixel closest to the coordinates of the in situ sampling points was chosen to approach as closely as possible the in-situ sampling point.

The in situ water samples used for the estimation of the TSS were collected over the period December 2014 – September 2017 in the Bagré reservoir (Burkina Faso) (Robert et al., 2016), in Lake Agoufou (Gourma region in Mali) (Robert et al., 2017) and from mid-2015 to early 2016 in the Niger River in Niamey (Kennedy Bridge). These sites cover the different types of surface water (lakes, reservoirs and rivers) found in West Africa. At each site, measurements were performed every week during the rainy season and every 15 days during the dry season. For the Bagré site, a field mission was also carried out in July 2015 to study the spatial variability within the lake. In total, 52 in-situ measurements were used for this study: 21 for the Bagre Lake, 25 for the Agoufou Lake and 6 for the Niger River.

For all these sites, the TSS concentration was calculated by filtering the water samples using 0.7 µm glass fibre filters. Before filtration the filters were dried for 1 hour at 105° C and weighed. After filtration, the filters were dried again under the same conditions and weighed. The TSS concentration was calculated as the difference between the weight after and before filtering, divided by the filtered volume. For each sample, two replicas were used and the average TSS value was used for the analysis.

Correlations were evaluated using the R2 (coefficient of determination, equivalent to the Pearson's correlation), with the R software.

RESULTS

Relationship between satellite reflectance and TSS

Landsat 8 reflectance for different combination of visible and near-infrared bands proposed in the literature were plotted towards in-situ TSS and fitted using power relationships (Robert et al., 2016, 2017). Then, the TSS retrieved from Landsat 8 using the relationships obtained for each band combination were compared to in-situ TSS (Table 1).

Table 1 Value of R2, RMSE and bias obtained by linear regression of retrieved TSS towards in-situ TSS

Bands or ratio of bands	R^2	RMSE	Bias
NIR	0.91	389.2	-27.9
R	0.53	925.1	-71.6
NIR + R	0.86	492.3	-15.5
NIR/R	0.76	1562.8	-608.7
NIR/B	0.81	939.7	-262.3
(R-NIR)+(R+NIR)	0.69	2715.8	-1063.2

The best results are obtained for the NIR band (Table 1) with the following power relationship (Fig. 2):

$$Refl\_bande5 = 256.46 \times TSS \text{ ^ } (0.3539),$$

where *Refl_bande5* is the mean reference value of band 5 of the Landsat image. TSS are then estimated by the following equation:

$$TSS = Refl\_bande5 / 256.46 \text{ ^ } 1/ 0.3539$$

TSS retrieved from Landsat 8 are well correlated to in-situ TSS ($R^2 = 0.91$), with a very low bias (-27.9) and RMSE equal to 389.2 mg/L (Fig. 2b). TSS in the Senegal River basin were therefore estimated by reversing this power relationship, which is assumed to be generally applicable to surface waters up to values of about 2500 mg/l.

Variation of TSS in the upper basin as a function of rainfall and discharge data

Daily data

We compared the TSS, calculated from Landsat 8 satellite data, at the outlet of the upper Senegal River basin with rainfall data from the Kédougou station and hydrological data from the Bakel station (Fig. 3).

The seasonal rainfall pattern shows very heavy rainfall in the rainy season, which can reach more than 100 mm per day with a maximum recorded during the month of August. Total rains are close to zero during the dry season months (Fig. 3). The same is true for discharge in the basin charcaterised by two periods: the high water period centred on the months of July, August, September and October with a maximum in September; the low water period is centred on the rest of the year, with the lowest discharges of the year (Fig. 3) due to the absence of rain. Local precipitation is combined with water inflows from the river upstream of Bakel and its tributaries. The enrichment in suspended solids during the rainy season is due, particularly in the upstream part of the basin, to the strong erosion of the slopes which leads to leaching and particle loading into the river (Mbaye et al., 2016). Surface runoff in the region of

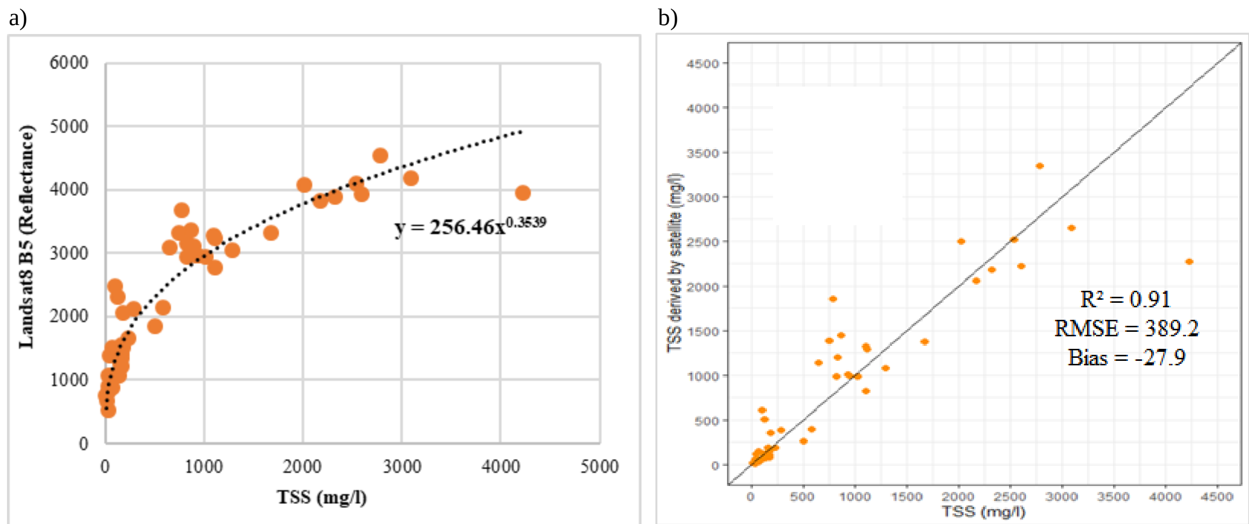

Fig. 2 Relations: a) Landsat reflectance in band 5 versus TSS measured in situ (in mg/l), b) TSS derived from Landsat 8 vs. In-situ TSS (N=52). R^2 indicate the Pearson's correlation. RMSE the Root Mean Square Difference, bias the mean difference. The 1:1 line is also indicated in black

