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Evaluation of material flows in the Mé River watershed (Ivory Coast)

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ABSTRACT: Soil erosion by precipitation, rainfall and runoff is a widespread phenomenon in different countries of the world. It becomes disastrous in particular on the slopes because of the torrentiality of the flow, of the strong vulnerability of the grounds (soft rocks, fragile grounds, steep slopes). The present study has for objective: The analysis of the data of concentrations of sediments in suspension are measured at the station of the rivers highlights relations, linking the concentration (or the solid flow) of the sediments in suspension to the liquid flow and to quantify the seasonal, monthly and interannual and intra annual variation of the surface degradation. Annual tonnage estimates of solids loads to the Mé were derived from the power law for all seasons. From this deduction, the annual quantities of sediment transported by the Mé from 2015/2017 is 7.06.106 t/year, or a specific degradation of 1.79.103 t/km^2/year. On the other hand, in 2017, the value of this solid input is 3.06.106 t/year. However, the annual solid input is estimated at 7063.03.103 t/year with a specific degradation of 1784.47 t/km^2/year at the Mé from 2015 to 2017.

KEYWORDS: Abidjan District, Solid Transport, Solid Flow, Sediments, Suspended Matter.

1 INTRODUCTION

Soil erosion by precipitation, rainfall and runoff is a widespread phenomenon in different countries of the world. It becomes disastrous especially on slopes because of the torrentiality of the flow, the high vulnerability of the land (soft rocks, fragile soils, steep slopes), the strong degradation of the vegetation cover by agricultural activities, the demographic pressure by the continuous growth of land clearing and development of new lands often to the detriment of wooded areas and high water and air temperatures in the hot season that increase the ability of water to destroy soil aggregates ([1]; [2]; [3]; [4]). Furthermore, sediment fluxes in streams are the results of different erosion and particle transport processes in the watershed. Therefore, it is important to understand the dynamics of suspended solids and to establish reliable balances of TSS fluxes transported by streams if we want to determine a good management of the river system and hydraulic structures. It is a natural problem that becomes worrying when the tolerable threshold is exceeded. Some reports estimate that globally, reservoirs intercept up to 25% of the sediment that would otherwise flow to the oceans [5]. Approximately 1% of the world's water storage capacity in reservoirs is lost each year through sediment deposition in reservoirs [6]. Erosion and solid transport are thus serious problems globally, but are of much greater concern in some regions of the world [7]. For many cultivated soils, erosion is related to the superficial structural degradation of soils through the formation of battance crusts that reduce the infiltration capacity of soils and lead to increased runoff. The consequences of this runoff include an increase in the solid load of watercourses, silting and siltation of water reservoirs [8]; [9], modification of the water cycle regulation processes, and an increase in pollutants in receiving environments.

Suspended particles resulting from soil erosion have both a high adsorption capacity and a high cohesive capacity and are particularly involved in the transport of pollutants and the clogging of riverbeds and receiving environments [10]. The problem of the degradation of the vegetation cover, soil erosion and the flow of material derived from this soil degradation is therefore becoming a major concern in Côte d'Ivoire. This degradation seems to have increased over time due to socio-economic transformations, global changes, [11].

The purpose of this study is to:

- Analysis of measured suspended sediment concentration data are measured at stations on the Mé River;
- To highlight relationships, linking the concentration (or solid flow) of suspended sediments to the liquid flow;
- Quantify seasonal, monthly, and inter- and intra-annual variation in surface degradation.

2 Material and methods

2.1 Material

2.1.1 Geographic Location

The Mé is a coastal river in the south of Côte d'Ivoire which drains a watershed of 4070 km^2. This river takes its source in the North of Adzopé under the name of "Min" or Mé then flows in the North in the South. The watershed is located between longitudes 380,000 and 450,000 m and latitudes 6,000,000 and 680,000 m (UTM WGS 84 zone 30 North). (Figure 1) Due to its location, the Mé is totally included in the low forest Ivory Coast where rainfall is higher than 1400 mm/year. Its flow in flood period is 200 m^3 /s and 1 to 2 m^3 /s in low water period. The basin is dominated by ferralitic soils.

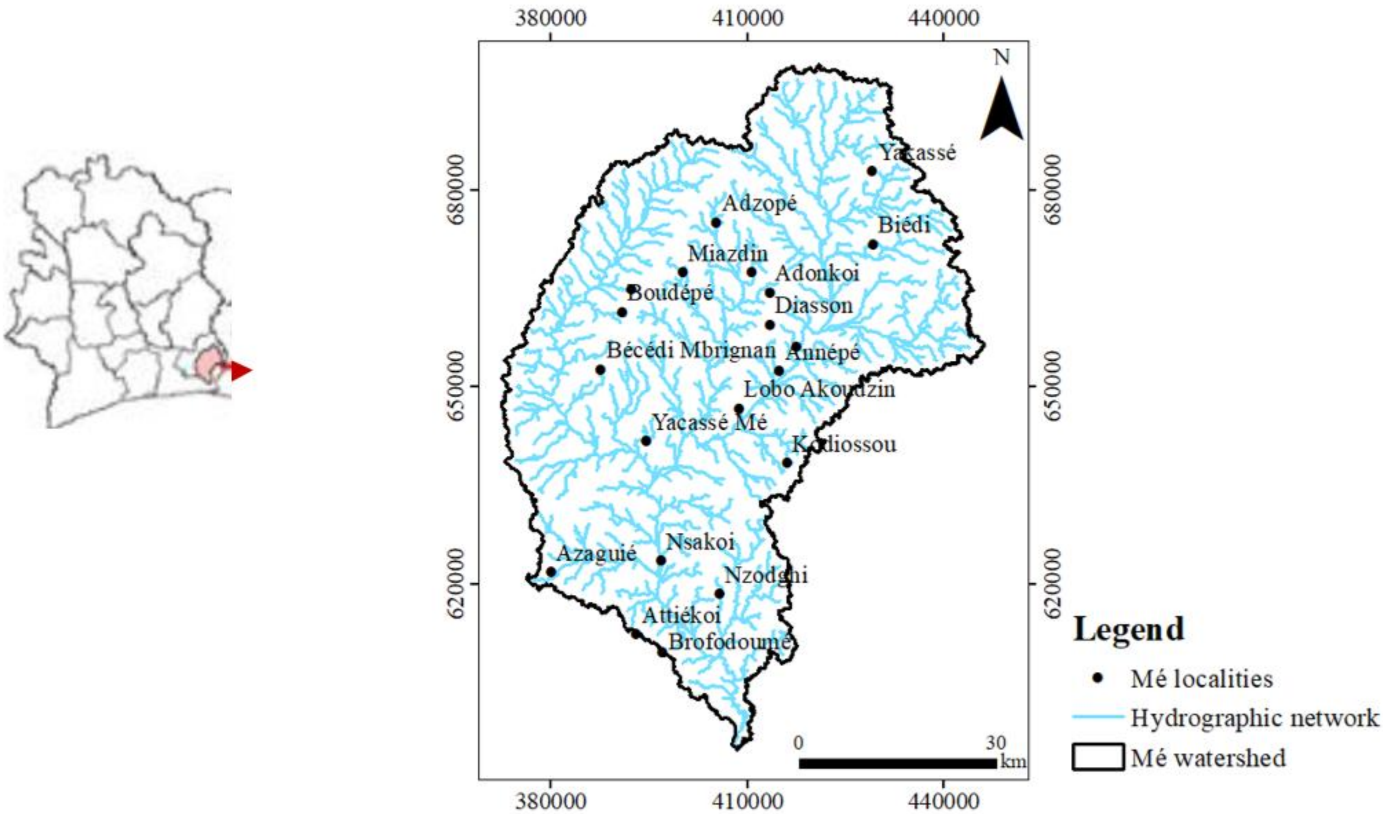

Fig. 1. Location of the study area

2.1.2 CLIMATES

The distribution of the climate is regulated by the seasonal movement of air masses that sweep through the southeast region. The very dry tropical continental air descends from the Sahara in the north south direction (harmattan) while the humid maritime equatorial air, called monsoon, fed by the St. Helena high pressure. The ballet between these two air masses regulates the climate where the study area is located and subdivides it into four major seasons that mark the hydrological cycle.

The annual rainfall recorded in Abidjan district during the period 1950-1997 ranged from 3,128 mm in 1951 to 1,050 mm in 1988 with an average of 2,089 mm. Annual rainfall in the 1950s varied between 2,000 and 3,000 mm. The Abidjan district is subject to a transitional equatorial climate divided into four (4) seasons in the annual cycle (Saley et al., 2009 [12]):

- Great dry season from December to April;
- Great rainy season from May to July;
- Small dry season from July to September;
- Small rainy season from October to November.

The long rainy season is centered on June while the short rainy season is centered on October. The same is true for the long and short dry seasons, centered on January and August, respectively. The unequal distribution of the two rainy seasons is due to the upward and downward movements in the North-South direction of the ITD (Intertropical Front) (Kouamé, 2007 [13]).

