



Dynamics of fluvial suspended sediment transport and yield in volcanic highland's agricultural basin: case of the Noun River, Western Cameroon

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Abstract

The dynamics of suspended sediment transport in the Noun River has been quantified using 93 runoff samples. Daily flow and monthly normalized difference vegetation index (NDVI), leaf area index (LAI), rainfall, and dam management data allowed the quantification of the total suspended solid (TSS), on the one hand, and the interpretation of the dynamics of solid transport within the drainage basin, on the other hand. The TSS concentrations range from 3 to 1375 mg L⁻¹ for a volume weighted mean concentration of 90.33 to 110.49 mg L⁻¹ and a specific sediment yield (SSY) of 41 to 57 t km⁻² year⁻¹. The basin's hydrological characteristics between March to June and December to February have been reversed, revealing a strong impact of a dam. The maximum TSS concentration obtained during the second hydrological year at the beginning of the rainy season (April) is paradoxically three times higher compared to that recorded in July during the first measurement period. This occasional high TSS concentration for the single month of April released sedimentary fluxes superior to those recorded over the period of July to November combined, in comparison to those obtained during the first year. This situation causes sediment depletion not only on the next regular maximum TSS concentrations but also on the quantities of sediments exported later. The monthly TSS concentration/discharge does not present a clockwise hysteresis curve observed on tropical streams such as the Mbam and Sanaga in Ebebeda, with annual variations in its evolution.

Keywords Noun River · Total suspended solid · NDVI/LAI · Sediment stock · Hysteresis curve · Bamendjin dam

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Introduction

River catchments degradation is one of the most important contemporary environmental problems affecting water quality in tropical countries (Masocha et al. 2017). High amounts of suspended solids in rivers can affect their ecology. In agricultural basins, measurement of fluvial solid transport can be used to quantify and predict the decline in soil fertility and hence proposes better anti-erosion techniques. Therefore, effective monitoring and analysis of the hydrologic, transport, and deposition variables are required (Bezak et al. 2015, Boulesteix et al. 2019). There is growing interest in understanding the dynamics of TSS in small basins of variable lithic and anthropogenic nature, either subjected to the practice of intensive or regulated agriculture (Lefrançois et al. 2007; Casali et al. 2008; Lopez-Tarazon et al. 2009; McDonald and Lamoureux 2009) or subjected to contrasting climatic conditions (Scheurer et al. 2009; Mano et al. 2009; Fang et al. 2011). In Cameroon, the first solid transport measurements were carried out in the northern part of the country in 1955–1956. These measurements made it possible to appraise qualitative trends in the phenomenon of erosion. Toward the end of the 1960s, hydrologists from ORSTOM-Yaoundé, notably Cadier, Lefèvre, and Nouvelot, developed an appropriate methodology for studying suspended solid transport in the Cameroonian climate context. Thus, some measurement campaigns were then carried out, mainly on the watersheds of the Sanaga at Nachtigal, from Mbam at Goura (tropical transition zone) and from Mayo Tsanaga at Bogo (tropical area). The results have been the subject of several publications (Nouvelot 1969, 1972a, b; Olivry et al. 1974; Olivry and Hoorelbecke 1975; Olivry 1976, 1977, 1978). Subsequent measurements were carried out during development projects such as the construction of the Menve'ele hydroelectric dam on the Ntem and the water supply of 25 urban centers (Boum et al. 1983), the Gulli hydroelectric dam project on the Mentchum (Tanyileke 1988), the Yaere project (Naah 1990), and the Lom-Pangar reservoir on the Lom (Sigha-Nkamdjou et al. 1998). Other measures have been carried out, particularly in the southern zone, in the framework of regional programs such as Program on the Environment of the Intertropical Geosphere (PEIG), DYNAMIC of LATÉritic Covers (DYLAT) and Soil-Erosion-Program (PROSE) on hydrobiogeochemical cycles (Sigha-Nkamdjou 1994; Olivie-Lauquet 1996; Ndam Ngoupayou 1997; Viers et al. 1997; Braun et al. 1998), African and Malagasy Cooperation for University and Scientific Promotion (CAMPUS), and currently Regional Observatory of the Environment-Basic or Experimental Watershed (ORE-BVET). Worth of mention is the ex-campus CORUS program on tropical water dynamics with an example of the Nyong upstream basin (Boeglin et al. 2000; Nkoué Ndondo 2008). The project aimed at understanding the impact of climate and anthropogenic variability on water resources and the transport of suspended solids from some representative basins of climate units in Cameroon, leading to

numerous publications (Liéno et al. 2005a, c; 2009; Ndam Ngoupayou et al. 2007a, b; Kpoumié 2015; Ndam Ngoupayou et al. 2016). Focusing on the Cameroonian ecosystems, it appears that the decline of vegetation cover has a predominant influence on the solid load of rivers. Thus, the vegetation gradient is superimposed from south to north on inverse gradient of TSS concentration (Liéno et al. 2005a). Also, solid transport has been impacted by the decrease in precipitation preceding not only that of discharges (Liéno et al. 2009; Ndam Ngoupayou et al. 2016) and land use changes but also differentiated impacts of dams established on the course of some rivers (Ndam Ngoupayou et al. 2016). However, information on the concentrations of suspended solids in Cameroon's agricultural catchment areas is scarce, especially on the Noun River. Only the watershed of Mouda in northern Cameroon (Sahelian climate) has been the subject of such investigations (Thébé 1987). Studies carried out (Nouvelot 1969; Olivry et al. 1974, 1988; Ndam Ngoupayou 1997; Ndam Ngoupayou et al. 2016) on the solid transports of the two main tributaries (Mbam and Sanaga before confluence with Mbam) of the Sanaga River indicate notable differences between the two rivers. Mbam's solid transport is entirely conditioned by those of Noun River (tributary of Mbam's right bank, which drains the Bamileke and Bamoun regions). However, no measurement campaign covering a hydrological year has been carried out or published on this important watercourse which as follows: (1) crosscut volcanic formations, (2) has been intensely reworked by agricultural activities, and (3) is regulated on its main course by a hydraulic structure (Bamendjin dam). Also, recent studies on the temporal evolution of solid transport in West (Aka et al. 2008) and Central (Liéno et al. 2009) Africa did not consider the land use evolution, which is one of the key factors explaining the dynamics of solid transport (Soro et al. 2013; He et al. 2016), hence, the importance of this study which allows quantification by long-term and continuous field measurement of the solid transport of this agricultural, volcanic, and regulated basin of Central Africa where tropical mountain climate prevails. This study is also a major contribution to the understanding of the solid transport dynamics of the intensively cultivated tropical African mountain zone, by coupling monthly-annual remote sensing and field data.

Study area

The Noun River basin (4740 km²), in the western region of Cameroon (Central Africa), is located between latitudes 5° N and 6° N and longitudes 10° E and 11° 05' E (Fig. 1). It has its source on the side of Mount Oku (3011 m) on the lavas of the highland around 2600 m above sea level. It runs for 269 km and sags in a vast marshy drainage basin closed by the Bamendjin dam (Dubreuil et al. 1975). The study area belongs to the western highlands, which is divided into two parts: the Bamileke (1400 to 1600 m) and the Bamoun (1100 to 1200 m)