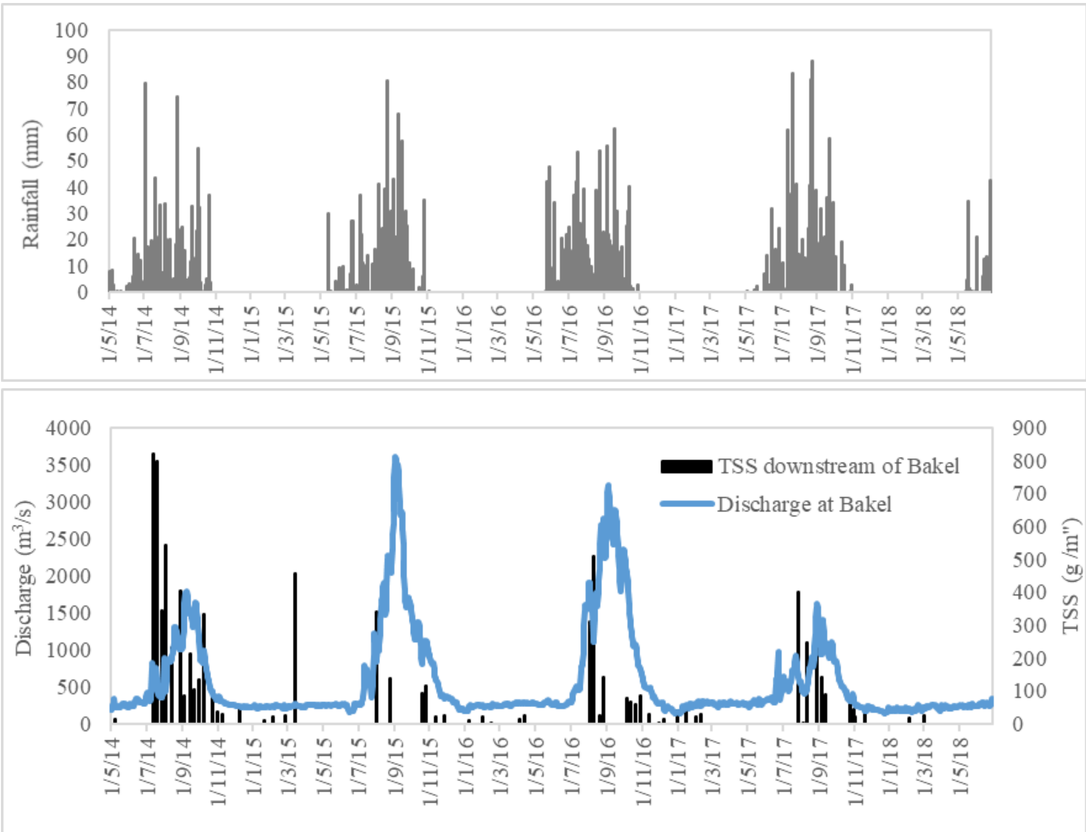

Fig. 3 Relationship between the daily rainfall (Kédougou station), daily concentration of TSS (downstream of Bakel) and the daily discharge at the outlet of the upper Senegal River basin (Bakel station) from 2014 to 2018

these soft sediments have a suspended matter concentration of ~1 g/l 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). During the dry season, the river becomes very "calm", while its turbidity and discharge remain low.

During the 2013-14 flood period, the main inputs recorded in Bakel came from unregulated tributaries (Falémé: 39.6% and Oualia: 26.8%), with Manantali providing only 10.5% of the 42.2% it received from Bafing upstream. On the other hand, during the low water period of the same year, the regularized tributary of the Bafing River provides almost all the discharge at Bakel, through the support of the low discharge of the dam. Similarly, discharge at Falémé and Bakoye rivers (2.69% and 1.15% respectively) contribute very little to the discharge at Bakel in Senegal River. This reverse operation allows the control of large discharge during the flood period (i.e. an average discharge released of 197 m^3/s) while during the low water period, the gates of the Manantali structure are more open for water releases (i.e. an average discharge released of 262 m^3/s).

Figure 3 shows that the TSS concentration generally increases with the arrival of the first rains and before the increase in the river discharge. However, the TSS experiences significant variations with the highest values between May and September, and which sometimes approach 1000 g / m^3 (820 g / m^3 on July 11, 2014). At this station, while most of the peaks occurred between July (beginning of the rainy season) and August (820 g/m^3 in 2014-15, 342 g/m^3 in 2014-15 and 400 g/m^3 in 2017-18 in July and 508 g/m^3 in 2016-17 in August), some peaks of suspended solids are recorded in September (this is the case on 13 September 2014 with 214 g/m^3), when river discharge is highest and at the time of annual precipitation maxima. A secondary peak, which is not explained by hydrological variations (rain or discharge), is observed in March 2015.

The concentration of TSS at the outlet of the Falémé basin was estimated between 2014 and 2018 and compared to the discharge at Kidira station (Fig.4). For the year 2014, the results remain fairly similar to those noted at the outlet of the upper Senegal River basin, with always the peaks of TSS preceding the peaks in discharge. For the other years, TSS data at the beginning of the rainy season, when cloud cover prevents visibility and therefore detection with optical images, are not in sufficient number to establish a relationship.