2.1.2.1 RAINFALL REGIME

The interannual average rainfall over the period 1949-2016 is 1677.1 mm. The IRHO la Mé station shows an average monthly rainfall between 25.8 mm (January) and 421.3 mm (June, peak of the first rainy season). The peak of the second rainy season (October) has an average monthly accumulation of 170 mm (Figure 2).

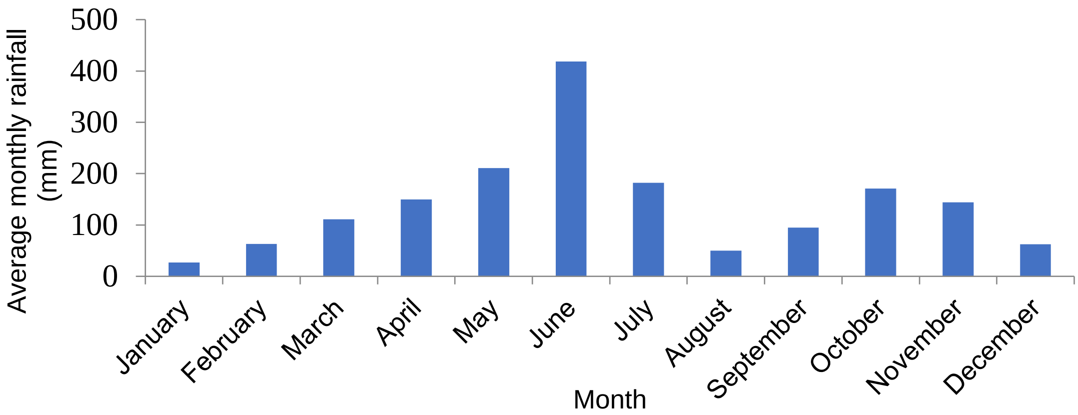

Fig. 2. Average monthly rainfall at the IRHO La Mé station from 1949 to 2016.

2.1.2.2 INSULATION

The average monthly duration of insolation from 1957 to 2012 at the IRHO la Mé station varies from 74.5 h (August) to 191.5 h (April). The highest values are in March (189.6 h) and April (191.5 h) in the long dry season. A strong cloudiness marks the months of June to September. The minimum value of sunshine is located in August (74.5 h) (Figure 3).

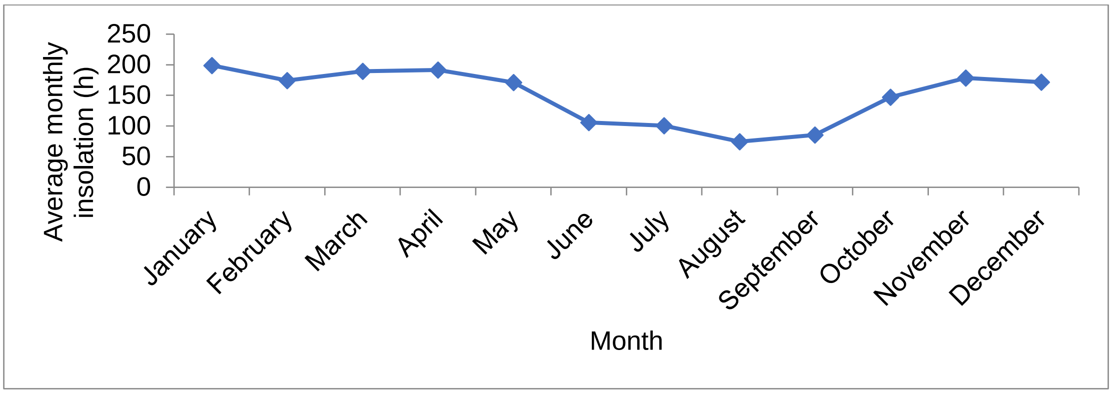

Fig. 3. Insolation at the IRHO La Mé station from 1957 to 2012.

2.1.2.3 Relative Humidity

Figure 4 shows the monthly variation in relative humidity from 1957 to 2012 at the La Mé station. The relative humidity ranges from 78.4% (February) to 87% (June). There is an increase in relative humidity until it peaks in June with a value of 86%. This is followed by a slow decrease until December with a value of 83.9%.

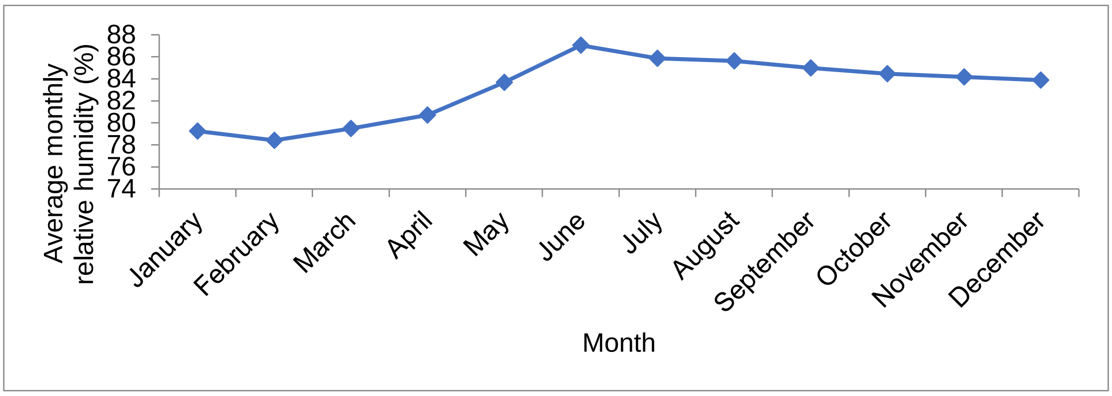

Fig. 4. Average monthly relative humidity at the IRHO La Mé station from 1957 to 2012.

2.1.2.4 Average Temperature

The average monthly temperature at the IRHO la Mé station over the period 1957 to 2012 ranges from 24.7°C to 27.8°C. The highest temperatures are observed from February to April during the long dry season. The onset of the main rainy season with the appearance of clouds leads to a drop in temperature with the lowest temperature in August (24.77°C) (Figure 5).

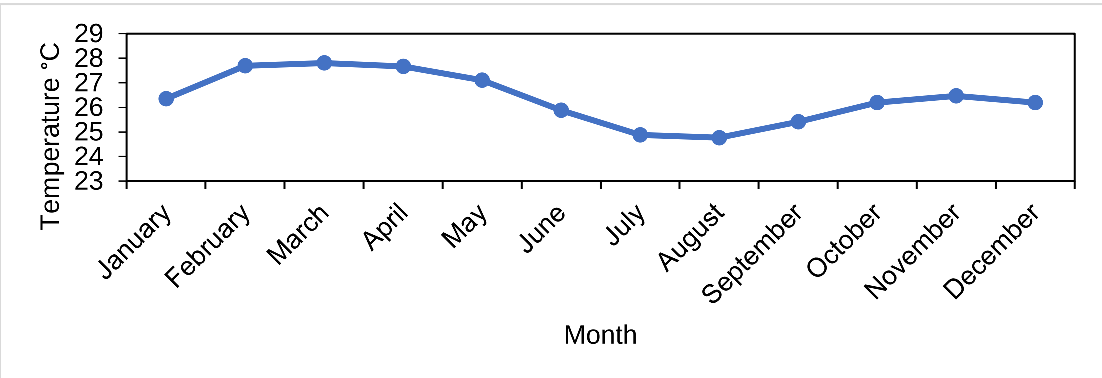

Fig. 5. Average monthly temperature at the IRHO La Mé station from 1957 to 2012.

2.1.2.5 VEGETATION

The vegetation of the Mé is dominated by the tropical rainforest made up of protected forest massifs such as the Besso as well as patches of secondary forest and fallow land which, moreover, have favored the establishment of numerous wood industries. The primary forest is found only in the seven classified forests, namely Massa-Mé, Mabi, Mé-Mafou, Hein, Agbo, N'toh and Besso. The vegetation is overexploited.

2.1.3 HYDROGRAPHIC NETWORK

The hydrographic network of the basin in Figure 6 represents the hydrographic network of the Mé River. The main course of the Mé, about 140 km long, is a real collector that receives water from its main primary tributaries (Mafou, N'Zo) and secondary tributaries, some of which are intermittent. There are many streams due to the abundant rainfall. The hydrographic network is dense, the Besso, the Bamin, the Zo and the anvolo which is a tributary of the Massan on which a dam has been built to supply drinking water to the population of the town of Adzopé.