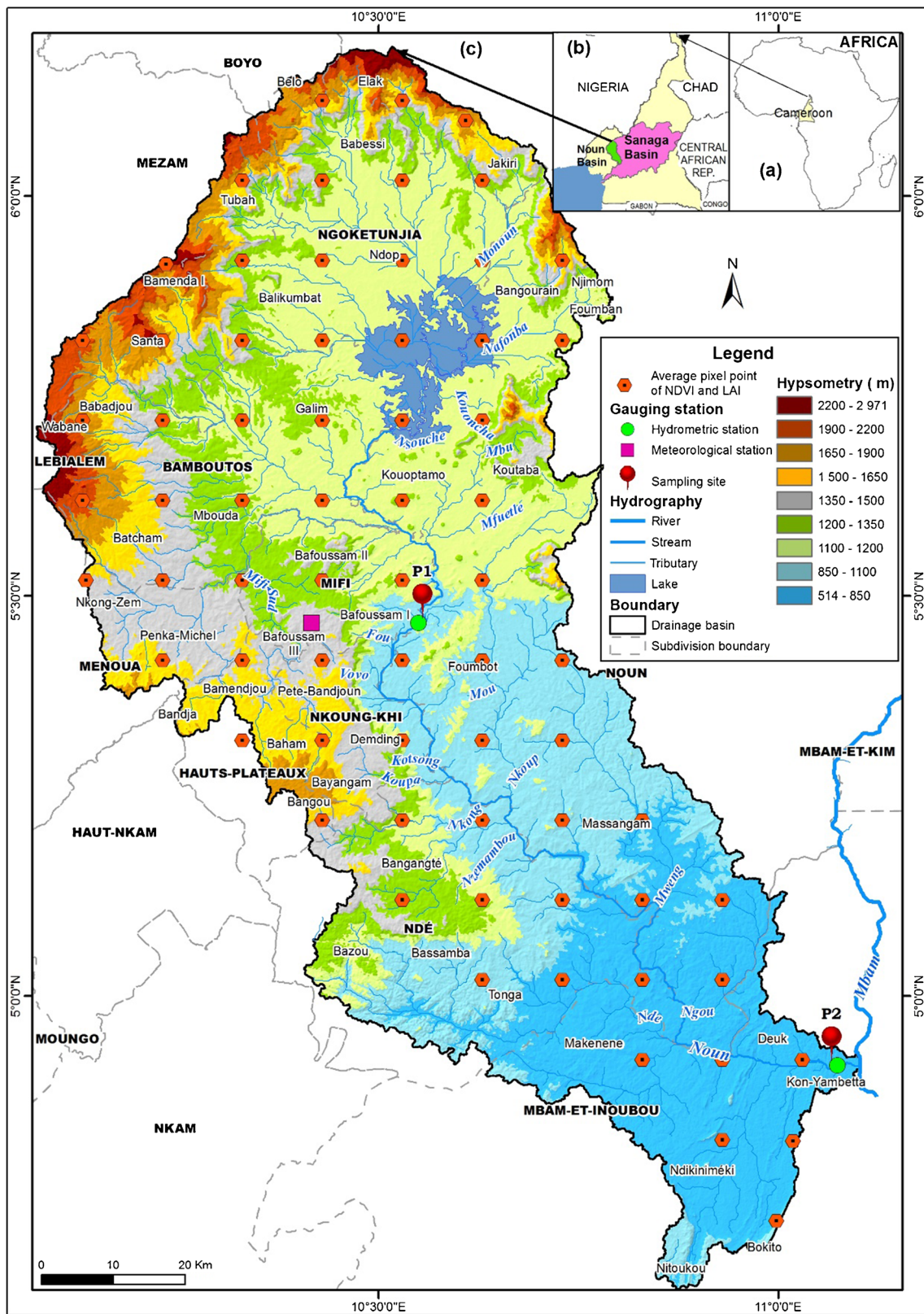


Fig. 1 Location of the Cameroon in Central Africa (a); the Sanaga and Noun basins within Cameroon (b); the Noun River basin in West Cameroon with the meteorological and hydrometric stations, the sampling sites (T1 and T2); and average pixel points of NDVI and LAI used in this study (c)

plateaus. Some of the Noun tributaries on the right bank are North Mifi, South Mifi, Nkong, Ngam, Nde, and Manoui and those on the left bank are Nafoumba, Mou, Nkoup, and Mwing. After receiving the Ndé right bank, following the east direction, the Noun flows for 25 km into Mbam at the Bayomen locality (9754 km²), at an altitude of 525 m. This confluence point is one of the currently functional flow measurements and control stations on the network of Cameroon hydrometric stations. The Noun has been regulated since 1974 on its upstream part by the Bamendjin dam (Fig. 1).

The regional geology is dominated by Neoproterozoic basement (Nguessi 1994; Tagne 1994; Tchouankoue et al. 1994; Tchakounté et al. 2018), with prevalence of granites and gneisses. The recent geological formations comprise volcanic rocks, mainly basalts and pyroclastic ashes and lapilli. Alluvial material caps most of the low-lying terrain in the study area (Fig. 2). Soils are young, hydromorphic and mainly ferrallitic, fairly desaturated, and of high fertility attributed to volcanic parent material. The vegetation consists of woody savannah and is green throughout the year (Njonfang et al. 2008). The climate is of monsoon subequatorial type (pseudotropical) with alternating rainy seasons (March–November) and a dry season (December–February) for an annual precipitation average of about 1400 mm (Fig. 3).

Materials and methods

The methodology applied in this study involved the combined analysis of hydroclimatological and suspended solids data obtained in the field with satellite imagery to quantify and elucidate the dynamics of solid transport in the Noun catchment area in Cameroon. It is centered around (1) sampling of surface runoff at the Bafoussam and Bayomen stations along the Noun stream; (2) filtration of the different samples in the laboratory in order to quantify their suspended solid concentrations; (3) collection of rainfall and flow rate data at the same stations; (4) then mathematical quantification of the solid component flux, using empirical formulae adapted to tropical rivers; and finally (5) inferring the dynamics of solid transport following the land use patterns and water management at the Bamendjin dam.

Hydroclimatological data

Monthly rainfall from the Bafoussam station covering the period from 1944 to 2014 and daily discharge at the Bayomen station (longitude 11° 05' E, latitude 4° 55' N, altitude 525 m) from January 1, 2005 to December 31, 2014 constituted input data. This hydrometric station drains the entire Noun watershed with an area of 9754 km² (see Fig. 1). The data set was obtained from the Cameroon National Meteorology Directorate for rainfall data and the company in charge of

the hydroelectric production (Enéo) for discharge. The Bayomen station is equipped with a Direct Reading staff gage. The daily discharges obtained are deduced from the daily average of water levels compared to a pre-calibrated rating curve of the gauging station. To minimize errors or uncertainties in the measurements, the hydrometric stations are regularly re-calibrated.

Total suspended sediments (TSS)

Between December 2010 and December 2014, 93 water samples were collected from the Noun River, at Bafoussam (latitude 5° 28' 48, 6" N; longitude 10° 33' 12, 8" E; altitude 960 m) on a bi-weekly to twice a month frequency, and in the Bayomen station (longitude 11° 05' E, latitude 4° 55' N, altitude 525 m), during the different stages of discharge rise and fall. The first point (T1) is located at the Noun Bridge on the national road No. 6 between the localities of Bafoussam and Foubot, and the second point (T2) is located at the outlet of the Noun Watershed. Eighty-eight water samples were collected at the first point (T1) between December 2010 and August 2013, and 5 (five) control water samples were also taken at the second point (T2) during the year 2014 with the aim of validating the TSS flows evacuated at this station compared to the fluxes calculated from the concentrations obtained in point T1. The water samples were collected along the same longitude and at the surface, preferentially where the flow velocity was high enough to allow for good homogenization of solid particles of different sizes (Nouvelot 1969; Olivry et al. 1974; Ndam Ngoupayou 1997; Liéno et al. 2005a, b, 2009; Nkoué Ndondo 2008; Ndam Ngoupayou et al. 2016). This technique was developed by ORSTOM/IRD ORSTOM hydrologists in the late 1960s. In fact, for the large streams of the tropical zone of Africa, including those of Cameroon, the technique of sampling along one vertical which, besides, is rather simple, fast, and practical and gives results that are satisfactory and relatively close to those of the full solid gauging method (Nouvelot 1972a, b; Olivry et al. 1988; Liéno et al. 2005a, b; Sigha-Nkamdjou et al. 2005).

In the laboratory, the different water samples were filtered with cellulose acetate 0.45 µm membranes using a polycarbonate Millipore filtration unit. Particulate fractions retained were dried in the oven at 105 °C, then weighted on a Mettler type balance (0.1 mg of precision), after passage through a desiccator.