Monthly averages

On a monthly basis, the average TSS concentration values over the period 2014-2018 indicate a unimodal evolution (in the form of a bell) with a maximum in July with 590 g/m^3 and a minimum in February with 21.1 g/m^3 in Bakel (Fig. 5). This behaviour alternates between July and August over the different years of the series with a maximum noted in July with 554 g/m^3 in 2014-15, 343 g/m^3 in 2015-16 399 g/m^3 in 2017-18 and in August with 226 g/m^3 in 2016-17. For the monthly minimum of TSS, the value can be very low, falling to 0.09 g/m^3 in January over the 2014-2018 period. Over the period 2014-2018, the Kidira station on the Falémé River shows a maximum in August with 351 g/m^3 and a minimum in December (6.42 g/m^3) (Fig. 5 and Table 2).

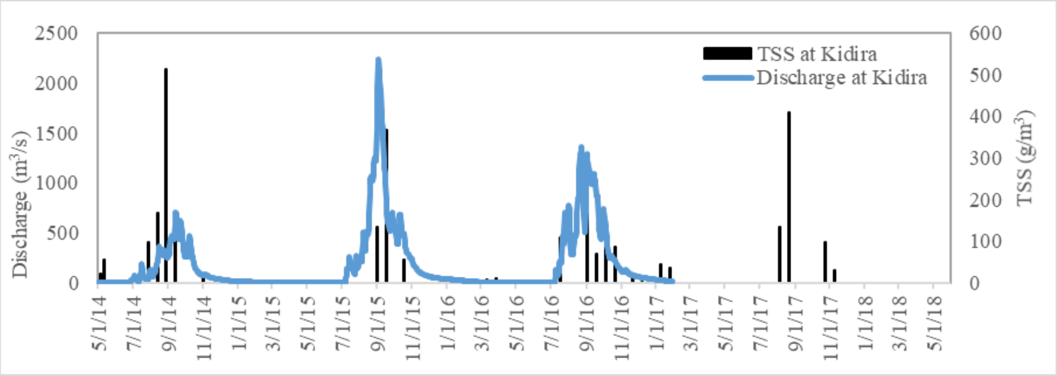

Fig. 4 Relationship between the daily concentration of suspended solids at the outlet of the Falémé basin (upstream of Bakel) and the discharge (Kidira station) from 2014 to 2018

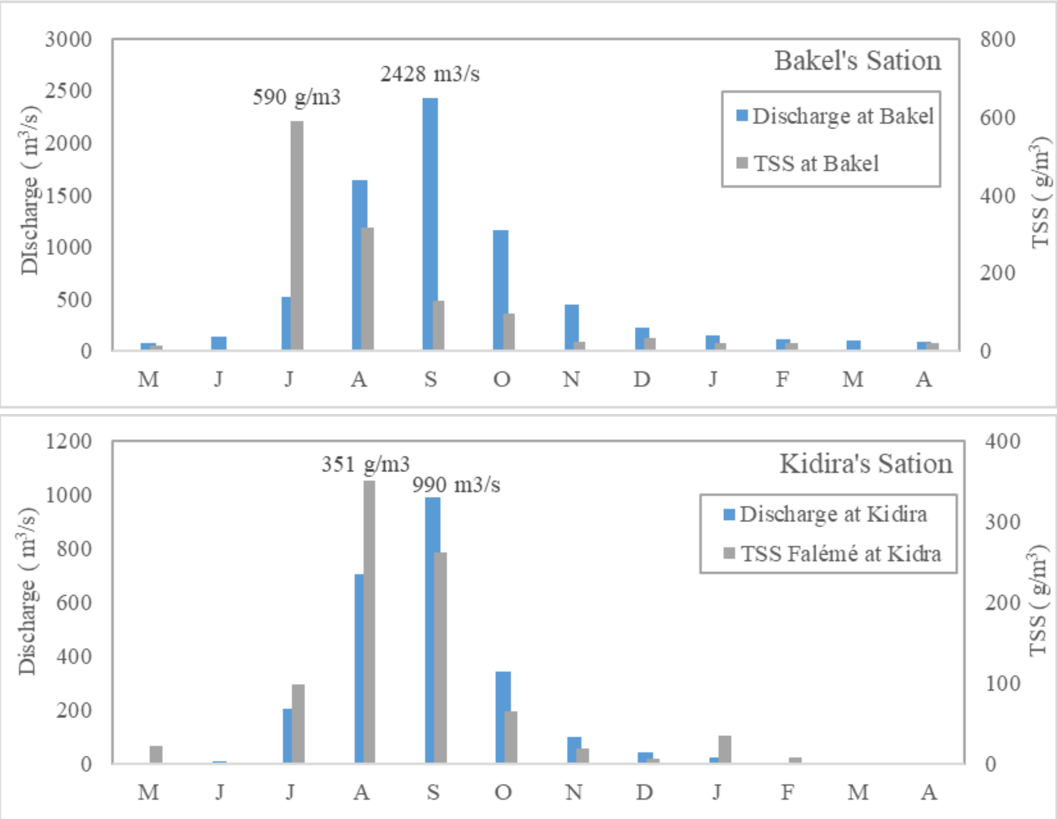

Fig. 5 Relationship between the monthly concentration of suspended solids and the monthly discharge at the outlet of the upper Senegal River basin and at the confluence with the Falémé from 2014 to 2018

The comparison between the discharge and the TSS concentration clearly shows the difference between the two peaks at Bakel and Kidira (Fig. 5). In Bakel, while the peak of TSS is recorded in July with 590 g/m^3 (when the discharge was only 524 m^3/s), the peak of discharge is recorded two months later, in September with a value of 2428 m^3/s (when the TSS was only 128 g/m^3). For the Kidira station on the Falémé, this same lag persists with a peak discharge noted in September (with a discharge of 990 m^3/s corresponding to a discharge of 263 g/m^3 for TSS), one month after that of the TSS with a value of 351 g/m^3 in August (when the discharge was 707 m^3/s).

