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RESEARCH ARTICLE

ASSESSING SUSPENDED SEDIMENT YIELD IN THE SAF SAF GAUGED CATCHMENT, NORTHEASTERN ALGERIA

K. Khanchoul*, Z.A. Boukhrissa

Department of Geology, Soils and Sustainable Development Laboratory, Badji Mokhtar University-Annaba, Algeria.

*Corresponding Author e-mail: kamel.khanchoul@univ-annaba.dz

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ABSTRACT

Many studies on sediment transport have been carried out on Algerian rivers but few studies have been undertaken in catchments of the Northeast of Algeria. The scarcity or discontinuity on sediment transport measurements reduces knowledge about soil loss. In some cases, researchers find often difficulties to apply the most suitable methods to estimate sediment load. The present work represents an assessment of suspended sediment yield from the Saf Saf catchment (322 km²) over 39 years. Long-term annual suspended sediment loads are estimated using non-linear power model, developed on mean discharge class technique as a sediment rating curve. There is a challenge to estimate suspended sediment load in the Saf Saf catchment, which is distinguished by rapid discharge variation. A second aim is to examine monthly and annual variations in discharge, suspended concentration, rainfall and load in this river and to find causes for these variations. The results show that the mean annual sediment yield is equal to 477 T km⁻² yr⁻¹ during the study period. Moreover, the long term variability analysis of sediment load seems to be very high from year to year depending on climatic conditions. The analysis of annual sediment load shows a decreasing trend along 39 years, mainly from 1997. Most sediment loads are transported during the winter season, which represents 78% of the total sediment load. The understanding of sediment transport relationships gained from this study should provide a good starting point for researchers and policymakers to begin addressing sediment issues within the catchment.

KEYWORDS

Northeastern Algeria, Catchment, Sediment rating curve, Sediment load prediction.

1. INTRODUCTION

Soil erosion that occurs within fluvial basins has a significant impact on landscape degradation, reservoir siltation and on decreasing agricultural productivity. Due to this high erosion level, many authors have been interested since the last decades to assess sediment load and study the spatial and temporal erosion variability on different river basins in Algeria.

Recent published studies of suspended sediment transport in northeastern Algeria are extremely limited and those that have been carried out have focused on determining some overall transport rate on an annual basis [1]. Sediment yield from a catchment is an integrated result of all water erosion and transport processes occurring in the entire contributing area [2]. For the different gauged systems, suspended sediment yield was computed from rating curves established from different period term measurement series [3-8].

Mediterranean climate is identified by seasonal contrast, where the soil erodibility can be affected by the dry and warm summer climate, and where the soil erosion can be affected by the concentration of precipitation events, particularly in the fall [9-11]. This event may lead to serious degradation of the soil with further negative damage on natural resources [12, 13]. Both climate changes and also human interventions are responsible for the dramatic reductions in runoff and sediment load [14-16].

To predict reliable quantity and rate of sediment transport from land surface into streams, rivers, to identify erosion problem areas within a

catchment and to propose the best management practices to reduce erosion impact, models should be used [10,17,18]. Uncertainty of the sediment concentration prediction has been extensively discussed when constructing a model and, depending on the catchment characteristics, generally good concentration predictions are obtained with errors smaller than 15% [19, 20].

This study aims to contribute to a better understanding of suspended sediment transport from a headwater catchment under humid conditions by using a temporal scale of rainfall, water discharge and suspended sediment data, located in northeast of Algeria. More specifically, the objectives are to: (i) investigate the applicability of a regression between measured suspended sediment concentration (SSC) and water discharge (Q) at different time scales (1976-2015); and (ii) identify the short-temporal variability of the sediment load responses.

2. STUDY AREA

The Saf Saf catchment is located on the ridge of the Tell mountains, northeast of Algeria and has an area of 322 km² at the gauging station of Khemakhem (Figure1). Several geologic formations of the Mio-Pliocene orogeny are characterized by limestone, sandstone and weak rocks. The study catchment has 44% of its area covered by weathered or unconsolidated geologic formations that generate very erodible soils such as marly limestone of Senonian, Triassic gypseous-sandy clay, clayey conglomerate of Miocene and the lower Numidian clay; usually affected by folds and faults. The areas with gypsum clay and clay are highly dissected by gullies [1].