The instantaneous TSS concentration (C_i) was assessed from the difference in weight between the loaded filter (M2) and the virgin filter before filtration (M1) on the volume of water brought to 10³ mL. Thus, this TSS concentration is obtained as shown in Eq. (1) below:

$$C_i = (M2 - M1) / V \quad (1)$$

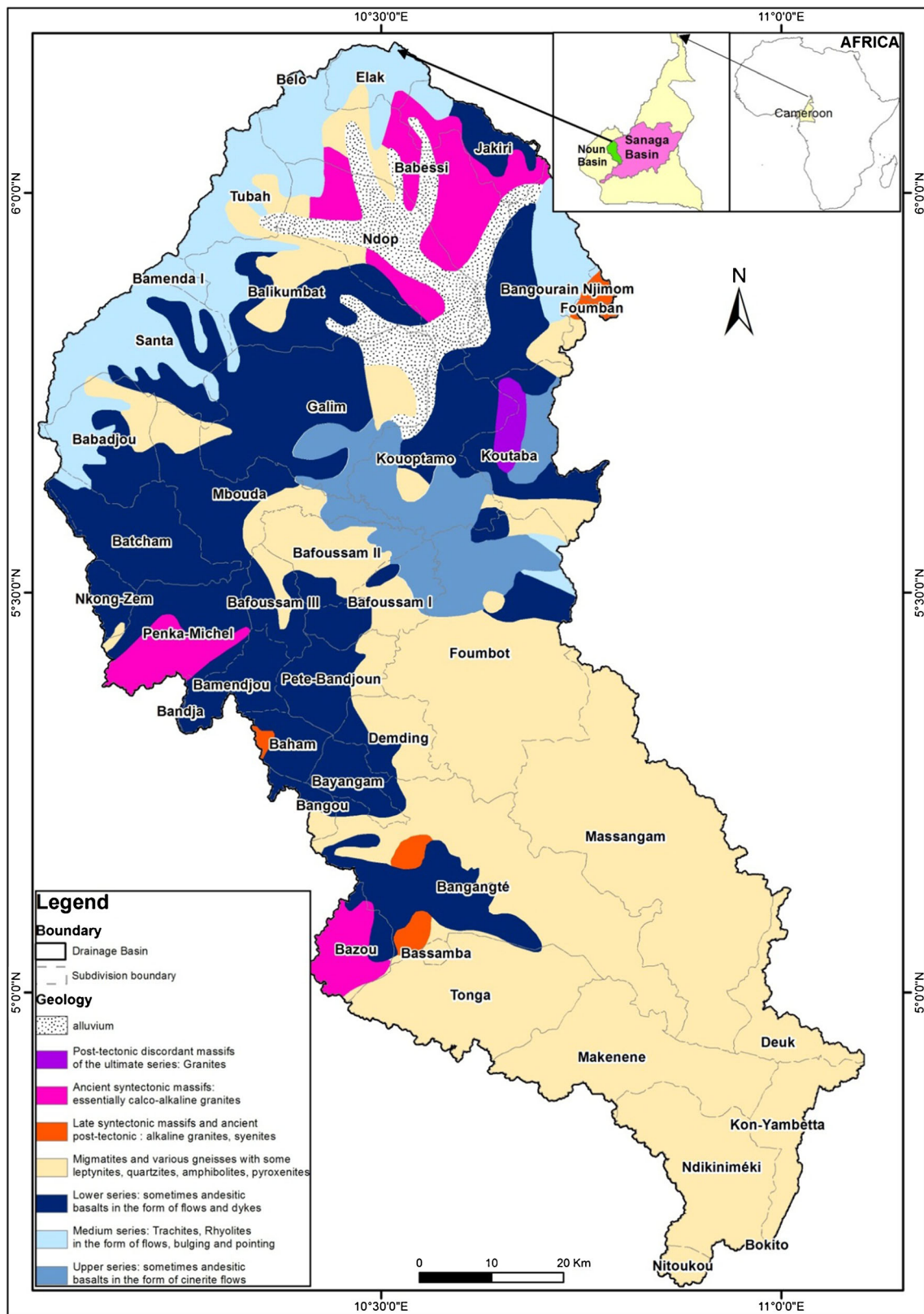
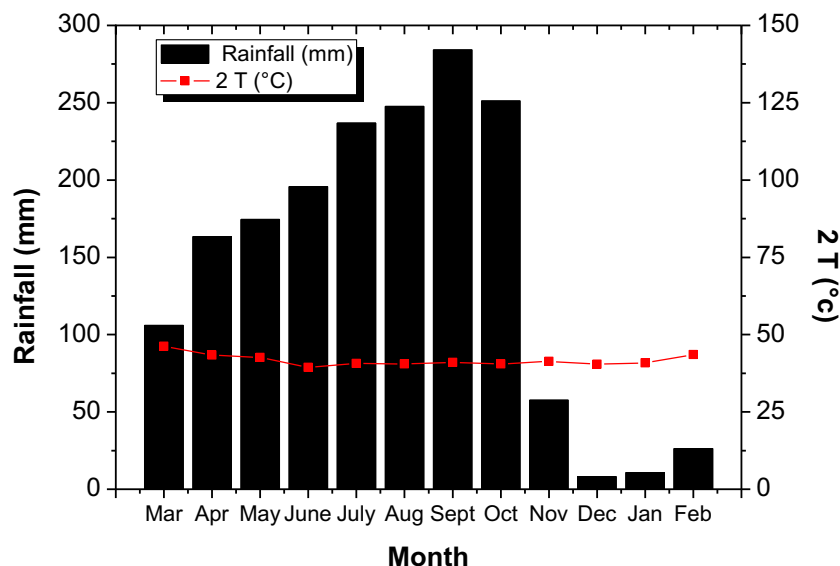


Fig. 2 Geological map of the Noun River basin

where C_i = the instantaneous TSS concentration (mg L^{-1}), $M1$ = the mass or the weight of the filter after filtration and drying (mg), and V = the volume of water filtered (mL).

Fig. 3 Ombrothermal diagram at the Bafoussam station (mountainous tropical climate of the West), 1944–2014 (according Bangouls and Gaussen 1969)



For this procedure, Maneux (1998) calculated a theoretical error of 5%, when suspended sediment concentration obtained is less or equal to 10 mg L^{-1} and of 3% for more than 10 mg L^{-1} .

The determination of the volume weighted mean (VWM) concentration of TSS for a given period was made using the partial balance equation, which fits best for streams transporting the greatest part of their solid load during high flows (Walling and Webb 1981). This is formulated as follows:

$$C_{\text{VWM}} = \frac{\sum_{i=1}^n C_i V_i}{\sum_{i=1}^n V_i} \quad (2)$$

where C_{VWM} = the volume weighted mean (VWM) concentration of TSS (mg L^{-1}), C_i = the instantaneous concentration (mg L^{-1}), and V_i = the discharge volume of water (L) for the period between two successive samplings. The denominator is the whole sampling period discharge volume.

The suspended sediment yields (SY) exported annually out of drainage basins are usually calculated from the VWM concentration and the total volume of flow (V_{TY}) for the year. The equation used here is formulated as follows:

$$\text{SY} (\text{t year}^{-1}) = C_{\text{VWM}} \cdot V_{\text{TY}} \quad (3)$$

The specific sediment yield (SSY) and the physical denudation rate (DR_{ph}), which conventionally expresses the amount of ground lowering for the whole catchment, are then obtained respectively using Eqs. (4) and (5) given below (Martin and Meybeck 1979; Walling and Webb 1981; Boeglin and Probst 1996; Meybeck et al. 1996), which are perfectly adapted to tropical streams:

$$\text{SSY} (\text{t km}^{-2} \text{ year}^{-1}) = \text{SY}/A = C_{\text{VWM}} \cdot R \quad (4)$$

where A = the catchment area (km^2) at the sampling site and R = the annual runoff (mm).

$$\text{DR}_{\text{ph}} (\text{mm kyear}^{-1}) = \text{SSY}/D \quad (5)$$

where D = the density of soil exposed to mechanical erosion (Nuzhat and Shive 2017) in g m^{-3} .

Acquisition of Landsat ETM+ image and geoprocessing

The land use data set was obtained from a Landsat ETM+ image scene from December 2010, which can be downloaded free of charge from the Glovis US site: <http://glovis.usgs.gov/>. For the equatorial zones, the dry season is recommended for the acquisition of such images in order to avoid the cloud covers which complicate image treatment. The image consists of 7 spectral bands, which have undergone a preliminary scrapes correction pretreatment, equalization of the histograms, combination of the layers, and the atmospheric correction of the signal. The actual processing of the image consists in the exploration of the image, analysis of the spectral profiles of the objects, sampling of the different themes, evaluation of the different samples, and supervised classification using the maximum likelihood algorithm (Koné et al. 2007; Hoang et al. 2008; Tapboda and Fosting 2010; Soro et al. 2013). The ultimate supervised classification validation step of the analysis requires field mapping.

Normalized difference vegetation index and leaf area index data acquisition

Additional satellite data provided monthly land use status (GLCCs) that are normalized difference vegetation index (NDVI) and leaf area index (LAI) data aggregated to 0.1° on

the vegetation cover. They were downloaded for about 50 points (Fig. 1) from NASA’s (National Aeronautics and Space Administration) website <https://neo.sci.gsfc.nasa.gov>. These data are spread over 10 years, that is between February 2000 and February 2017 and thus cover the sampling period of water samples.

The NDVI is an index that measures the health of green vegetation. Combining its normalized difference formulation with the highest absorption and reflectance regions of chlorophyll make it robust over a wide range of conditions. It can however be saturated in dense vegetation conditions when LAI becomes high (Rouse et al. 1973). It is given by:

$$NDVI = \frac{(NIR-Red)}{(NIR + Red)} \tag{6}$$

The value of this index ranges between - 1 to 1. The common range for green vegetation is 0.2 to 0.8.