Evolution of TSS in the valley and delta of the river

Beyond the upper basin, which covers 56% of the basin's surface area and extends from the source to the Bakel hydrological station over a distance of 980 km, the TSS are assessed in the valley, which covers 35% of the basin's surface area and extends over 600 km, and the delta, which extends from Richard-Toll to the mouth of the river over 170 km (Thiam, 2016). To characterize the TSS in the Senegal River valley and delta, the stations of Matam and Podor (for the valley) and Saint Louis (delta) were selected.

Figures 6 and 7 show that the concentration of TSS generally begins to increase with the arrival of the first rains, before the river's discharge increases, and TSS peaks mainly in late July (727 g/m^3 in Matam and 531 g/m^3 in Podor) and August (344 g/m^3 in Saint Louis), often slightly later (Fig. 7) than for some sites previously studied in the upper basin (Bakel for example). At the same time, in the valley and delta of the basin, rain peaks are recorded, as are TSS, in August (137 mm in Matam, 92.1 mm in Podor and

Table 2 Monthly average values of suspended matter concentration in the Senegal River and discharge (at the outlet of the upper Senegal River basin) from 2014 to 2018

TSS and discharges	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**	**J**	**F**	**M**	**A**	**Yrs**
Discharge at Bakel	76	143	524	1643	2428	1166	441	226	150	114	97.9	83.1	591
TSS at Bakel	14.1	-	590	316	128	97.0	24.2	35.1	21.6	21.1	-	20.3	127
Discharge at Kidira	0.60	10.2	208	707	990	346	98.8	45.0	23.1	4.04	1.80	0.58	203
TSS Falémé at Kidra	21.8	-	98.3	351	263	65.7	20.1	6.42	34.7	7.54	-	-	96.5
TSS per section	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**	**J**	**F**	**M**	**A**	**Yrs**
TSS Senegal in Saint Louis	21.8	-	116	344	181	67.0	27.4	13.3	9.4	9.2	14.7	10.4	74.0
TSS Senegal in Podor	47.3	-	531	457	346	167	95.0	83.5	26.8	14.7	40.1	71.1	171
TSS Senegal in Matam	40.8	-	727	290	132	176	24.8	22.0	27.3	26.6	28.5	22.9	138
TSS Bakoye in Oualia	-	203	108	177	262	135	59.0	25.2	49.5	26.4	16.0	-	106
TSS Senegal after confluence with the Bakoye	4.8	-	29.6	120	122	29.3	12.9	6.2	8.6	3.4	2.0	5.4	31.3
TSS Senegal before confluence with the Bakoye	4.0	-	28.1	47.1	95.7	39.4	10.3	3.4	5.8	4.1	2.0	2.4	22.0
TSS Senegal after confluence with Falémé	-	-	143	298	168	108	34.0	10.7	6.57	18.0	-	-	98.3
TSS Senegal before confluence with Falémé	-	-	47.7	177	239	63.0	7.15	14.7	3.71	4.80	-	-	69.6
Senegal downstream Manantali	-	3.0	32.2	36.3	0.2	53.6	15.4	13.6	3.4	0.6	1.0	-	15.9
Senegal upstream Manantali	-	21.3	12.4	36.5	52.8	17.2	5.9	4.3	2.9	1.7	1.0	-	15.6

81.2 mm in Saint Louis), one month before those of discharge that are recorded in September (502 cm in Matam, 350 cm in Podor and 102 mm in Saint Louis).

Although the TSS show significant variations with the highest values between July and September and a gradual evolution from upstream to downstream, they are, on the other hand, more important in the river valley (the maximum being 811 g/m^3 on 29 July 2018 in Matam and 818 g/m^3 on 25 July 2014 in Podor) than in the delta (where the maximum is only 666 g/m^3 on 12 August 2018 in Saint Louis). The lowest TSS values are recorded during the low water period.

In the valley and the delta which is in the alluvial plain of the basin, it is the heights of water which are available and indicated in place of the discharge as in the other parts of the basin.

Indeed, the TSS values in Saint Louis are much lower than those observed in Podor (Fig. 7 low), despite a fairly similar rainfall dynamic (Fig. 7 high). This is in agreement with Kane (1997) who estimated a solid transport of the Senegal River, although highly variable from one year to another, relatively low during these hydrological cycles, with an average value of 2 million tonnes/year. This may be due to the Diama dam, whose commissioning in 1985 introduced a reduction in solid inputs, and modify the hydrological regime towards the lower estuary, also affecting the sediment balance that contributes to the maintenance of coastal areas and the coast south of the mouth of the Senegal River (Kane, 2005). Thus, the TSS that pass through from the Diama dam are essentially made of fine materials, indicating a river of low competence in its estuary, with clays and silts transported in suspension tending to settle upstream of the dam (Kane, 1997).

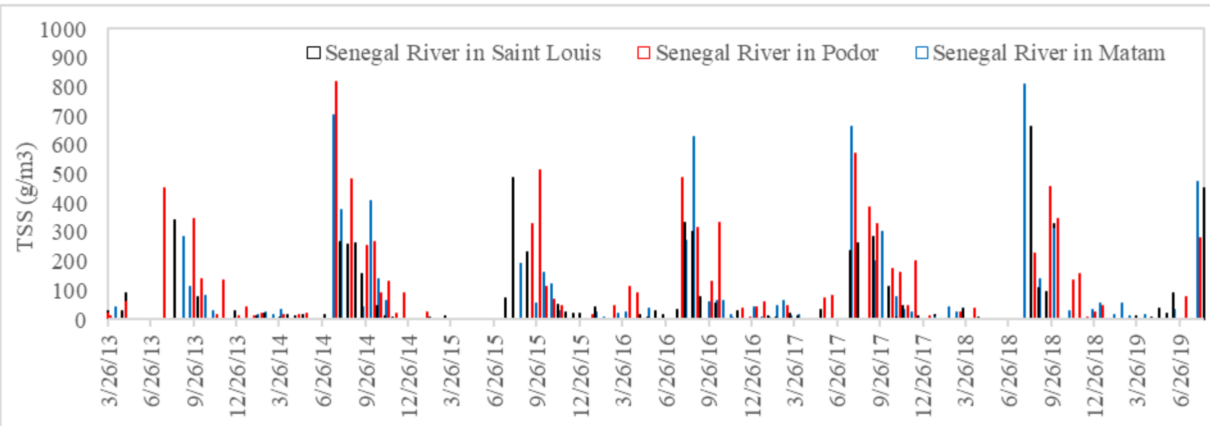

Fig. 6 Daily evolution of the concentration of suspended solids from the Senegal River in the valley (Matam and Podor) and the delta (Saint Louis)