Most spectacular landslides occur in soils developed on gypsic clay, provoked mainly by bank erosion at the stream base of Bou Adjem and Khemakhem rivers. Rotational slides are associated with soils on clayey marl and are visible along the Bou Adjem at slopes exceeding 20%.

Figure 1: Location map of the Saf Saf catchment.

In the Saf Saf catchment more than 50% of the basin area is occupied by cultures (wheat and barley). Sparse forest and shrubs (*Oleo-lentiscus* and *Erica europae*) cover 30% of the basin and are found mainly on poorly developed soils on sandstone and conglomerate. Overgrazing is observed in pasture and open shrubland, where plants are exposed to intensive grazing for extended period of time [21].

The Saf Saf catchment belongs to a temperate and humid climate of the Mediterranean type, with a slightly fresh winter and a hot dry summer. Based on recorded daily rainfall of the 39-year period, the Saf Saf basin is characterized by irregular annual precipitation, with a mean annual rainfall of 661 mm and a mean annual temperature of 21°C. There are rainfall events greater than 30 mm/day during an average of 4 days/year from November to February.

3. METHODS

3.1 Suspended sediment measurements and analysis

Surveys of suspended sediment concentration and water discharge are being carried out in the Saf Saf River at the gauging station of Khemakhem, controlled by the National Agency of Hydraulics (ANRH) in Constantine and Algiers.

The water sampling is performed at surface water using one-liter plastic bottles, and the analysis of the samples are done in the laboratory. With every flow measurement, water samples are taken close to the bed of the river in order to determine suspended sediment concentration. The sediment concentration of each sample is calculated by filtration method, evaporating the sample, and then weighing the remaining sediment [22]. The filter and the mud contained in the bottle is weighed after drying in a special oven for 30 minutes at a temperature of 110°C. It is assumed that the addition of dissolved solids to the suspended sediment through evaporation is negligible. The samples are taken every day in dry weather (no flood) and every quarter-hour or half-hour during flood periods, which makes 650 daily datasets in 39-year period (1976–2014) [23]. Water flows are directly given by the rating curve $H = f(Q)$ and the heights of water measured by a limnometric ladder and float water level recorder.

3.2 Sediment rating curve development

Reliable estimates of daily suspended sediment load are difficult to achieve in the absence of detailed time series of suspended sediment concentration and flow. Thus, for storm events with no water samples,

instantaneous flow and sediment transport data are used to develop sediment transport ratings and to reconstruct the missing suspended sediment concentration records [24]. Generally, the mathematical functions that best-fit sediment rating curves are not linear and among the ones mostly used are the power type.

The hydrometric record for the Khemakhem gauging station consists of intermittent daily measurements of suspended sediment concentration. Obtaining an accurate estimation of the monthly and annual sediment loads from these data require considerable attention to statistical details [5]. The sediment rating curve technique has been widely used by researchers for a large variety of purposes. The sediment rating curve is defined as the statistical relationship between suspended sediment concentration (SSC) and stream discharge (Q) [25]. Several researchers have used SRCs to estimate suspended sediment concentration and/or sediment load for subsequent flux computations in the absence of actual SSC [6, 25–28].

Since the most straightforward rating curve approach typically uses an empirically calibrated power-law relation between water discharge and sediment concentration, the sediment concentrations are calculated with a sediment rating curve by making use of log transformation of the relationship between daily mean concentration and daily mean water discharge such as [29, 30]:

$$C = aQ^b \quad (1)$$

where C is suspended sediment concentration (g/l), Q is water discharge (m^3/s), and a and b are regression coefficients.