The LAI is used to estimate foliage cover and to forecast crop growth and yield (Boegh et al. 2002) as follows:

$$LAI = (3.618 \times EVI-0.118) \tag{7}$$

where EVI is the enhanced vegetation index value.

This index was originally developed for use with MODIS data as an improvement over NDVI by optimizing the vegetation signal in areas of high LAI. It is most useful for high LAI regions where NDVI may saturate. It uses the blue reflectance region to correct for soil background signals and to reduce atmospheric influences, including aerosol scattering (Huete et al. 2002). It is usually calculated using Eq. 8 below:

$$EVI = 2.5 \times \frac{(NIR-Red)}{(NIR + 6 \times Red-7.5 \times Blue + 1)} \tag{8}$$

Results and discussion

Current hydrology of the Noun River

Between January 2011 and August 2013, daily discharge of the Noun River varied between 23.68 and 448.70 m³ s⁻¹ with

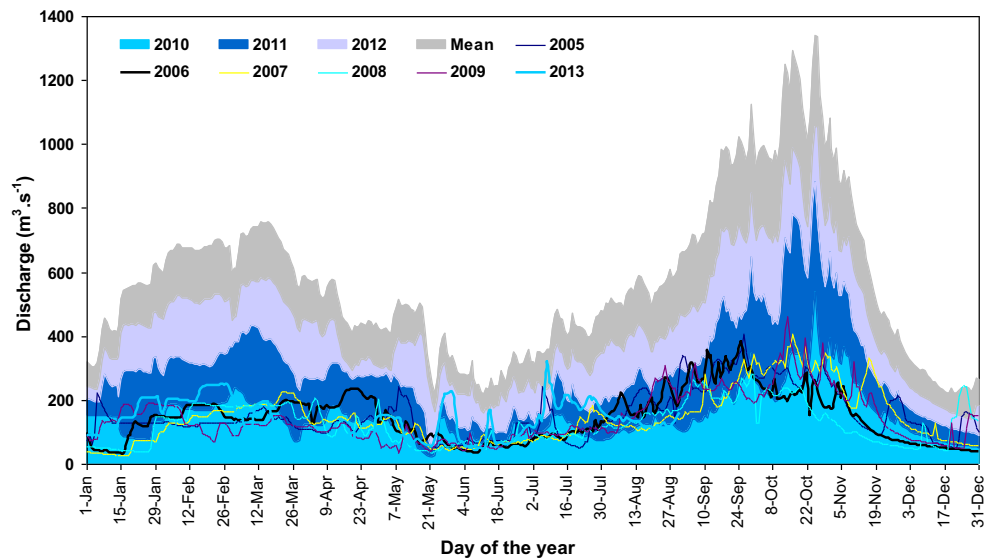
an arithmetic mean of 137.11 ± 70 m³ s⁻¹. In an average year, the daily discharges ranged between 56 and 310 m³ s⁻¹ for an average daily flow of 143.92 ± 61.43 m³ s⁻¹ corresponding to average annual water yield of 4.53 × 10⁹ m³. However, high flows were observed during the dry season in the absence of any rainfall impulses, for example, the 248 m³ s⁻¹ was recorded on 27 February 2013, representing 46% of the maximum daily flow of the time-series (Table 1). Abrupt variations with several phases of decreases or successive upswings of water were also noted. As a result, there have been abrupt variations in flow rates, ranging from 18.40 m³ s⁻¹ on 8 July 2011 to 208.27 m³ s⁻¹ on 17 October 2011, then down to 17.51 m³ s⁻¹ to 5 January 2012 (Fig. 4). For the period 1944–2014, the monthly rainfall varied between 8.1 mm in December and 284.2 mm in September for an inter-annual average of 1762 ± 102 mm. Overall, the climate regime is mountain tropical western Cameroon (Fig. 3), although years taken separately from 2005 sometimes show decreases in rainfall in May, June, or July (Fig. 5). This sometimes evokes a change in climate regime. The monthly discharge fluctuated between 70.34 and 268.18 m³ s⁻¹ for the months of June and October, respectively, corresponding to inter-annual module of 143.08 ± 60.48 m³ s⁻¹ and a runoff of 465.18 mm year⁻¹. The open gate monthly discharge of the Bamendjin dam range from about 118 m³ s⁻¹ in February and March and from 1.70 to 2.34 m³ s⁻¹ in July and August, respectively. The Bamendjin dam average water volume oscillated between 420 million m³ in December and 1600 million m³ in October, for an average of 1020 million m³. Regarding water management, this dam has a filling period that runs from June to November and a destocking or emptying period that goes from December to May (Fig. 6). It is important to note a change of Noun’s current hydrological regime at the Bayomen station. Between December and June, there is a reversal of monthly flow trends over two distinct periods that are contrary to the usual behavior in other watercourses of the tropical zone in a natural or non-anthropized context. Thus, during the first period (December–March), a decrease in flow due to the dry season is observed, which gradually increases between March and June, due to the arrival of the rainy season. Consequently, the evolution curve of the monthly mean flows then presents

Table 1 Descriptive statistics of daily discharge (m³ s⁻¹) for the Noun River Western Cameroon

	Q_{Min} (m ³ s ⁻¹)	Q_{Max} (m ³ s ⁻¹)	Q_{Max}/Q_{Min}	Q_{mean} (m ³ s ⁻¹)	Sdv	CV	Med	Min. recorded date	Max. recorded date
(a) Estimation of the Noun at Bafoussam (4740 km ²)									
2011–2012	16.54	217.92	13.18	70.25	40.15	0.57	67.94	05/23/2011	10/13/2011
2012–2013	11.50	145.13	12.62	67.53	29.84	0.44	67.88	05/04/2012	10/26/2012
2011–2013	11.50	217.92	18.95	68.89	35.38	0.51	67.88	05/04/2012	10/13/2011
(b) Noun at Bayomen (9754 km ²)									
2011–2013	23.68	448.70	18.95	137.11	70.05	0.51	139.20	05/04/2012	10/13/2011

Min minimum, *Max* maximum, *Sdv* standard deviation, *CV* coefficient of variation, *Med* median

Fig. 4 Daily flow discharges (Q) in the Noun Basin at Bayomen (9754 km²) measured during a 9-year period (2005–2013)



two phases of rising water during the hydrological year, corresponding to the periods from December to February and from June to October, which are followed respectively by periods of recession (March to June and October to December). Thus, the periods of December–March and March–June are more affected by a strong impact of the dam which probably dominates that of the response of the basin to the rain. Between June and December, although the Noun stream was regulated since 1974 by the Bamendjin dam, the discharge of this river follows the effects related to rainfall rather than the impulse of the dam. The flow regime has a bimodal curve with two peaks recorded in October and February and two minimums in June and December, although rainfall remains unimodal overall. This could be explained by

the implantation and the mode of operation of the Bamendjin dam whose objective is to regulate the flow of the Sanaga River. However, the maximum precipitation always precedes that of the flows of a given month (Fig. 7). The latter situation is observable on several other stations of the Sanaga watershed (Kpoumié 2015). The bimodal evolution as well as abrupt variations at certain times of the hydrological year could be explained by the mode of hydrological management or operation of the dam located upstream of the gauging station. The dam also helped to maintain the lowest average flows in June and December at values nearby or close to 70 and 77 m³ s⁻¹. The availability of the water resource to be released for downstream purposes for hydroelectric production as well as the retention capacity of the dam (1697 Mm³)

Fig. 5 Relationships between monthly rainfall and flow discharges of Noun River between January 2005 and May 2013