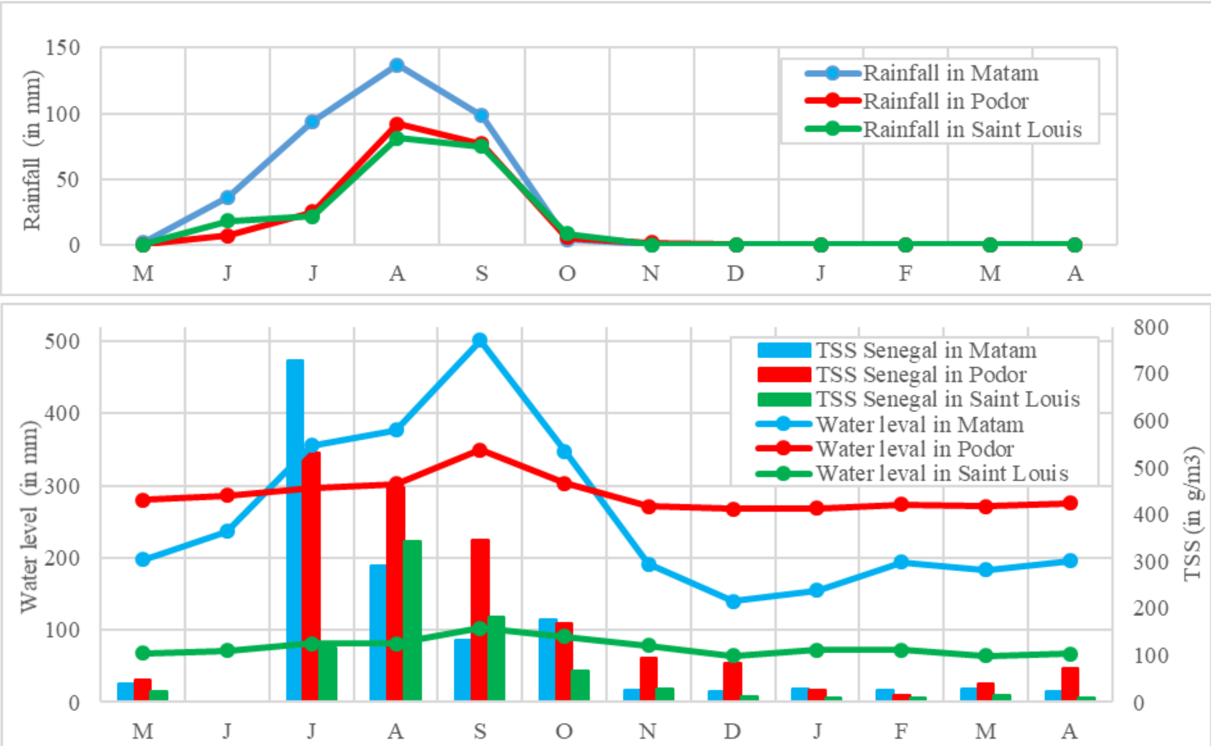

Fig. 7 Monthly evolution of TSS concentration, rainfall and water levels in the valley (Matam and Podor) and delta (Saint Louis) of the Senegal River

The seasonal variability of the concentration of suspended solids in the Senegal River valley and delta shows a peak at the beginning of the rainy season in Matam and Podor that precedes the peak precipitation by one month and the peak water level by two months (Fig. 7). This is in line with the TSS -rain-discharge relationships observed at the Bakel station. In Saint Louis, after the Diama dam, the peak of TSS is observed in August.

Impacts of tributaries on water and sediment supply in the Senegal River

To characterize the impacts of tributaries on the water and sediment supply of the Senegal River, we characterized the TSS of the Senegal River on its upstream and downstream section and each of its tributaries: first on the Senegal River upstream and downstream of the Manantali Dam; then on the Senegal River upstream and downstream of the confluence with the Falémé River; finally on the Senegal River upstream and downstream of the confluence with the Bakoye) (Fig. 8).

On the section of the Senegal River before the confluence with Falémé, the peak of TSS is noted later (in September with 239 g/m^3) compared to the part after the confluence with Falémé (whose peak is noted in August with 298 g/m^3) (Fig. 8). With the exception of September, the concentration of SS on the part after confluence with the Falémé is higher than that of the part before confluence of the Senegal River with the Falémé. On an annual scale, because the concentration of TSS is higher in the Falémé (with 128 g/m^3) than in the Senegal River upstream of Kidira (47.1 g/m^3), it is higher in the downstream part confluence between the Falémé and the Senegal River (with 119 g/m^3) than in the upstream part (Table 3).