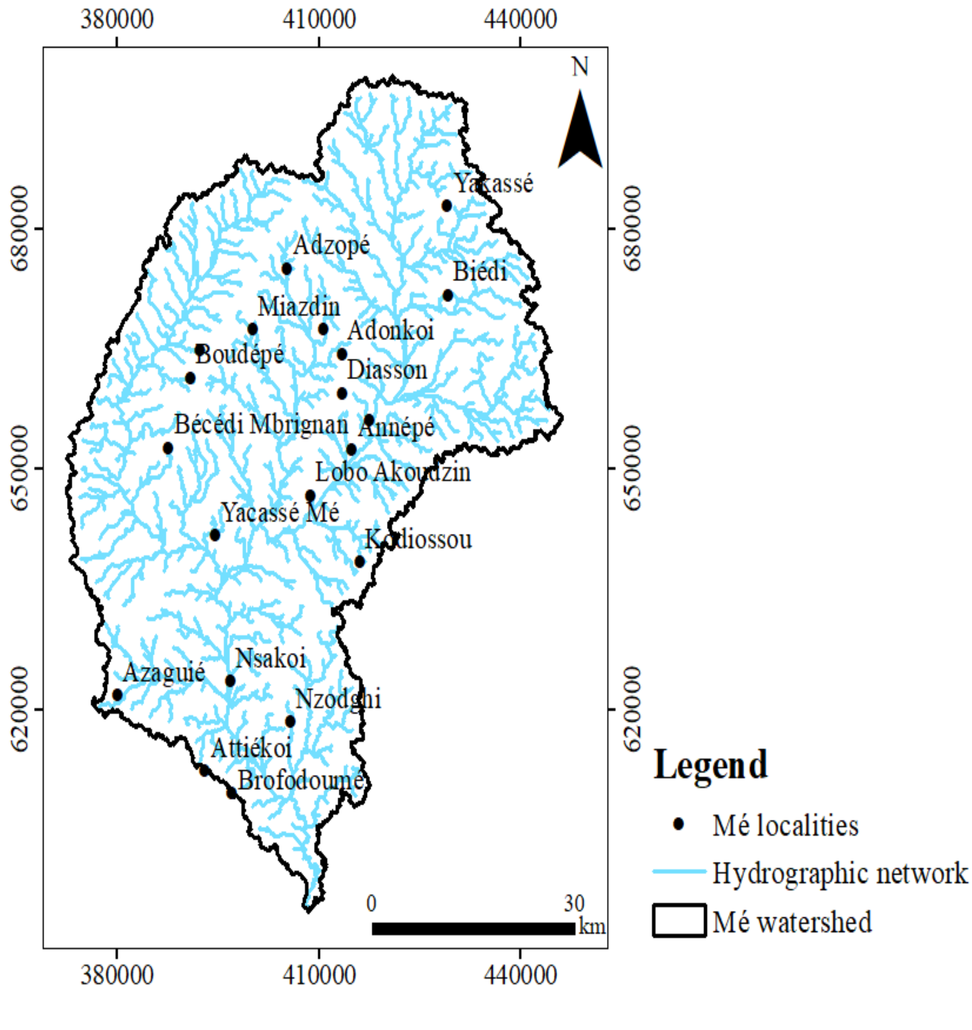

Fig. 6. Hydrographic Network of the Mé Watershed.

2.1.4 GEOLOGICAL OVERVIEW AND HYDROGEOLOGICAL

The sedimentary basin in which the southern part of the Mé watershed is located is a large, flattened crescent, bordering the Atlantic coast from Sassandra to Ghana. It extends over 45 km inland and does not exceed 130 m in altitude with an area of 8,000 km^2. The sedimentary basin is of Cretaceous Quaternary, Meso-Cenozoic and Paleoproterozoic age. It is composed mainly of clayey sands and coastal sands.

The basement is part of the old Precambrian shield of West Africa. It consists of two major lithological units. The architecture of the basement is characterized by two Precambrian domains of unequal extensions: the formations of the crystalline and crystallophyllous basement are constituted of fine gneisses with biotite and amphibole. The basement consists of birimian formations which are schists, metaarenites and metasiltones. In these formations, intrusions of Eburnian granitoids composed of gneiss, granites, granito-gneiss, with which are associated aureoles of metamorphism.

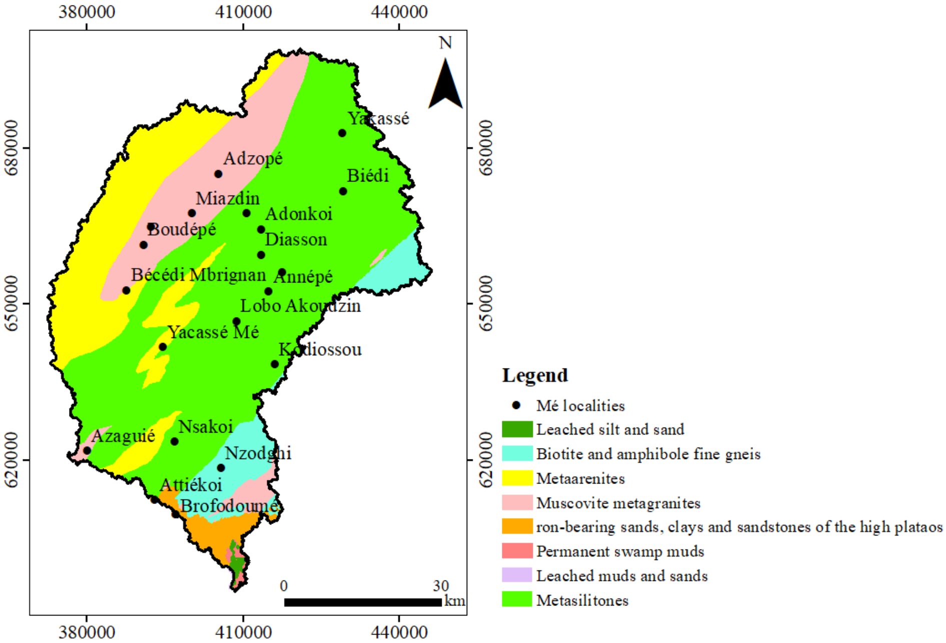

Fig. 7. Geological map of the Aghien watershed [14] modified.

2.1.5 Topography of the Watershed

2.1.5.1 Altitude

Figure 8 shows that the altitude map varies between 0 and 207 m. The altitudes decrease from north to south. The highest altitudes are found in the north of the watershed in the regions of Yakassé, Biédé, Adzopé, etc. They range from 136 m to 207 m. They range from 136 m to 207 m. In the south of the watershed are located the low altitudes from 0 to 73 m. They cross the following localities: Azaguié, Brofodoumé, Attiékoi etc. These altitudes more or less form the water divide. These low areas are more or less homogeneous and appear to be plains. The middle elevations cover the center of the basin.

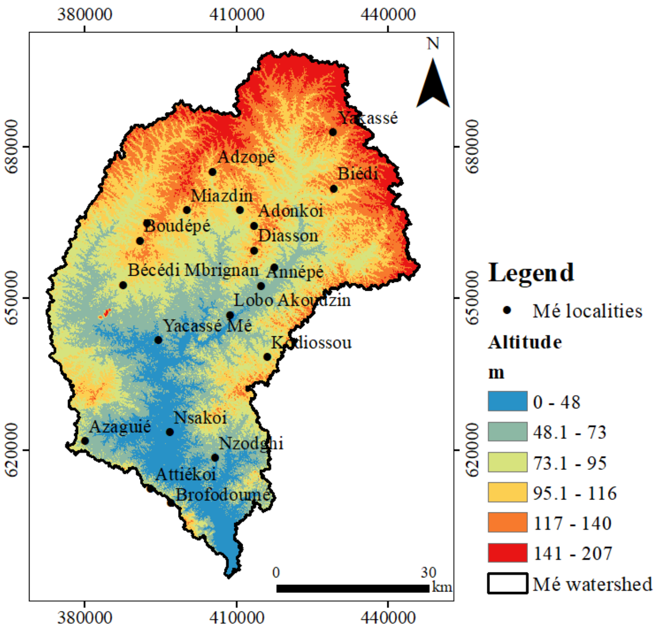

Fig. 8. Elevation Map of Mé Watersheds.

2.1.5.2 Slope

The slopes of the Mé watershed range from 0 to 35.13° with an average of 4.31° and a standard deviation of 3.43°. They are generally low as indicated by the average. The weak slopes are located in the plains. The steep slopes are located in the central east and south of the watershed and at the edges of the plateau incisions. The western half has low slopes that are monotonous and less rugged in contrast (Figure 9).

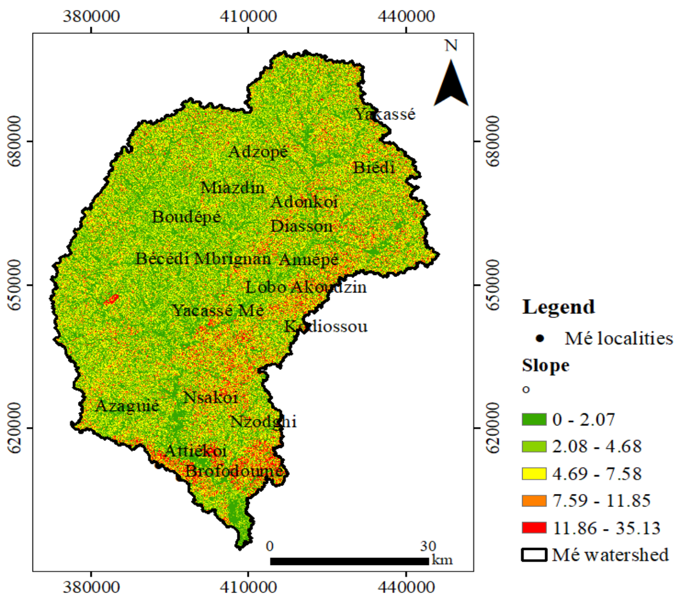

Fig. 9. Map of the slopes of the Aghien and Mé watersheds.