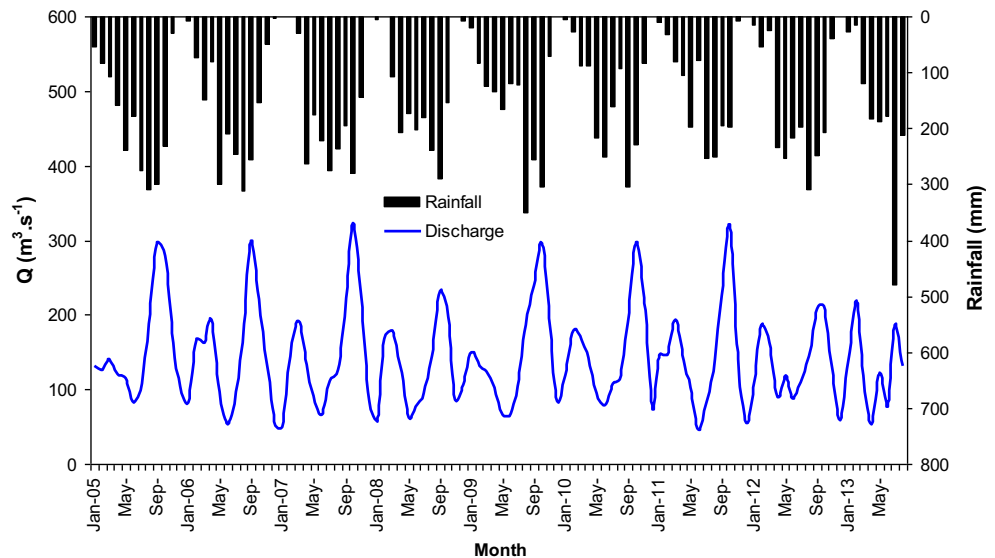
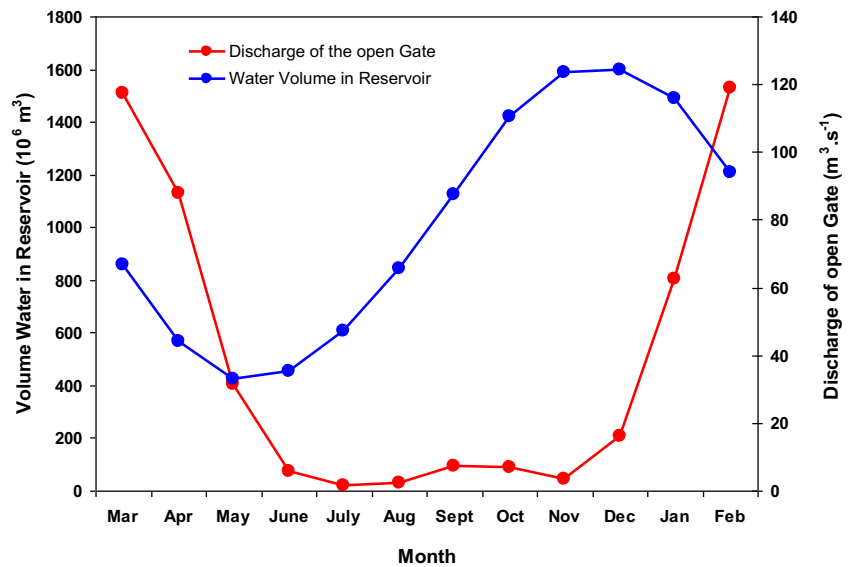


Fig. 6 Relationship between water volume in reservoir and discharge of open gate releases of the Bamendjin dam



condition this management. Thus, this mode of operation cannot be identical from 1 year to the next.

Annual variation in TSS concentration and fluxes

The daily flow discharge and instantaneous TSS concentrations measured in the Noun at Bafoussam during two hydrological years, between January 2011 and August 2013 (see Fig. 8), ranged between 3 and 1375.40 mg L⁻¹ for an arithmetic mean of 106.06 ± 199.46 mg L⁻¹ (Table 2) and a VWM concentrations of 90.33 mg L⁻¹. The SY are of the order of 196.24 × 10³ t year⁻¹ for a SSY of 41.40 t km⁻² year⁻¹ and a physical denudation rate of 31.85 mm kyear⁻¹. In 2014, the TSS concentration in the Noun at the Bayomen station, varied from 33 to 225 mg L⁻¹ for the VWM concentrations, the SY, the SSY, and the physical denudation rate respectively of 110.49 mg L⁻¹, 553 × 10³ t year⁻¹, 57 t km⁻² year⁻¹, and 44 mm kyear⁻¹ (Table 3). At the Bafoussam station, the

Noun River has not yet received the suspended solid load from the Nkoup River estimated to be 8715 and 8901 t year⁻¹ for 2003/2004 and 2004/2005 respectively, corresponding to a specific degradation of 47.3 and 48.3 t km⁻² year⁻¹, respectively. In this catchment, ridged-crop agriculture is the dominant land use with maize and beans as the principal crops. Many market of vegetables and a few coffee plantations also exist. Some pasture lands can also be found on distant hill tops (Tita 2008). The key causes of soil degradation by water erosion result due to intensive cultivation and plowing of the soil on hillside slopes (Olivry et al. 1974; Didoné et al. 2014; Ndam Ngoupayou et al. 2016). All of these factors contribute to the Nkoup River alone disposing of a significant amount of TSS and constitute a very important TSS contributor in the Noun watershed. We can associate the impact of agricultural activities on the Mifi South and Mifi North upstream sub-basins, still unregulated at this high rate of availability of particles transported.

Fig. 7 The inter-annual rainfall vs monthly discharge relationships at the Noun station in Bafoussam for the period 2005–2013

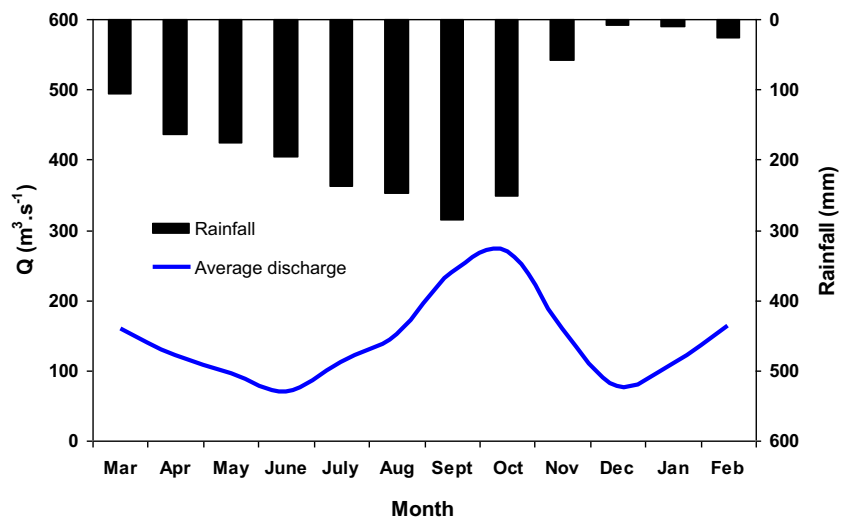
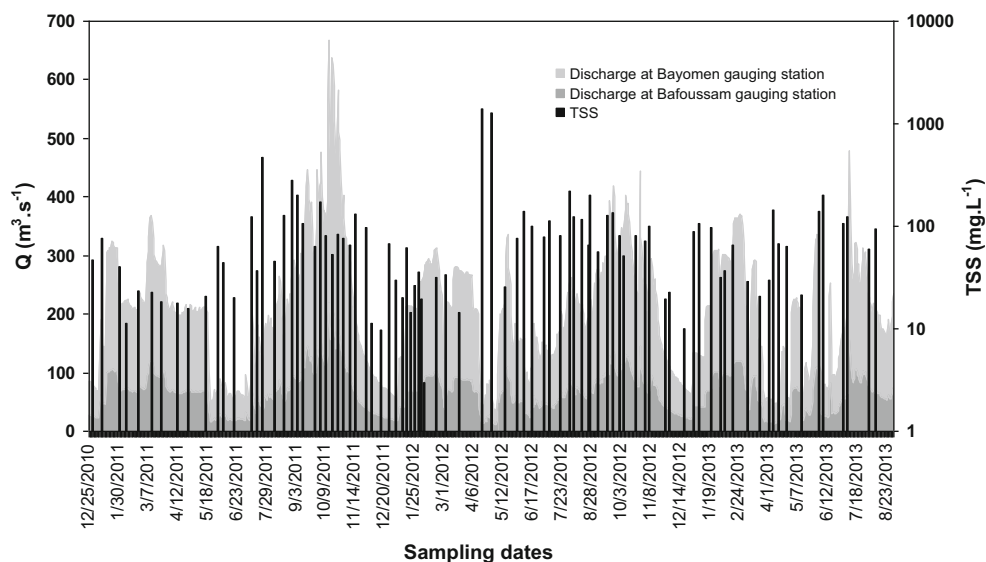


Fig. 8 Daily flow discharges and instantaneous TSS concentrations measured in the Noun waters during a two hydrological year period



Similarly, Noun and Mifi rivers drain compartments of the basin that are densely populated (Bamiléké and Bamoun region). The erodibility of the superficial formations is relatively high because of their characteristics (thick soil on rocks with dominant volcanic features, presence of pyroclastites) and the relief. It is further enhanced by intensive development and agricultural practices. These enhance water erosion and sediments production (Nouvelot 1972b; Olivry 1976; Ndam Ngoupayou 1997). It should also be noted that several factors are required to mitigate the solid transport on the Noun River basin: (1) anti-erosive practices (agriculture on billons and following the orientation of contours), (2) implantation of the Bamendjin dam which would retain all the sediments coming from the Ndop plains, and (3) decrease in precipitation and flow in the Sanaga watershed (Dzana et al. 2011; Kpoumié et al. 2012; Kpoumié 2015; Ndam Ngoupayou et al. 2016), including the Noun River. Without these different influences, a much larger flow would have been recorded. However, no previous data allows for its accurate quantification but Olivry (1976) reported a SSY of about 2000 t km⁻² year⁻¹ at the Bamoungoum station. The current low physical denudation rates associated with the presence of volcanic rocks would

play a role in maintaining the soil fertility in the Noun watershed. Shi et al. (2013) note that water erosion is the result of the interactions among different environmental factors, including topography, soil properties, climatic characteristics, runoff, and land use and management.