In general, discharge at Bakel station are much higher than those measured at Kidira (Fig. 8). According to OMVS (2012**)**, the annual modules of the main rivers in the basin are as follows: 180 m^3 /s at Manantali on the Bafing; 149 m^3 /s at Oualia on the Bakoye; 134 m^3 /s at Gourbassi on the Falémé; 676 m^3 /s at Bakel on the Senegal River. A tributary such as the Falémé, whose discharge remains natural, has a slightly higher concentration of suspended solids than the Senegal River upstream of Kidira, a fact that could be explained by the role of the Manantali dam in retaining sediments in its lake and thus reducing sediments in the downstream part of the dam. Thus, although Falémé is more heavily loaded with suspended solids, its sediment supply to the Senegal River is mainly marked by its relatively smaller volume of water than that of the Senegal River (Falémé representing only 25% of the discharge flowing into Bakel.

By comparing the TSS of the different tributaries of the Senegal River (Bafing, Bakoye and Falémé), through a characterization of the TSS of the Senegal River on its upstream and downstream section and of each of the tributaries, we can generally observe an increase in the concentration of TSS after the confluence of the tributaries (Table 2 and 3). If we take the section of the confluence with the Bakoye basin, the average concentration of TSS over the period studied before the confluence, which is 18.1 g/m^3, increased slightly to 19.4 g/m^3 after the confluence, an increase of 1.3 g/m^3 (at a rate of 7.2%), indicating a slight excess of the TSS concentration in the Bakoye over the Senegal River. Similarly, for the section of the confluence with the Falémé basin, the average concentration of TSS over the period studied before the confluence, which is 69.6 g/m^3, increased to 98.3 g/m^3 after the confluence, an increase of

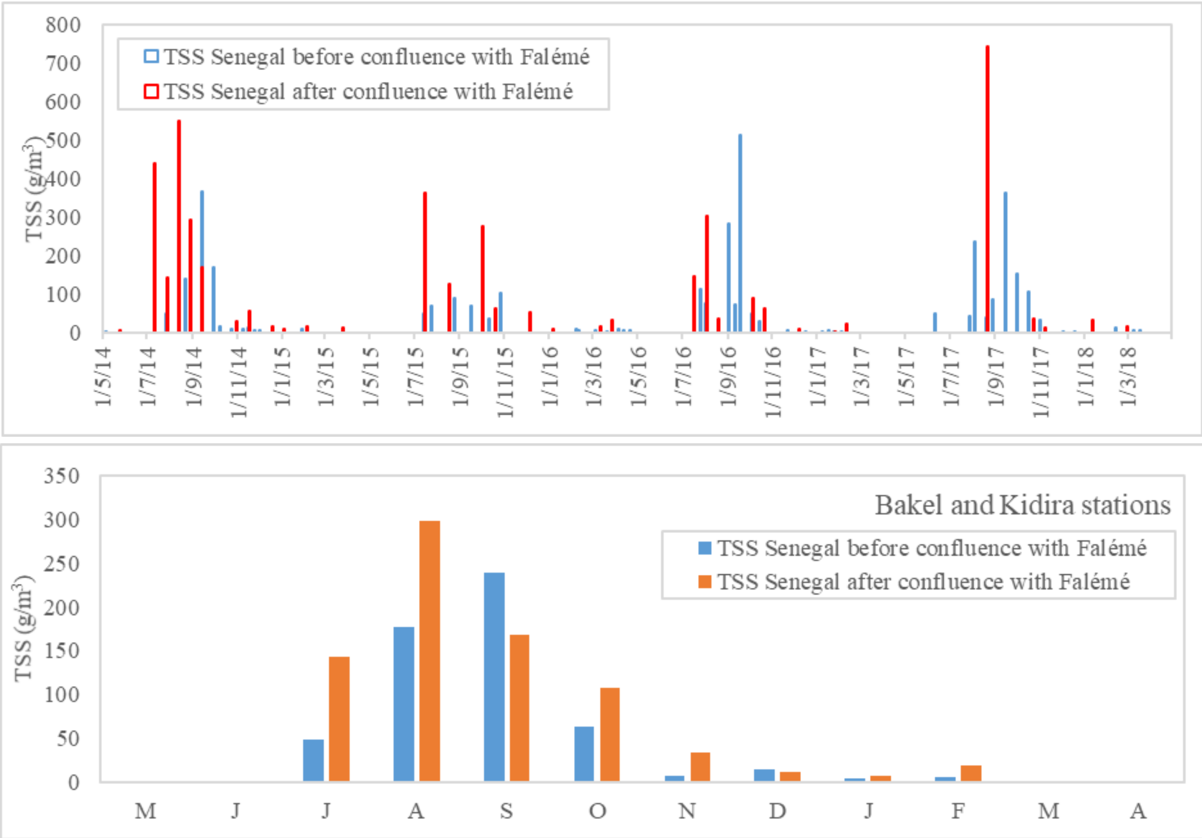

Fig. 8 Daily and monthly evolution of the Senegal River TSS concentration (upstream and downstream of the confluence with Falémé) from 2014 to 2018

Table 3 Evolution of the annual concentration of TSS (in g/m^3) of the Senegal River from upstream to downstream in the basin

Valley and delta	**2014-15**	**2015-16**	**2016-17**	**2017-18**	Average
Senegal in Saint Louis	82.3	65	88.2	104.2	84.9
Senegal in Podor	168.8	144.8	181.8	130.8	156.6
Senegal in Matam	130.7	99	123	142.6	123.8
Senegal in Bakel	237	74	98.1	115	131
Falémé in Kidira	169	98	78.6	167	128
Bakoye in Oualia	90.7	90.6	99.9	71.3	88.1
Senegal - Falémé	**2014-15**	**2015-16**	**2016-17**	**2017-18**	Average
Senegal downstream of Falémé	102	123	70.3	169	119
Senegal upstream of Falémé	68.2	49.0	66.5	57.7	47.1
Senegal - Bakoye	**2014-15**	**2015-16**	**2016-17**	**2017-18**	Average
Senegal downstream of Bakoye	23.0	28.3	10.5	16	19.4
Senegal upstream of Bakoye	33.0	13.9	16.3	9.3	18.1
Senegal - Manantali	**2014-15**	**2015-16**	**2016-17**	**2017-18**	Average
Bafing downstream of Manantali	19.9	48.3	60.6	35.3	41.0
Bafing downstream of Manantali	21.4	21.1	49.6	53.3	36.4
Section at the entrance of the Manantali dam	13.9	6.9	13.7	16.5	15.6
Section at the exit of Manantali	21.4	39.9	16.1	18.0	15.9