2.2 METHODS

2.2.1 SAMPLING OF SUSPENDED SOLIDS (SS)

Several campaigns were conducted on the Mé River from April 2015 to June 2017 (Figure 10). During the campaigns, water samples were collected and kept cool in a cooler and subsequently analyzed in the laboratory. A total of 32 samples at the Mé (Figure 10).

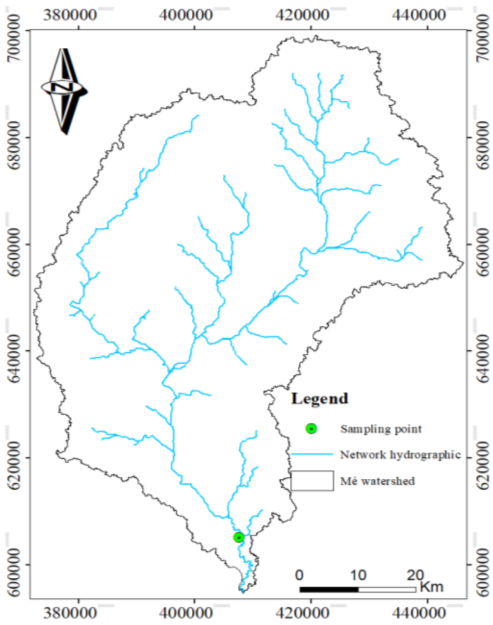

Fig. 10. Suspended solids (SS) sampling station.

The samples taken from the Mé River during the study period were collected at low, medium and high water. These samples are representative of the Mé River as they were taken at different seasons of the year.

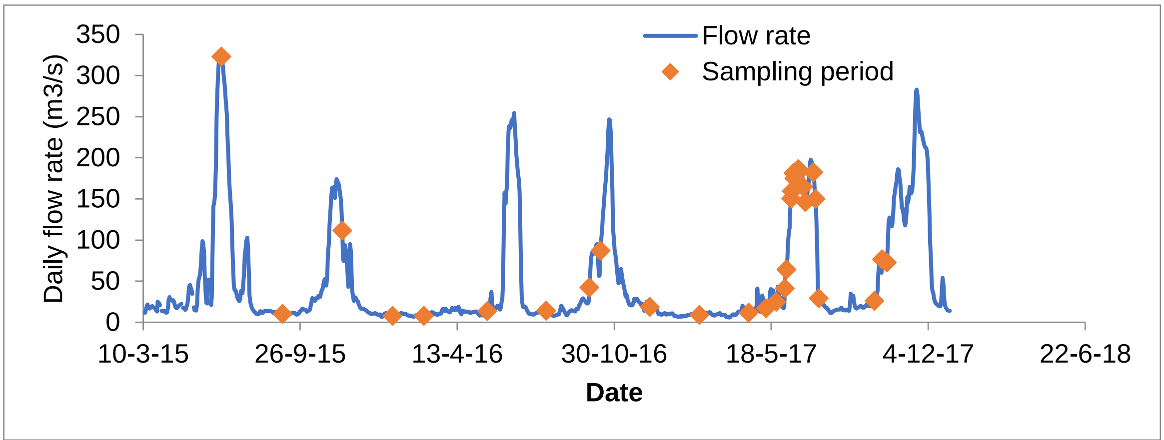

Fig. 11. Suspended solids sampling points at the Mé river.

2.2.2 DESCRIPTION OF THE METHOD

In the laboratory, the filter (0.45µm) is dried beforehand for 2 hours at 105°C in the oven, after drying the filter is weighed. The empty mass is noted M_1. A volume V of 100 to250 ml of water was taken from the sample. This volume was filtered on the previously dried filter (dry weight M1 in mg). The filter containing the filtrate was then dried for 2 hours at 105°C in the oven.

After drying, the filter is weighed again (weight M_2 in mg). The concentration C is then expressed in g /l according to the equation: 1

$$C_s = \frac{M_2 - M_1}{V} \quad \text{(Eq 1)}$$

M_1= initial mass of the filter in (mg)
M_2= mass of the filter after filtration in mg
V= volume filtered (L)
Cs = material concentration (mg/L)

2.2.2.1 DETERMINATION OF THE SOLID FLOW

The removal of solids from the slopes and the bed and banks of the Mé River, and their eventual transport by streams, are two distinct but related phenomena. Sediment sampling in the Mé River allowed the calculation of the load from the average concentration (C in g/L) of the samples. Solid flow (Qs in kg/s) is calculated with average TSS concentrations multiplied by liquid flows (Ql in m3 /s) as shown in Equation 2 [15]; [16]; [17]; [18].

$$Qs = Cs * Ql \quad \text{(Eq 2)}$$

2.2.2.2 QUANTIFICATION OF SUSPENDED SEDIMENT INPUTS

2.2.2.2.1 SOLID TRANSPORT CURVE

The statistical treatment of liquid flow and TSS concentration is to find a regressive model (Qs= f (Ql)). The regressive statistical methods were used to reconstruct the TSS concentration data. Suspended sediment concentration (C) and liquid flow (Q) evolve according to a power model proposed by Kennedy (1895) [20] and commonly known as the solid transport curve [21]; [22]; [23]. The parameter (a) reflects the sensitivity to erosion of the watershed and (b) (equation 3) is related to the erosive capacity of the river as well as the increase in sediment availability with flow [24]; [25]; [26]; [27]; [28].

$$Q_s = aQ_l^{\,b} \quad \text{(Eq 3)}$$

Qs: solid flow (m^3 /s), Ql: liquid flow (m^3 /s), a and b: parameter.

Equation 3 can be used as a basis for filling observed gaps and allow the evaluation of solid inputs at different time steps.

2.2.2.2.2 SEDIMENTARY FLOWS

To quantify the solid fluxes (Fs), we proceed as if the concentration and the flow did not undergo any variation over a duration equal to the adopted time interval, or more precisely to the sum of the two half-intervals preceding and following the considered sampling. The sediment fluxes will be expressed in t/day, the concentrations in kg/m3, and the daily flow in (m3 /day). The formula for sediment flux is as follows [29]; [30]; [25]; [26], equation: 4.

$$F_S(\,tonnes/jour) = C_S * Q_l * 86{,}4 \quad \text{(Eq 4)}$$

2.2.2.2.3 SPECIFIC SEDIMENT FLOWS OR SPECIFIC DEGRADATION

Specific degradation is the ratio of solid flow by watershed area according to equation: 5 [25]; [26]; [29]; [4]; [31].

$$Q_{ss} = \frac{Q_s}{A} \quad \text{(Eq 5)}$$

Qss: specific solid flow t/km^2/year; A: surface area of the catchment area km^2.

3 Results and Discussions

3.1 Results

3.1.1 Dynamics of Sediment Flows in the Watershed

The results obtained show (Figure 12) that the solid flow (Qs) is positively correlated with the liquid flow (Ql). This model provided better results in terms of regression. The correlations obtained are all significant and above 80%.