Comparing the temporal variations of TSS from one hydrological year to the next reveals some major particularities. Thus, during the second year of follow-up, the one-off evolution shows values of TSS concentrations greater than 1250 mg L⁻¹. These high concentrations of TSS, however, were oddly recorded at the beginning of the hydrological year (1375 mg L⁻¹ and 1258 mg L⁻¹ respectively on 15 and 27 of April 2012) and were observed during very low discharge periods (20.61 and 21.72 m³ s⁻¹ respectively; Fig. 8). The instantaneous TSS concentrations of this type are generally recorded in the Sahelian zones of Cameroon, like the Mayo Tsanaga watershed in Bogo, where values of around 8000 to 10,000 mg L⁻¹ are sometimes obtained at the beginning of the rainy season (Thébé 1987; Liéou 2007; Liéou et al. 2009). Events within a catchment that display a direct response to rainfall, discharge, and sediments are categorized as a flash flood type (Zabaleta et al. 2007). These authors explain these

Table 2 Descriptive statistics of TSS (mg L⁻¹) of the Noun River at Bafoussam gauging station—Cameroon

	Min (mg L ⁻¹)	Max (mg L ⁻¹)	Max/min	Mean (mg L ⁻¹)	C _{VWM} (mg L ⁻¹)	Sdv	Med	Min. recorded date	Max. recorded date
(a) Noun River at Bafoussam (4740 km ²)									
2011–2012	3.00	470.20	156.73	74.89	75.81	89.59	45.80	02/05/2012	07/23/2011
2012–2013	10.00	1375.40	137.54	157.69	108.47	303.34	80.60	12/18/2012	04/15/2012
2011–2013	3.00	1375.40	458.47	106.06	90.33	199.46	65.40	02/05/2012	04/15/2012
(b) Noun at Bayomen (9754 km ²)									
2014	33.00	225.00	6.82	81.40	110.49	80.94	50.00	03/14/2014	09/26/2014

TSS total suspended sediments, *Min* minimum, *Max* maximum, *C_{VWM}* volume weighted mean concentration, *Sdv* standard deviation, *Med* median

Table 3 Estimates of TSS and equivalent physical denudation rates of the Noun River—Cameroon

	Q_{mean} ($m^3 s^{-1}$)	Q_s ($L s^{-1} km^{-2}$)	Rf ($mm year^{-1}$)	C_{VWM} ($mg L^{-1}$)	SY ($10^3 t year^{-1}$)	SSY ($t km^{-2} year^{-1}$)	DR_{ph} ($mm kyear^{-1}$)
(a) Noun River at Bafoussam ($4740 km^2$)							
2011–2012	70.25	14.79	468.67	75.81	168.41	35.53	27.33
2012–2013	67.53	14.25	449.29	108.47	231.00	48.73	37.49
2011–2013	68.89	14.53	458.34	90.33	196.24	41.40	31.85
(b) Noun River at Bayomen ($9754 km^2$)							
2011–2013 ^a	137.11	14.06	443.30	90.33	390.58	40.04	30.80
2014	144.78	14.84	468.09	110.49	553.05	56.70	43.60

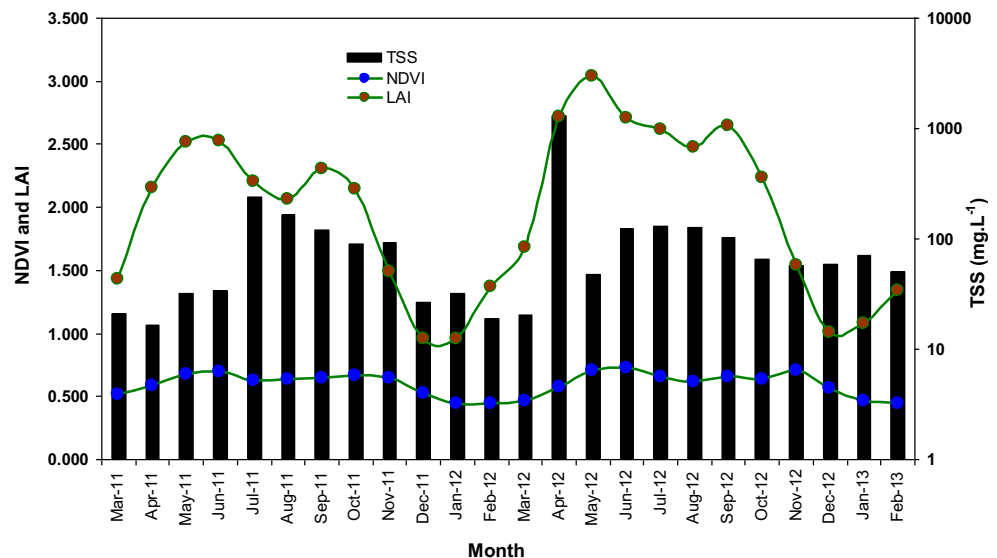
Q_s specific water discharges, Rf annual runoff, C_{VWM} volume weighted mean (VWM) concentration of TSS, SY suspended sediment yields, SSY specific sediment yield, DR_{ph} physical denudation rate;

^a Estimated

very high concentrations in Cameroon’s dry tropical zones by the mobilization of soils, made pulverulent by the long dry season, and by the prolonged trampling of animals. At the Noun River, these high concentrations are due to a very stormy rainy season beginning, marked by numerous rainy and abnormal events. Thus, during such events, the first horizons of the soil, mainly those of surface, are saturated with water because of the strong intensity of the rain. This results in a mechanical lateral leaching favored by the steep slope of the relief, accompanied by a powdery pyroclastic soil (Doranzo and Dellino 2010). When the soil is dry, the water penetrates except in certain places where the surface encrusting limits the infiltration and sets in motion large quantities of dry sediments. As vegetation cover is not yet developed and flows are still very low at this time of the year, the ratio of a large amount of sediments leached from the slopes to the low water level generates high concentrations of TSS (Bouanani 2004; Shin et al. 2013). In addition, soils preparations for planting of April and May crops occurs in the months of drought end (January–February–March) increasing soil detachment and

transport toward the drainage network. The growth of vegetation and the well-developed organic soil horizons can reduce the runoff and prevent particles detachment and transport while the prolonged drought can increase the risk of desertification and critical soil erosion (Megnounif and Ghenim 2016). Fang et al. (2011) also confirm this finding by stating that the high soil loss rates can also occur during intense thunderstorms when these conditions are met. Other authors explain this result by natural conditions to which are added the torrential rains that occur at the end of the dry season and are responsible for most of the erosion and sediment load of the flood waters (Marzougui and Ben Mammou 2006). The runoff during these showers then has time to evacuate a good part of the pulverulent matter since the vegetal cover is not yet developed. The variation of the instantaneous TSS concentration is also intimately related to the state of soil moisture and hence of the seasons (Nouvelot 1969; Seeger et al. 2004; Giménez et al. 2012). The intensity of the showers at the beginning of the rainy seasons is essential as well as the notion of effective rain that remains for the basins to the extent that