28.6 g/m^3 (with a rate of 41.1%), also indicating a very high sediment supply from the Falémé to the Senegal River. In the Bafing basin, the concentration on both sides of Manantali remains lower in the upstream part (36.4 g/m^3) than in the downstream part (41.0 g/m^3). In the valley, the transverse gradient, marked by an increase in TSS from upstream to downstream, remains strong (123.8 g/m^3 in Matam; 156.6 g/m^3 in Podor), while in the delta, with the presence of marine dynamics and the sediment retention role of the Diama dam (Kane, 2005), the concentration of TSS is declining (84.9 g/m^3 in Saint Louis).

Figure 9 shows the monthly evolution of the concentration of suspended solids along the Senegal River. It appears that, in general, the concentration of TSS increases, in relation to the increase in the volume of water flowing, from upstream (the source) to downstream (valley area), even if the seasonal distribution is not the same.

Impacts of the Manantali dam on sediment deposition in the Senegal River

The comparison of the upstream and downstream TSS concentration curves shows a more or less similar evolution over some periods, and different over others (Fig. 10). However, analysis of TSS values in the upstream part of Manantali indicates the relatively low sediment supply of Bafing in the lake of the Manantali dam (the annual average of the series being 13.3 g/m^3). This indicates a relatively limited accumulation of SS in the lake of the Manantali dam.

If we compare the average concentration of TSS in the upstream part (with 13.0 g/m^3) with those in the downstream part (with 20.1 g/m^3), the average concentration of TSS in the downstream part of the dam is sligthly higher than that in the upstream part of the dam (with a difference of 7.1 g/m^3). Only for 4 dates the average concentration of TSS in the upstream part is higher than in the downstream part indicating a potential sediment deposition in the dam lake.

Overall the potential sediment deposition is relatively low. However, some peaks can occur upstream and are accompanied by significant retention. This is why, the potential weak sediment deposits in the lake of the Manantali dam (noted over certain periods where the TSS upstream are higher than those downstream) do not allow us to affirm the absence of excessive sedimentation. This is why, the Manantali dam is for the moment spared from excessive sedimentation which constitutes one of the major problems associated with dams (this sedimentation can block the valves of a dam and cause its failure under certain conditions) (Zhang, 2014).

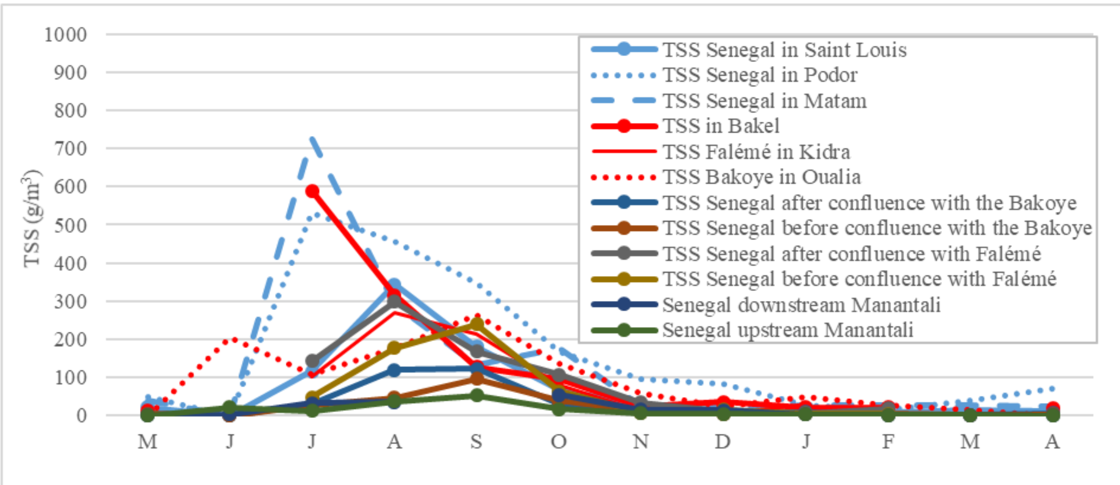

Fig. 9 Monthly evolution of the Senegal River TSS concentration from upstream to downstream in the basin

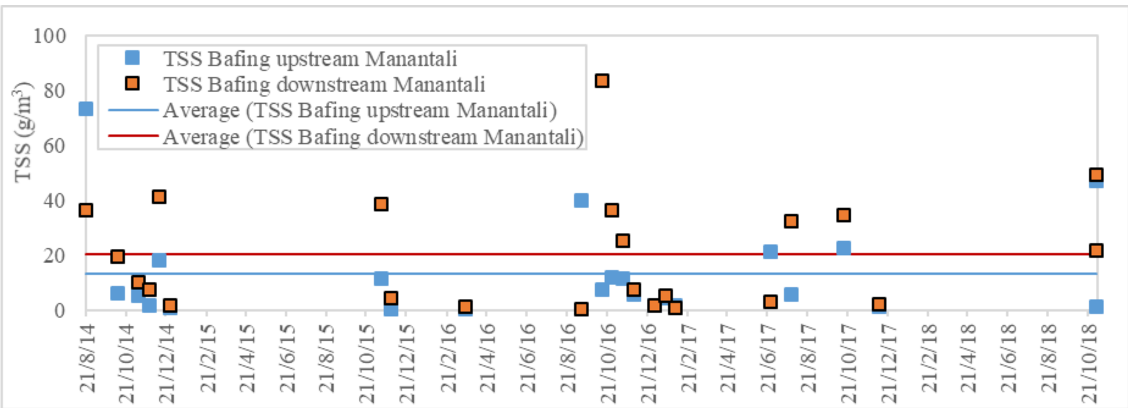

Fig. 10 Relationship between the concentration of TSS on the Bafing section (upstream and downstream of the Manantali dam) from 2014 to 2018

DISCUSSION

The use of the NIR band of Landsat 8 images has proven to be very appropriate for turbidity monitoring in a river characterized by high turbidity values and high spatial and temporal variability. These same Landsat satellite data were selected by Robert et al. (2017) to document TSS and turbidity in the Gouma region of Mali. Our study confirms the potential of sensors and the infrared band for monitoring the dynamics of TSS in West African surface waters.