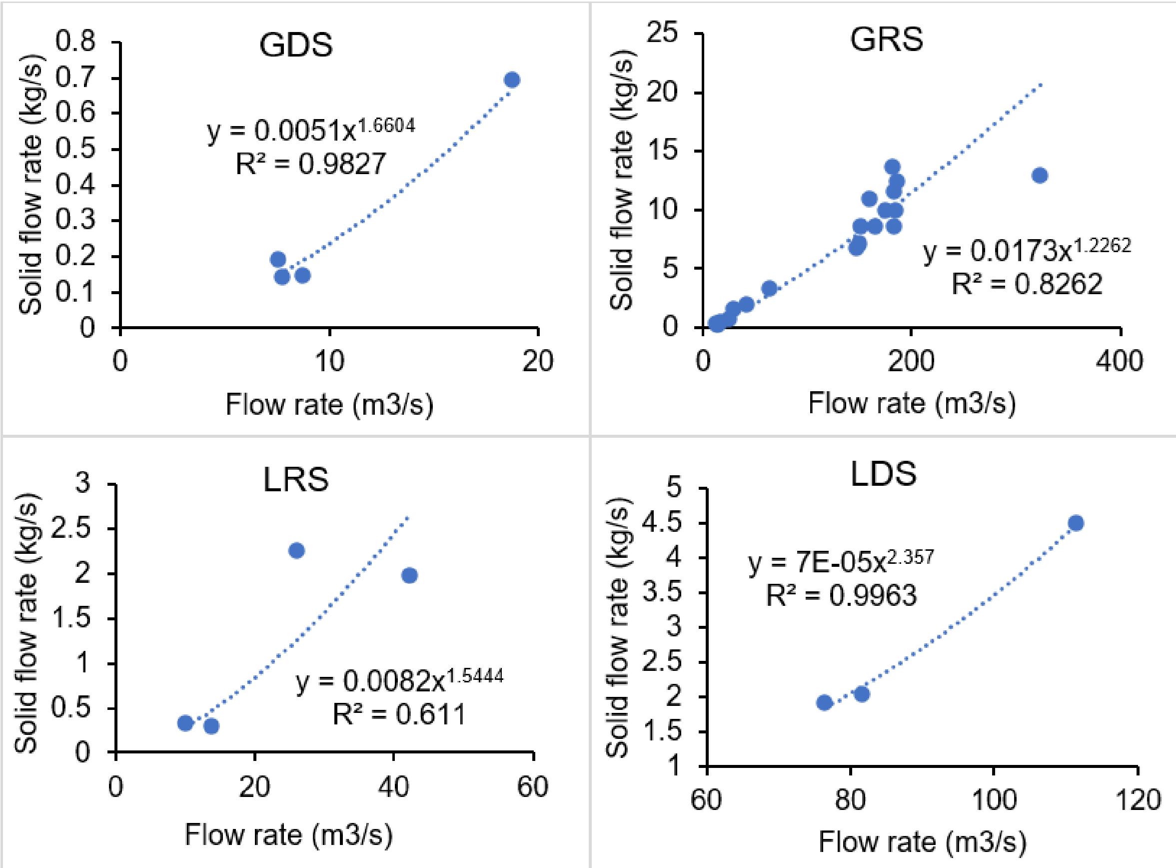

Fig. 12. Modeling of solid and liquid flow with the trend curve for different seasons. GDS: Great Dry Season, GRS: Great Rainy Season, LRS: Little Rainy Season, LDS: Great Dry Season, Qs: solid flow, Ql: liquid flow.

3.1.2 Seasonal and Monthly Variation of Liquid and Solid Inputs

3.1.2.1 Seasonal Variation of Liquid and Solid Inputs

To understand the phenomenon of erosion and solid transport, it would be wise to analyze the seasonal variation of flows and suspended solid inputs in the basins.

The variation in solid and liquid inputs follows the seasonal trend in general. The observation is that the solid inputs are below the liquid inputs. For large volumes of water observed at the drain the quantities of suspended solids less important. The proof in 2015 for a volume 789.8 Hm3 corresponds to 42.26 10^3 t, in 2016 we have a drop in volume 789.8 Hm^3 to 92.04 Hm^3 or a decrease of 88.35% resulting in a solid flow of 25.91 10^3 t. During the year 2017 an increase 86.89% is observable, this increase in liquid flows drained a volume of 702.4 Hm^3 for a quantity of 35.58 Mt of particulate suspended solids, This during the great rainy season. On the other hand, solid inputs in 2017 are high and follow the curve of liquid flows that in the short rainy season with values of 819.07 Hm^3 and 67.28 10^3 t. The quantities of balance flows conveyed in 2015 and 2016 are low 15.47 Hm^3 and 21.57Hm^3 (Figure 16). Table 1 is a record of the results observed on the Mé.

Table 1. Seasonal liquid and solid inputs to the Mé station.

Station	Year	Inputs balance	GDS	GRS	LDS	LRS	Total
Mé	2015	Apports liquids (Hm^3)	78.84	789.82	61.34	397.12	1327.12
		Apports solids (10^3t)	2.87	42.26	1.94	15.47	62.54
	2016	Apports liquids (Hm^3)	120.87	504.73	92.04	447.28	1164.93
		Apports solids (10^3t)	3.33	25.91	4.16	21.57	54.96
	2017	Apports liquids (Hm^3)	189.60	702.41	101.06	819.07	1812.14
		Apports solids (10^3t)	17.02	35.58	4.29	67.28	124.16

At the Mé, we observe a notable amount of water dominated by the major rainy season in 2015 and 2016 for respective rates of 59% and 43%, followed by the minor rainy season in the same succession of 30% and 39%. The large and small dry seasons are distinguished by low erosive intensity due to almost no rainfall activity. The same trend is found in the solid inputs between 2015 and 2016. Suspended matter is 67% of the annual total in 2015 and 47% in 2016, all of this flow transited during the big rainy season. The minimum values in the 2 years of observation are attributed to the dry period (Figure 13). In 2017 the contribution in liquid flow of the short rainy season is higher than that of the long rainy season, 45% for the short and 39% for the long. The large and small dry seasons only contribute small values because the small and large dry seasons are governed by water coming from underground and often enameled with sporadic floods. In the same year, the solid inputs provided by the short rainy season are far greater than all the inputs of the other seasons combined (54%). The large and small dry seasons are seasons with insignificant erosion, probably resulting from the rainfall.

Another piece of information we can draw from Figure 16 is that liquid inputs change inversely during the large and small rainy seasons. While liquid inputs decrease in the long rainy season, they increase in the short rainy season. The increase or decrease in the volume of water flowed is reflected in terms of quantities on the flows conveyed per year and per season.

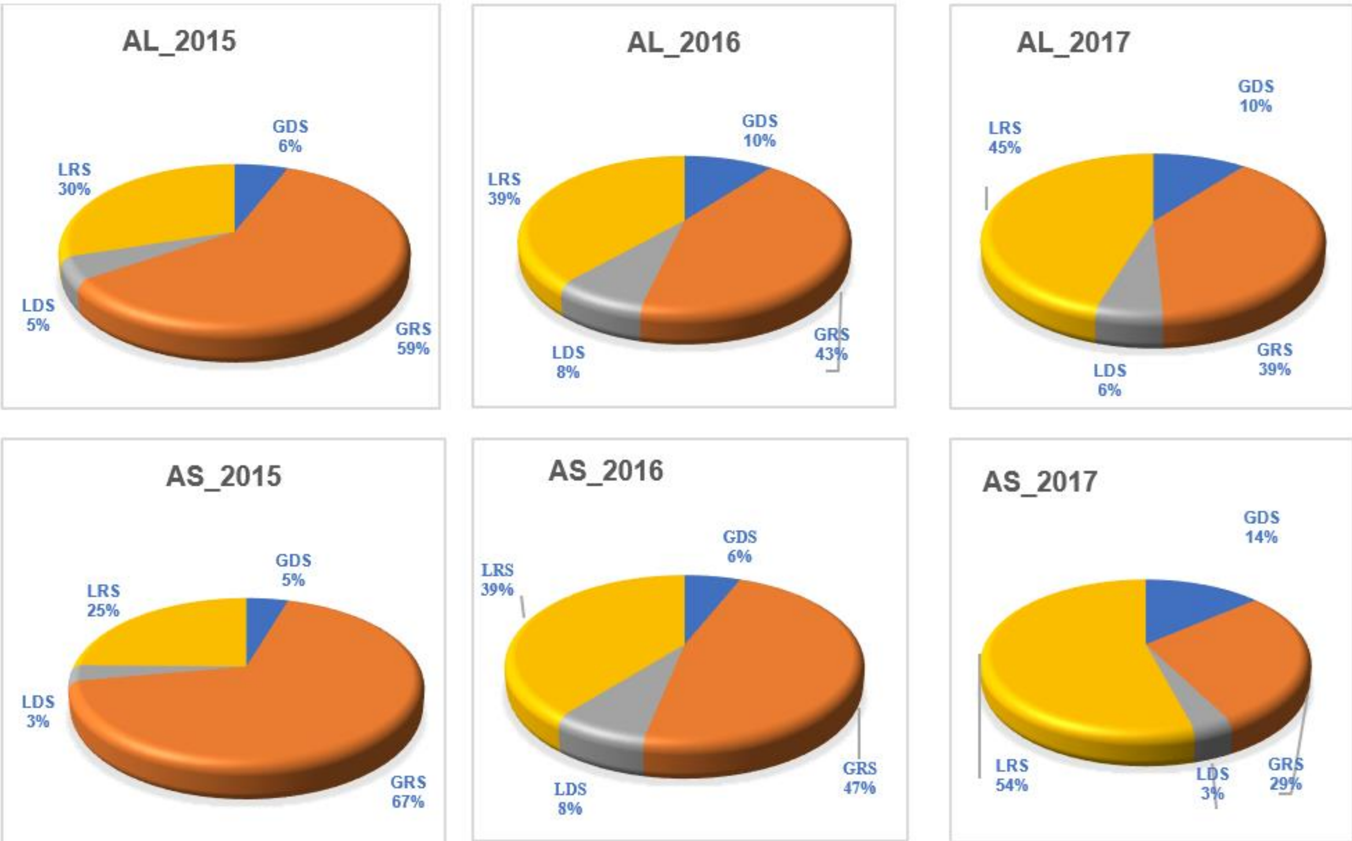

Fig. 13. Seasonal percentage contribution of liquid and solid inputs to the Mé sub-watershed (GRS: Great Rain Season; LRS: Little Rain Season; GDS: Great Dry Season; LDR: Little Dry season).

3.1.2.2 Monthly Distribution of Liquid and Solid Inputs of the Seasons

Variations in monthly liquid inputs and suspended solids loads provide insight into the overall tendency of the watershed to transport suspended solids. The inputs follow a bimodal regime, resulting in two maxima, one in the main rainy season and the other in the short rainy season.