Fig. 9 Relationship between NDVI and LAI associated with monthly TSS



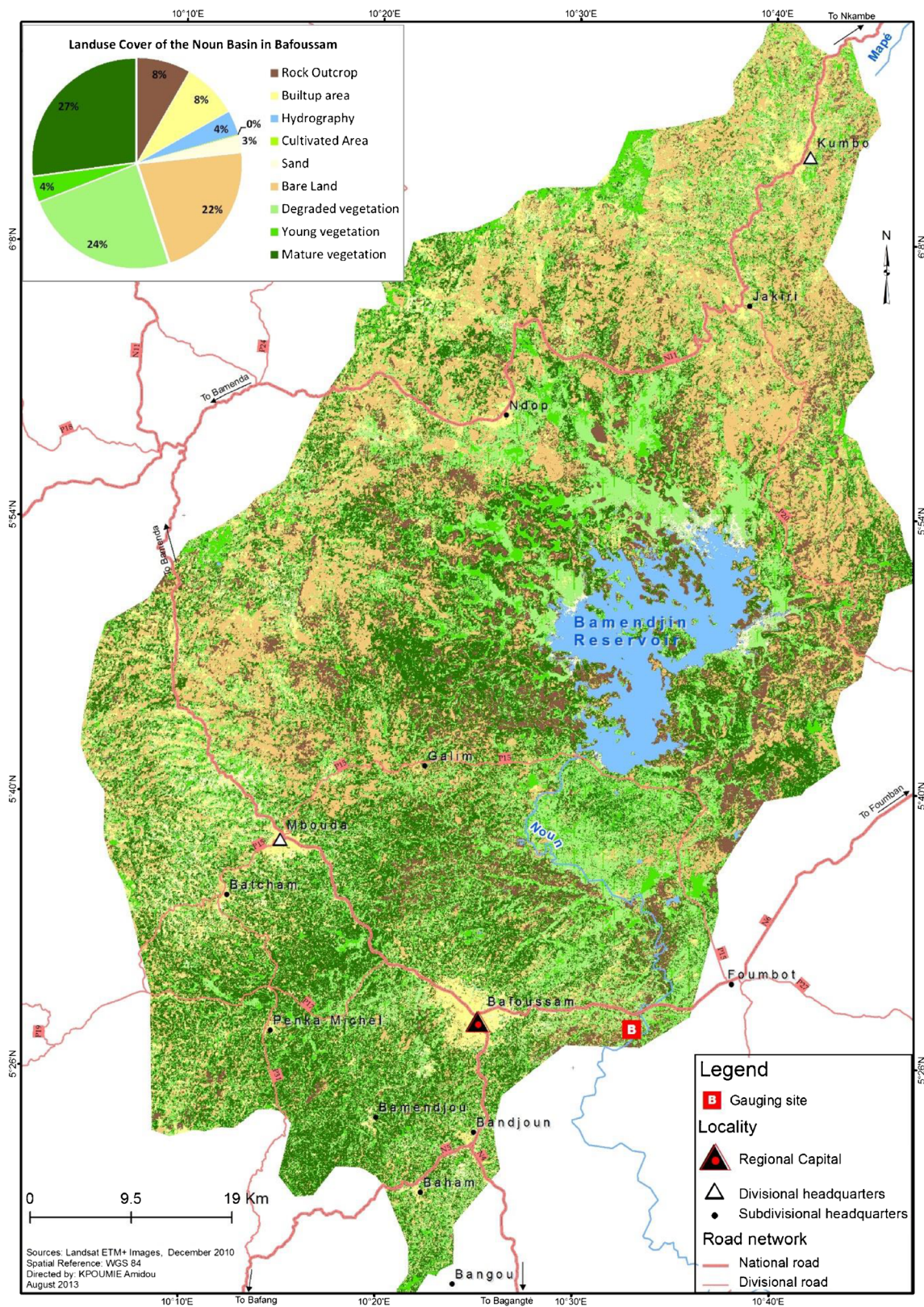
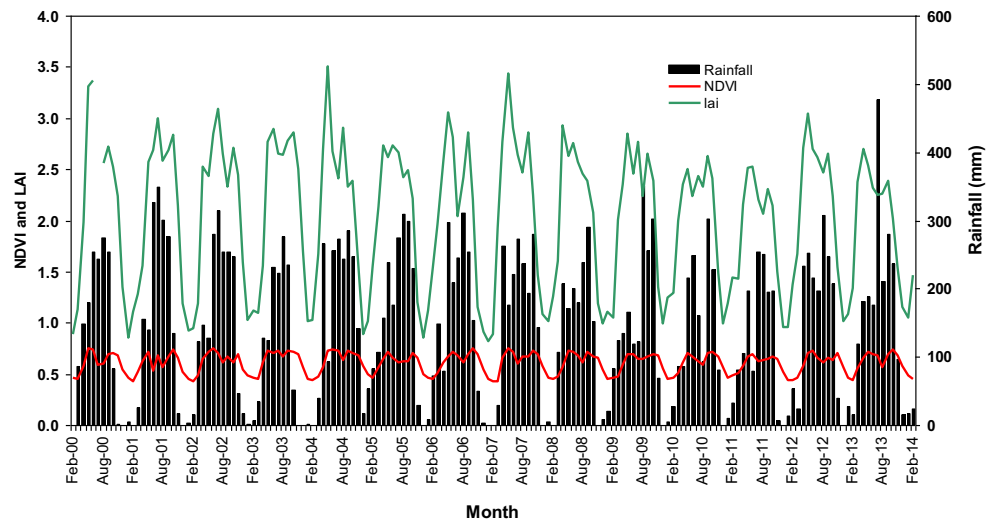


Fig. 10 Outputs of the supervised classifications obtained from the Landsat ETM+ images

one can define a limit intensity above which the first transport solids could appear. These high values of TSS concentrations

at the beginning of the rainy season had an influence on the maximum value expected in July of the second hydrological

Fig. 11 Relationship between NDVI and LAI associated with monthly rainfall



year. Thus, 221.4 mg L^{-1} was recorded as of 31 July 2012 against 470.2 mg L^{-1} at the same time of the previous year, which shows a decrease of approximately 52.91%, confirming that when the first rains are stormy, they lead to high concentrations of TSS. These have a negative impact on the maximum value of the next hydrological year, indicating a phenomenon of limit depletion of available sediment stock. A similar conclusion was reached by Rodríguez-Blanco et al. (2010), who also stated that strong runoff at the beginning of the rainy season can also be caused by persistent rainfall in saturated soils with low infiltration capacity. This behavior during the second year of follow-up is contrary to those generally observed in regulated or unregulated Cameroonian rivers and is specific to this study. These rivers show variations in the instantaneous concentrations and fluxes of TSS which perfectly follow those of the daily flows (Fig. 13), but with

particularities (Liéno et al. 2005a, b, 2009; Ndam Ngoupayou et al. 2016).

Intra-annual variation in TSS fluxes

The NDVI and LAI variations associated with monthly TSS between March 2011 and February 2013 (see Fig. 9), generally vary between 0.44 and 0.72 for an arithmetic mean of 0.59 ± 0.10 , while LAIs vary between 0.96 and $3.04 \text{ m}^2 \text{ leaf m}^{-2} \text{ soil}$ for an arithmetic mean of 1.97 ± 0.65 . The Landsat image of December shows vegetation cover rates of 4% for young vegetation, 27% for old vegetation, 22% for bare soil, and 8% for urbanization (Fig. 10). This confirms that the vegetation of the Noun sub-catchment is mainly constituted of woody savannahs (Olivry et al. 1974; Ndam Ngoupayou 1997; Ndam Ngoupayou et al. 2016). The monthly evolution

Fig. 12 Correlation between rainfall and NDVI/LAI monthly between February 2000 and February 2014