The surface reflectances of Landsat 8 made it possible to analyse the spatial and temporal variability of turbidity in the Senegal River basin over the period 2014-2018. In terms of seasonal cycle, the increase in TSS concentration is mainly caused by rainfall between the early rainy season and the mid-rainy season. The concentration of TSS therefore generally increases with the arrival of the first rains before the river's discharge increases. However, this does not concern the whole basin (but only the upper basin), because there is sometimes a temporal difference between the upstream (upper basin) and downstream (valley and delta) zone of the basin. In semi-arid environments, runoff induced by the first rains could lead to increased transport because the soil surface has very low vegetation cover (Mbaye et al., 2016). Later in the season, with the development of vegetation in cropland and pasture, erosion and sediment transport are reduced, as well as the concentration of TSS in rivers and lakes or reservoirs (Robert et al., 2016).

At the stations in the upper part of the basin, most of the peaks occurred between July and September (high water period), often before the annual peaks in precipitation and river discharge (as in the lower part of the basin where peaks are noted in late July and early August). These results confirm those of Mbaye et al. (2016) which indicate a concentration of TSS measured at a station in July 2012 (Dembancane; between Bakel and Mattam) of 540 mg/l, well above the concentrations observed in August 2013. They are also in agreement with the TSS concentrations presented in Kattan et al. (1987), which found maximums during the first rainy season in June/July before the peak discharge from August to October. Our work also confirms the results of Kane (2005) who notes a rapid increase in TSS with the arrival of annual flood waters that carry sediment from watershed erosion.

At the interannual scale (over the period 2014-2018), a large variability in the concentration of TSS was observed in the basin on all sections. Although there are significant variations in TSS, they are higher in the river valley than in the delta and upper basin. These results are consistent with those reported by Mbaye et al. (2016) which indicate much higher TSS concentrations during the rainy season with values between 5.4 and 366.4 mg/l, with a general increase in TSS at downstream stations and a slight reduction at estuarine stations. They are also in agreement with those of Kane (2005) who, based on the TSS measurements made, noted a rapid increase in TSS with the arrival of annual flood waters that carry sediment from watershed erosion. His study showed that concentrations remain relatively high (almost 200 mg/l) until the end of September - beginning of October, after which time solid loads decrease very rapidly. According to his study, hydrological cycles show that on a monthly scale, the months of August, September and October account for almost all (95%) of the solid load. It is worth noting the drastic decrease in tonnage from November onwards (around 2% and even less) and the insignificant percentages in December (less than 1%).

According to Zhang (2014), excessive sedimentation is one of the major problems identified and associated with dams and can block its doors, causing the dam to rupture under certain conditions). Fortunately, in the Manantali dam, small peaks of TSS are noted, peaks which can hardly cause the silting up of the dam. Finally, satellite estimates were also used to assess the dynamics of TSS in the Manantali dam. The comparison between an upstream and a downstream site shows first of all the low sediment supply from the upstream section and the relatively low impact of the Manantali dam on sediment retention in its lake. These results therefore confirm the estimates that have been made, which revealed that the Senegal River has brought small proportions of silt into this reservoir on average per year. They are also in line with the observations of SOGEM (Société de Gestion de l'Energie de Manantali) officials who confirm that the current siltation rate in the Manantali reservoir is negligible, which is consistent with the extreme clarity of the water in the reservoir (Faye, 2018). An impact study estimated that 530,000 tonnes of suspended solids, 50% of which were particles less than 0.002 millimetres in diameter, were added to the reservoir each year, estimating a lifespan of 450 years (estimated period of filling in the dead water volume of the reservoir by sedimentary deposits observed at the time) (Faye, 2018). However, TSS peaks may occur, as noted in this study, and lead to a significant potential sediment deposition. In addition, over an extended period of time, sediment will continue to accumulate behind the walls of the dam.

CONCLUSION

Landsat 8 satellite data provided valuable information on the spatial and temporal variability of suspended particulate matter in surface waters of the Senegal River basin. In the Senegal River basin, TSS are characterized by a high daily variability in their concentration, despite a fairly regular seasonal rhythm. TSS remains relatively high for much of the year. Daily rainfall and hydrological data were used to establish a relationship between river discharge and inverted TSS concentration from Landsat 8 satellite data for the site located at the outlet of the upper Senegal River basin. Shifts are noted between the peaks of TSS observed often in July and those of rainfall (August) and discharge (September). Satellite estimates are also used to assess the dynamics of TSS in the Senegal River basin and in the Manantali dam. Comparison of the TSS concentration on either side of the Manantali dam suggests low sediment retention in its reservoir, with possible peaks from time to time. The low concentrations of satellite derived TSS are consistent with the ranges of TSS deposits noted in the Manantali Dam reservoir.

This study has demonstrated the value of including water colour data in environmental studies to expand and complement analyses carried out through *in situ* measurements at broader spatial and temporal scales. In the future, it is therefore necessary to continue the qualification of Landsat-8 products, to carry out a post-processing chain for Landsat 8 images for "water colour" products, to develop regional algorithms for continental waters, to valorise products, to integrate water colour products into hydrological modelling (SWAT), to use water colour products for human health.

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