The solid input to the Mé River basin is correlated with the flow, and in addition to this correlation, the two flows are linked. Low water and high water respect the bimodality of the flows.

The year 2015 in the Mé was marked by an exceptional flood in June of 600 cm, this flood led to a volume of 521 Hm^3 generating in its surge a very important solid contribution of 31.23 10^3 t, for a rate of 49.94% of total transport. The second high water occurred in the month of November, has contributed to him, up to 312.27 Hm^3 for a load carried by 14.69 10^3 t corresponding to 23.49%. The load of the two high waters accumulates more than 46.02 10^3 t of the annual contribution (62.54 10^3 t), that is to say a portion of 73.43 %. To the low waters are associated the minimum values that oscillate between 0.7 and 5 10^3 t.

2016 was a less rainy year, which had an impact on the flow, and since solid flows are strongly correlated to liquid flows, the decrease in flow leads to a drop in solid flows. The liquid flows recorded during high water reached their maximum in June with a value of 372.83 Hm^3 and 350.82 Hm^3 October. The solid load resulting from these liquid flows is 21.19 10^3 t and 20.56 10^3 t in June and October respectively. The two months carried a load 41.75 10^3 t or 3/4 of the annual transport (54.96 10^3 t). In addition, the lowest loads of suspended solids are associated with low water and the minimum is 0.48 10^3 t in February.

The 2017 runoff experienced a resurgence due to the resumption of precipitation, thus high water alone (June and July; October and November) contributed the bulk of the solids loads during 2017. The months of June and July total a transfer of liquid flow of 594.54 Hm^3; while those of October and November carried a liquid flow of 819.07 Hm^3, the cumulative of these four months is 1413.61 Hm^3 out of 1812.14 Hm^3 or a rate of 78%. These flows have evacuated significant masses of material flows 99.06 10^3 t out of an annual total of 125.5 10^3 t equivalent to a proportion of 78%. However, the minimum solid flow was observed in January with a value of 0.49 10^3 t (Figure 14).

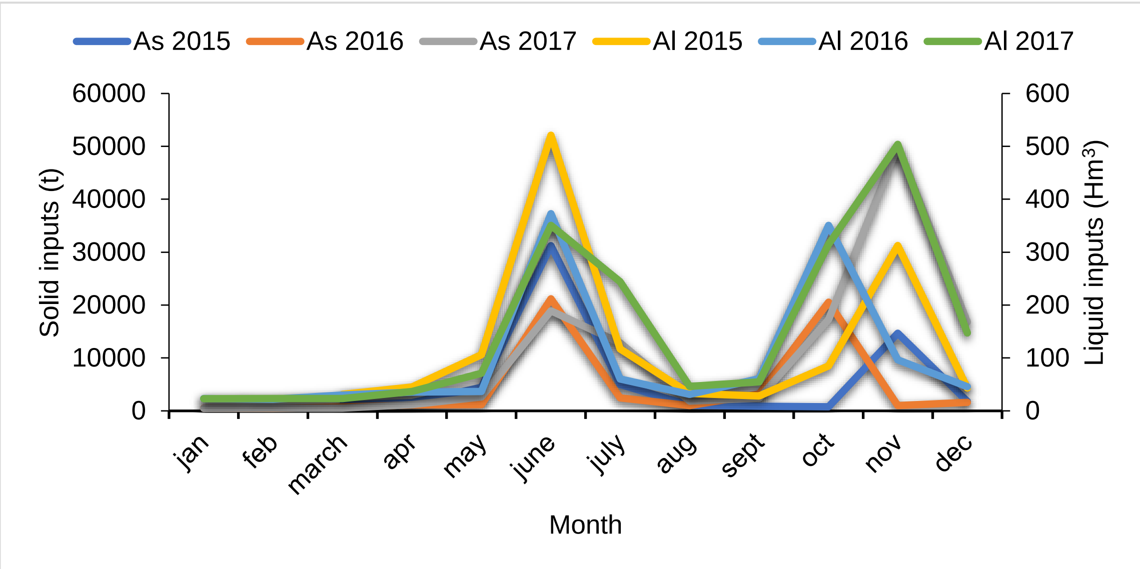

Fig. 14. Monthly Variation of Liquid and Solid Inputs to the Mé River.

3.1.2.3 Monthly Variation of Solid Inputs

Figure 15 highlights the variation in the months of the season's solid contributions to the during the study period in percentage. The average monthly contribution reaches its maximum in June on all the stations and also on the period of study mirror, of a bimodal regime. From the Mé the trend increases from year to year. The observed maxima of 2015, 2016 and 2017 are 41%, 47% and 46% at the Mé.

The study period contribution of some months in solids input does not exceed 2% of the annual total on the Mé. While only August can contribute 8-10% of the annual total in solids.

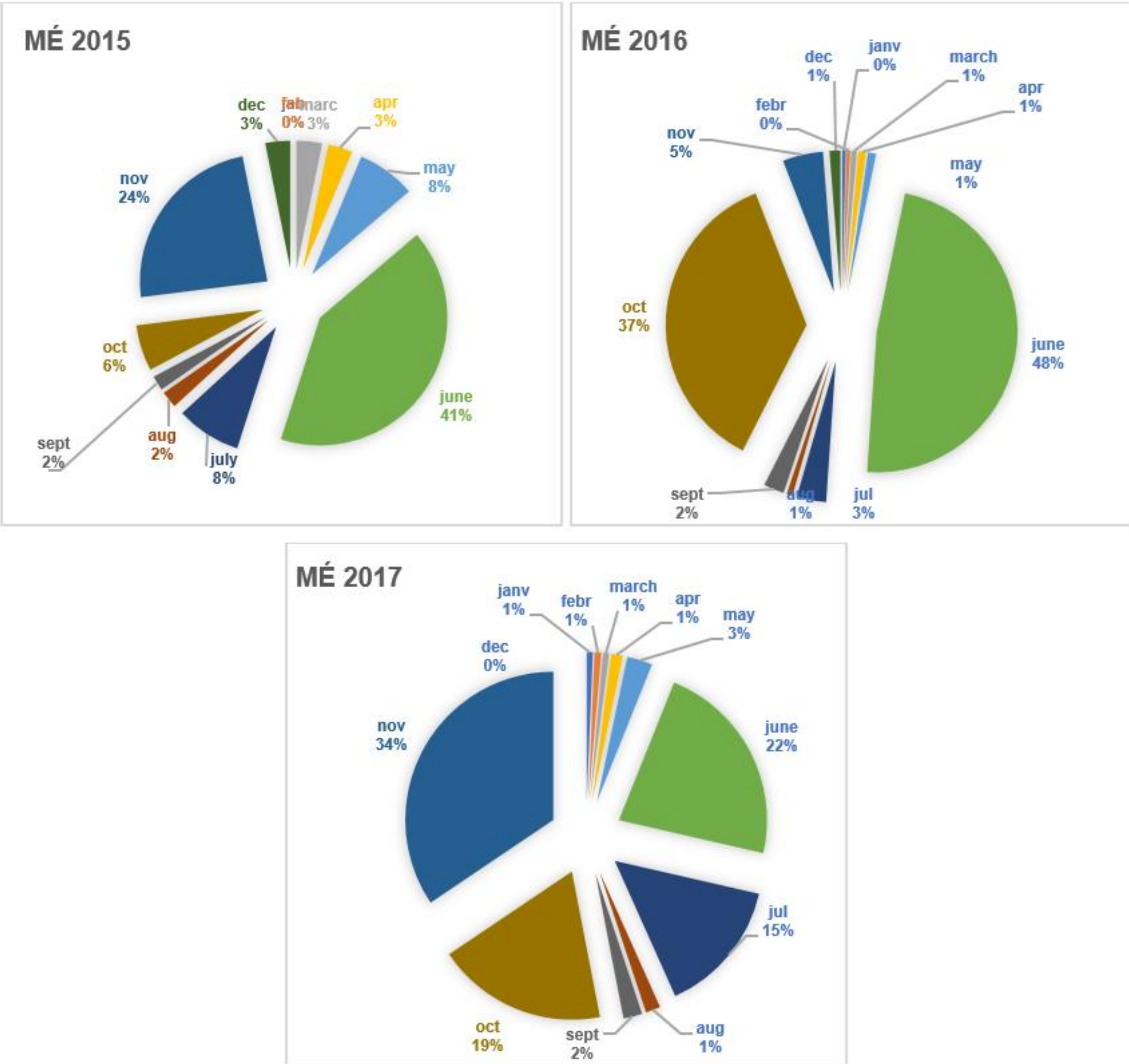

Fig. 15. Distribution of monthly solid inputs in percent.

3.1.2.4 MONTHLY VARIATION IN SOLID INTAKE PER PORTION

Variations in liquid inputs and suspended solids loads provide insight into the sediment produced by the Mé. Inputs follow a bimodal regime, one in the main rainy season and the other in the short rainy season. In general, monthly variations in sediment transport closely follow those in runoff. The complete series were used to calculate the monthly variation of suspended solids inputs in each of the watersheds.