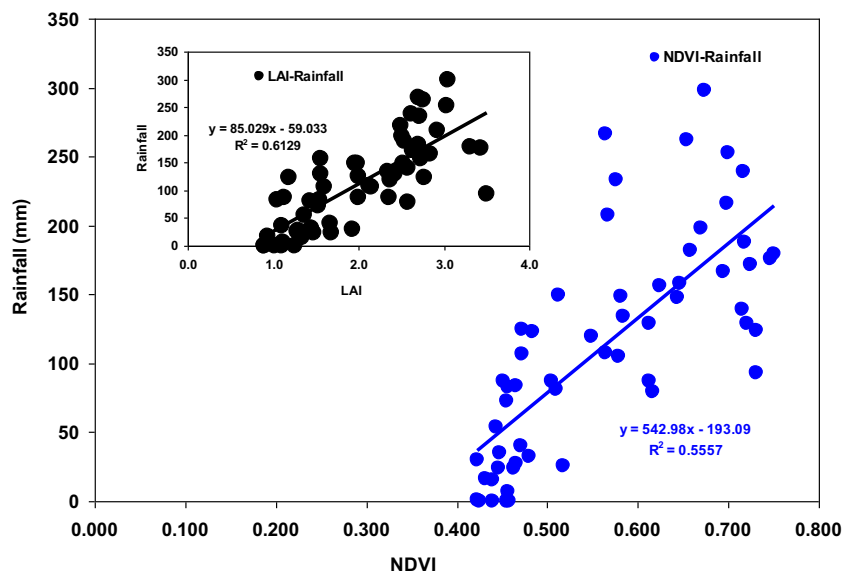
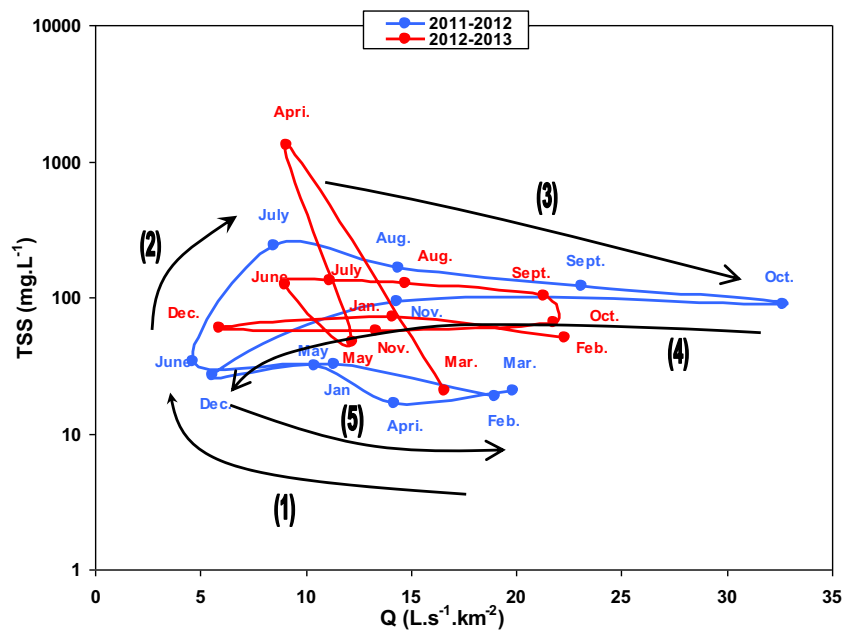


Fig. 13 Relationships between monthly TSS concentrations and flow discharges for the Noun River at Bafoussam, showing clockwise hysteresis loops with a modified counterclockwise last phase for 2011–2012 and chaotic pattern for 2012–2013



of TSS globally follows those of NDVI and LAI (Fig. 11). However, as soon as the first rains begin, vegetation cover grows very rapidly and the TSS gradually increases during the first 5 months to reach their maximum in July before the onset of decrease phase. Although NDVI and LAI evolutions present bimodal annual curves with the first peak observed in May or June and the second peak recorded in September (Fig. 9), we note, however, a good correlation between NDVI, LAI, and monthly precipitation (Fig. 12). This may be due to the fact that in the regions of western Cameroon, these months correspond to the period of maturity of the first seasonal crops (usually maize) sown at the beginning of the rainy season. Thus, at maturity, these crops lose their greenery initiating the period of harvest and plowing. However, this decrease (in June, July, and August) does not have a strong impact on the variation of TSS concentrations which reach their maximum during the year (Fig. 9). Overall, the maximum vegetation cover is 1 to 2 months ahead of the TSS concentrations. However, Masocha et al. (2017) spotted a consistent negative curvilinear relationship between TSS and NDVI. They explain this by the fact that the TSS and NDVI would depend on the moisture status of the catchment. So, in the drier catchments, 98% of the variation in TSS is explained by NDVI, while in wetter catchments, 64% of the variation in TSS is explained by NDVI.

The evolution of the TSS concentration vs monthly discharge relationships were complex and difficult to interpret during the 2 years of study. They are dissimilar from 1 year to the other and do not form clockwise hysteresis loops with very distinct phases of sedimentary dynamism (Liéno et al. 2005a, b, 2009; Oeurng et al. 2010; Ndam Ngoupayou et al. 2016). From the year 2011–2012, the months of March to December present a first phase where the loop evolves in the

clockwise direction while the months of January and February follow a contrary evolution. 85% of TSS flows are exported over 5 months between July and November. However, five different phases of variation of this curve are identified (Fig. 13). Between March and June, the TSS increases while the flow decreases (1). From June to July, the TSS and flow rates increase simultaneously. It is dilution with a hypodermic flow, favored when soils are protected by vegetation (2: initial erosion). Between July and October (3), the TSS fall while the flow rates increase (attenuated or late erosion). Between October and December, the TSS decreases while the flow also decreases but drastically. It is flood recession with decrease of TSS by reduction of the hydraulic power able to remobilize the bottom load (4: deposition). Unlike the first 4 phases, phase (5) evolving between December and February, is counterclockwise and follows the reverse path of phase (1). In 2012–2013, we observed a disordered form presenting both clockwise and counterclockwise patterns (Fig. 13). During this second year, in February alone, flows of TSS were higher than those recorded in the first year between July and November. This could be explained by the fact that Noun's hydrological regime at Bafoussam is currently conditioned by several factors, both natural and anthropogenic, including the geology, very steep slopes, the implantation of a reservoir dam, and very stormy precipitation episodes at the beginning of the year. Yet from a general perspective, in tropical streams, the magnitude of sediments yields as a reflection erosion and runoff assumes very high values from July to September with a peak in July (Lima et al. 2005; Barros 2012; Zhang et al. 2012). Also, in a small watershed, the concentration of sediment and variable discharge were not significantly correlated due to the small amount of sediment available for transport during the events and that the increment of the suspended

sediment concentration (SSC) is not of the same magnitude as the discharge, thus contributing to poor correlation between both variables (Zabaleta et al. 2007). However, the concentration vs monthly discharge relationships of TSS disordered have also been observed by several others, whether on agricultural catchment areas (Lefrançois et al. 2007) or on regulated or urbanized watersheds either at the scale of a rain event or at hydrological year scale (Lefrançois et al. 2007; Fang et al. 2011; Dominic et al. 2015; Warricka et al. 2015). For the Noun basin, the mode of sediment transport (along the bottom or in suspension) depends on hydrological and hydraulic conditions. In other anthropized basins, this relationship continues to give clockwise hysteresis loops; for example, in the agricultural catchment area of Navarre in Spain (Giménez et al. 2012), in the Three Gorges area in China (Fang et al. 2011), and in the rural catchment in the humid Spanish zone (Rodríguez-Blanco et al. 2010), TSS concentration vs monthly discharge relationship curve is in the form of eight. Thus, it is important to point out that several factors such as the lithological nature, the hydrological functioning regime of each basin and the intensity of anthropogenic actions can determine the shape of this TSS concentration vs monthly discharge relationships (Restrepo and Kjerfve 2000; Lima et al. 2005; Akraši 2011; Zhang et al. 2012; Barros 2012). The different degrees of soil moisture and rainfall intensities are also indicators of different processes of runoff and sediments transport (Seeger et al. 2004).

Conclusions

On the basis of instantaneous TSS and daily flow data, current dynamics of solid transport on the Noun River (Cameroon, Central Africa) was quantified. The monthly land cover, NDVI, and LAI data also permitted the characterization of the water and TSS dynamics of this important tributary of the Mbam River. Though the Noun River at Bafoussam has been disturbed by the Bamendjin dam implanted on its upstream segment since 1974, the basin still responds almost immediately to rainfall impulses between June and December, whereas between December and June, it is strongly impacted by regulation at the dam to the extent where its hydrological regime between December–March and March–June has been reversed. At the annual scale, the specific fluxes of TSS range between 41 and 57 t km⁻² year⁻¹ for physical denudation rates of 32 to 44 mm kyear⁻¹. The Nkoup River is one of the major suppliers of TSS on the Noun River like the North Mifi and South Mifi. The instantaneous maximum concentrations of TSS are generally obtained in July, preceded by maximum discharge as is the case in some tropical rivers. However, when the rains are very stormy at the beginning of the rainy season, a virtual maximum of the instantaneous concentrations of TSS (1375 mg L⁻¹) is observed and has an

impact on the July maximum regular concentration by continuous depletion of available sediments deposited in the riverbed. This situation led to higher solid transport in April than those observed during the months of July, August, September, October, and November combined in the first year of measurement. The TSS concentration vs monthly discharge relationships show a general clockwise evolution with a modified counterclockwise trend in the last phase during the first hydrological year. During the last hydrological year 2012–2013, this TSS concentration vs monthly discharge relationship curve is chaotic and reflects no logical sequence. The present situation can be explained by the implantation and mode of functioning of the Bamendjin dam which regulates the flow of the Sanaga River. But at this stage of measurements, the quantifiable impact of the dam on solid transport cannot yet be dissociated from the impact of rain and plowing.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interests.

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