The 2015 year at Me was marked by an exceptional 6 m high flood on June 16, 2015. The average flow recorded in June was 202.2 m^3 /s. The volume of water is estimated at $521.1.10^6$ m^3 generating in its surge a very important solid load of $1.09.10^6$ t, for a rate of 49.60% of total transport. The second high water occurred in November, has contributed to the height of $312.27.10^6$ m^3 for a load of $539.38.10^3$ t corresponding to 24.55%. The cumulative load by the two high waters is $1,63.10^3$ t of the annual contribution ($2,20.10^3$ t) that is to say of 14,15 % of this contribution. The minimum values which oscillate between 6,67 and $13,7.10^3$ t are met most in low water.

2016 was a less rainy year, which had an impact on the flow, and since solid flows are strongly correlated to liquid flows, the decrease in flow seems to induce a drop in solid flows. The liquid flows recorded during high water reached their maximum in June with a value of 373.89.10 m6 3 and 350.82.10^6 m^3 October. The solid load resulting from these liquid flows is 712.65.10^3 t and 604.57.103 t in June and October respectively. The two months carried a load 1.32.10^3 t or 72.9% of the annual transport (1.81.10^6 t). In addition, the lowest suspended solids load appears to be associated with low water and the minimum is 19.86.103 t in February.

The 2017 runoff experienced an increase over the 2016 runoff due to the recovery of precipitation. Thus, the two high waters alone (June and July; October and November) carried the bulk of the solids loads during 2017. The first high water (June and July) carried a liquid flow contribution of 594.54.10^6 m^3 (32.73%); while, the second high water (October and November) carried a water volume of 819.07.10^6 m^3 (45.09%). The cumulative total for these four months is 1.41.10^9 m^3 out of 1.81.10^9 m^3 or a rate of 77.81%. These flows carried a significant load of material flow 2.54.10^6 t, a rate of 83.11% on an annual total of 3.06.10^6 t (Table 2).

Table 2. Monthly and annual loads of solids inputs to the Mé (S = 395805.9 ha).

		Jan.	Feb.	march	apr.	may	June	july	Aug.	sept	oct.	nov.	dec.	total
2015	P (mm)		90,7				453	62,5	41	8,4		235	18,6	909,2
	Al (10^9 m^3)			31,45	45,03	106,37	521,1	117,32	33,11	28,23	84,85	312,27	47,385	1,28
	C (mg/L)			31,56	31,88	37,54	56,3	37,99	28,7	27,7	35,59	50,19	30,96	36,841
	As (kg/s)			0,58	0,63	1,68	12,61	1,83	0,36	0,31	1,19	6,24	0,57	25,42
	Flux (10^6 t)			50,03	54,24	145,01	1089,5	158,21	30,74	26,4	103,18	539,38	49,3	2,20
	Ass (t/ha)			0,13	0,14	0,37	2,75	0,40	0,08	0,07	0,26	1,36	0,12	5,55
2016	P (mm)	19		141,5	86,5	192	396	32	102	124,9	171,6	130	85	1480,5
	Al (10^9 m^3)	23,31	21,98	30,2	35,99	37,21	373,89	60,58	31,47	61,01	350,82	96,47	45,68	1,15
	C (mg/L)	26,26	26,32	27,97	29,51	29,21	49,58	30,92	28,17	32,98	51,02	37,28	30,88	33,34
	As (kg/s)	0,23	0,23	0,32	0,41	0,42	8,25	0,9	0,34	0,83	7	1,45	0,54	20,91
	Flux (10^6 t)	19,86	20,04	27,53	35,62	36,4	712,65	77,6	29,15	71,83	604,57	125,02	46,52	1,81
	Ass (t/ha)	0,05	0,05	0,07	0,09	0,09	1,80	0,20	0,07	0,18	1,53	0,32	0,12	4,56
2017	P (mm)	10,5	87	31,5	181,5	255	367	86	68,50	213,50	338,5	178	91,5	1908,5
	Al (10^9 m^3)	23,01	23,23	23,24	36,67	71,2	350,59	243,95	46,23	54,83	315,22	503,85	147,69	1,82
	C (mg/L)	26,15	26,89	26,22	29,42	34,49	50,86	43,48	30,94	32,75	49,87	56,92	38,44	37,2
	As (kg/s)	0,23	0,26	0,23	0,43	0,94	7,31	4,79	0,55	0,7	6,07	11,26	2,65	35,41
	Flux (10^6 t)	19,6	22,5	19,8	37,1	81,12	631,37	413,8	47,4	60,5	524,6	973,08	228,8	3,06
	Ass (t/ha)	0,05	0,06	0,05	0,09	0,21	1,60	1,05	0,12	0,15	1,33	2,46	0,58	7,73

Al: Liquid input; As: Solid input; C: Concentration of suspended matter; Ass: Specific solid input.

3.1.2.5 ANNUAL VARIATION OF THE SOLID CONTRIBUTION

The annual variation of the solid contributions shows a great irregularity during the year. This variation is linked to the precipitation, to the morpho-geological nature, to the presence of the vegetation cover, to the cultivation activities and especially to the nature of the slopes which are vectors of the speed of the runoff.

The contribution of solid flows is important and this is due to the aggressiveness of precipitation on soils without vegetation cover and easily disintegrated and with fairly steep slopes, thus conveying significant quantities of suspended matter through runoff. These inputs are even stronger when rainfall is abundant.

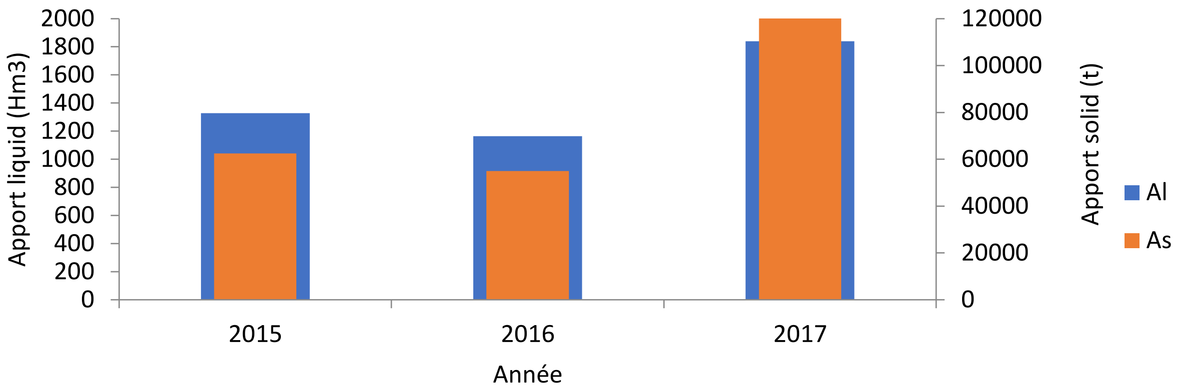

Fig. 16. Annual Liquid and Solid Inputs to the Mé.

Table 3 is a summary of annual material flows and solid inputs to the Mé River. Over the 2015-2017 period, the Mé River contributed huge amounts of material.

Table 3. Annual input balance of suspended solids quantities.

Station	Flux	2015	2016	2017	Total
Mé	Apport solid (10^3t)	62.54	54.96	125.49	242.99
	Proportion (%)	25.74	22.61	51.64	100
	Apport liquid (Hm^3)	1327.12	1164.93	1812.14	4304.20
	Proportion (%)	30.83	27.06	42.10	100

3.1.2.6 Specific Degradation of Solid Inputs

3.1.2.6.1 Monthly

Figure 17 shows the monthly specific inputs at the watershed level of the Mé River are bimodal. The first peaks are observed in June during the big rainy season, the values are 7.89 t/km^{2,} 5.35 t/km^2 and 4.78 t/km^2 respectively in 2015, 2016 and 2017. The second are observed in number and October in the short rainy season. In 2015 and 2017, the high values of specific inputs are 3.71 t/km^2 and 12.64 t/km^{2}and that in November. In 2016, in the month of October the inputs are 5.20 t/km^2. The low values of specific contributions are observed great and small dry season.

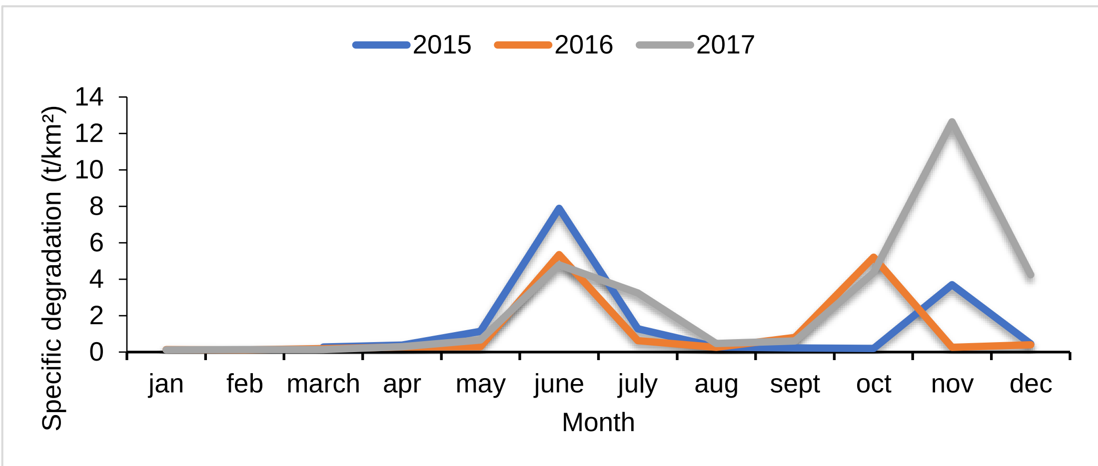

Fig. 17. Specific flow of monthly solid inputs to the Mé River.

3.1.2.6.2 ANNUAL

Figure 18 shows the specific input from the watersheds. The interannual average is 59.07 t/km^2/year (Table 4). The Mé carried a considerable amount of suspended matter in 2017. The low solid input from the Mé is largely due to the low rainfall in 2016

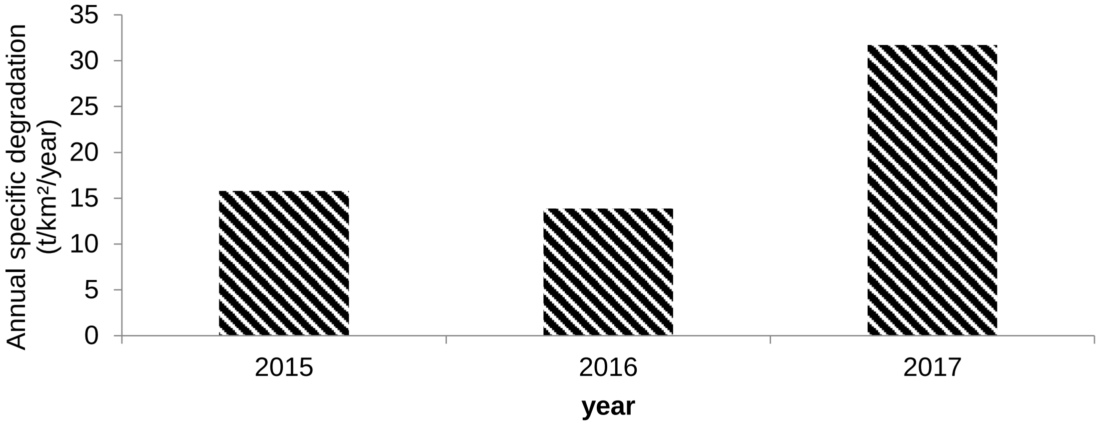

Fig. 18. Annual Specific Degradation.

Table 4. Summary of suspended solids exports (SSE in t/km²/year), flood runoff (FR in mm) and annual precipitation (AP in mm) for the 3 watersheds during the 2015 to 2017 wet seasons.

Period	Mé		
	SSE t/km²/an	FR (mm)	AP (mm)
2015	15.8	417	2087
2016	13.89	295.6	1480.5
2017	31.71	479.2	1908.5
Average 2015-2017	20.46	397.3	1694.5

4 DISCUSSION

Seasonal variation in solids loads to the Mé over the study period indicates that solids inputs are high during the long and short rainy seasons. Similarly, concentrations of suspended solids from the rainy seasons are high. High solids loads were recorded mainly during the long rainy season on all the rivers.

On the Mé, during 2015 and 2016, we observed two high waters concentrated in just two months. The first flood of the main rainy season is in June, with a solid load of 1.09.10^6 t/month in 2015 and 0.71.10^6 t/month in 2016. The second flood is recorded in November with a value of 0.5410^6 t/month in 2015 and in October with a value of 0.60.10^6 t/month in 2016. The months of June and November 2015 accumulated a rate of 74.10%, of which 49.55% was attributed to June and 24.55% to November. The cumulative share is 72.38%, June 39.23% and October 33.15%. The annual solid load is 2.20.10^6 t/year for a specific degradation of 5.55 t/ha/year. The solid load transported in 2016 was 1.81.10^6 t/year, with a specific degradation of 4.56 t/ha/year. 2017 was an exceptional year, with most of the solid load transport concentrated in four months (June, July, October and November). Monthly solid loads in 2017 were 0.63.10^6 t/month in June, 0.41.10^6 t/month in July, 0.5210^6 t/month in October and 0.9710^6 t/month in November. During the months of June, July, October and November, rainfall is significant and contributes to a considerable increase in sediment transport. As an indication, 82.68% of the solid load was transported during these four months: 20.59% in June, 13.40% in July, 17% in October and 31.70% in November. The accumulation of the first flood corresponding to the long rainy season was less than that of the second flood centred on the short rainy season. The annual solid load of the Mé was 2196.69.10^3 t/year, 1806.77.10^3 t/year and 3059.57.10^3 t/year in 2015, 2016 and 2017 respectively. The specific degradation due to solid loads was 5.55 t/ha/yr in 2015, 4.56 t/ha/yr in 2016 and 7.73 t/ha/yr in 2017.

The solid transport values estimated for the Mé are relatively low compared with those of [4] in the Oued Isser catchment area at the Koudiat Acerdoune dam (northern Algeria), which is of the order of 5.965 Mt, i.e. a surface degradation of 2141.652 t/km^{-2}/year, which is much higher than the specific degradation values for the Mé However, the work of [32] in a semi-arid basin (case of the upstream oued Mellegue), eastern Algeria, estimated solid transport at 56.10^4 t/yr, a relatively high value compared with that of the Mé, but a specific degradation of 161 t/km^2/year, a value much higher than that of the Mé.

The long rainy season brought less solid load than the short rainy season. Indeed, after a long dry season, the first rains find the soil dry and hard, which is difficult to erode [33]. The basin's response in terms of suspended solids is therefore less significant. On the other hand, the rains in October and November will pull up large quantities of solid matter, as the soil has become soft. The rainy seasons, on the other hand, have high concentrations of suspended solids because the soil is washed away by the rains. During the flood season (June), high concentrations of suspended solids are observed. The lowest concentrations are observed during the flood season (October and November). This may be due to the fact that the first rains wash away the bare or ploughed soil. These rains wash away some of the detrital material available on the soil surface. As the rain persists, all the less resistant detritic material is completely washed away. This is a classic development observed in most rivers in the Sudanian climate zone ([34]; [35]). The solid loads transported in high water are greater than those in low water. The specific degradation observed over the study period is significant in the Mé. The decrease in annual specific degradation with an increase in the surface area of the catchment may be due to a change in the ratio between the sediment removed from the slopes and the bed of the watercourse and the quantity of material that remains trapped in the catchment before reaching the outlet because of discontinuities and dead arms in the watercourse. When the surface area of catchment areas increases, the proportion of low-gradient areas (valley bottoms, floodplains) increases, thus favouring sedimentation phenomena. In addition, the sediment loads estimated over the three (3) years of the study (2015, 2016 and 2017) indicate that 2015 and 2017 were characterised by very high solid inputs. This could be explained by the abundance of exceptional floods in terms of volume and duration. On the other hand, the low solid input observed in 2016 at the Mé could be explained by the low rainfall recorded. The sediment input could be contributing to the silting up of the Aghien lagoon water body. In addition, most of the sediment or fine particles transported from upstream to downstream in the basin do not all reach the outlet of the Mé. A large proportion of the particles are deposited at the bottom of the lagoon due to the low slopes and speed of the lagoon water, causing it to fill in. According to [36], the transport of suspended matter is the main cause of the filling of water reservoirs.

5 CONCLUSION

Suspended solids transport in the Mé River watershed was calculated over the four seasons, namely the long and short rainy season and the long and short dry season. The solid flows vary according to the liquid flows according to a power law. From this relationship, the solid flow was extrapolated. The annual tonnage of solids loads transiting through the Mé was deduced from the power law for all seasons. From this deduction, the annual quantities of sediment transported by the Mé from 2015/2017 is $7.06.10^6$ t/year, or a specific degradation of $1.79.10^3$ t/km^2/year. On the other hand, in 2017, the value of this solid input is $3.06.10^6$ t/year. The results of the suspended solids analysis identified the different seasonal inputs. However, the annual solid input is estimated at $7063.03.10^3$ t/year with a specific degradation of 1784.47 t/km^2/year at the Mé from 2015 to 2017.

COMPETING INTERESTS

The contact author has declared that neither they nor their co-authors have any competing interests.

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CONTRIBUTIONS OF THE AUTHORS

Ehouman Serge Koffi wrote the manuscript with the data collected and compiled with Hydraccess software by Ehouman Serge Koffi and Maurice Guilliod. Dabissi Djibril Noufé, Bamory Kamagaté, Lanciné Droh Goné are the initiators of the "Lagune Aghien" project. Luc Séguis and Jean-Louis Perrin are our research partners in the Aghien Lagoon project. Anzoumanan Kamagaté and Amidou Dao helped to read and correct the paper.

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