The used regression has provided a fairly low coefficient of correlation ($r = 0.50$) and the C - Q data show a scatter distribution mainly at low and medium values (Figure 2). The developed regression on all separate measurements has underestimated the true sediment load by 61% when developed on all 650 datasets. Due to the underestimation of sediment load, a further has to be used to provide a better prediction of sediment load. Therefore, an attempt has been followed by using water discharge classes' technique [4, 5].

The chosen technique of rating relationships is started by sorting and regrouping the data into distinct classes of water discharge. The definition of the width of each class interval depends on the data base in question. For the low discharge values, the class interval can be narrow and may contain more values in a discharge class [1]. This class interval will become progressively wider as the data base becomes small at high water discharges. The mean sediment concentration in every class is computed and entered in a logarithmic plot to determine the regression equation and to check the goodness of fit of the developed regression.

Figure 2: Scatter plot of water discharge (Q) versus sediment concentration (C) values.

Optimization of the SRC method is then validated by comparing the predicted against observed values on scatter plots. Consequently, the use of log-transformed variables usually introduces a bias to the retransformed equations [3, 4]. When the least squares logarithmic regression procedure results in underestimation because of the bias given to the values below the fitted line by the regression a non parametric correction for the transformation bias may be used. Miller has proposed the following bias correction factor (CF) [31]:

$$CF = \exp(0.5\sigma^2), \text{ where } \sigma^2 = 1/(N-1) \sum_{i=1}^n (\ln C_i - \ln C'_i)^2 \quad (2)$$

σ^2 , C_i and C'_i are the variance (in base-10 logarithms), the measured and estimated concentration, respectively. The corrected equation is written as:

$$C = CF \times aQ^b \quad (3)$$

The computation of the daily sediment load (SL) in tonnes is given by the sum of the product of the three variables Q (m^3/s), C (g/l) and T (duration of time in seconds).

To test the validation of the sediment rating curve technique, it is possible to use the Nash-Sutcliffe model efficiency factor, which is to assess the predictive power of hydrological models such as the sediment transport. The best model is selected based on the EF value approaching one. The model efficiency factor is estimated using the equation:

$$EF = 1 - \frac{\sum_{i=1}^n (C_i - C'_i)^2}{\sum_{i=1}^n (C_i - \bar{C})^2} \quad (4)$$

where n is the total number of observations, C_i the i th observed value, $\bar{C}$ the mean of observed values, and C'_i the i th predicted value.

4. RESULTS AND DISCUSSION

4.1 Sediment load estimations

In this research, the relative sensitivity values are evaluated and found in the parameter estimation process. The sediment rating curve developed by the C-Q relationship for available data at Saf Saf catchment is presented in Figure 3. The latter figure is presenting the relationship developed from the total set of the mean water discharge values and the mean sediment concentrations. The best-fit power function line through the data underestimates the suspended sediment concentration at low water discharges and slightly overestimates sediment load at high discharges.

In the discharge(Q) and sediment concentration (C) relationship, the SRC has yielded an R of 0.93 as shown in Figure 3a. The best fit power function shows more variation between the observed and estimated discharge. After using the allocated dataset (42) for testing, the observed and estimated R is 0.90 as seen in Figure 3b.

Figure 3: Scatter plot of : (a) relationship between water discharge and sediment concentration, (b) observed and estimated sediment concentration.

The used discharge class technique has shown that the sediment rating curve procedure, even with infrequent sampling, can give satisfactory results. The application of the datasets of mean discharges and mean sediment concentrations has revealed interesting preliminary results (Table 1). The rating relationship is applied to the daily flow data and the resulting estimates of annual sediment load (SL) are compared with the loads computed from the observed (measured) record of sediment concentration in Table 1. The error of estimation is a measure of the accuracy of predictions in percentage. The percentage is calculated as follows:

$$\% \text{ error} = [(\text{predicted SL value}) - (\text{measured SL value}) / (\text{measured SL value})] \times 100 \quad (5)$$

The errors mentioned in Table 1 demonstrate that the annual sediment load estimated without using a correction for bias has underestimated the SL by 15.45%, but, when introducing the correction (CF), the underestimation has decreased to 7.46%. In general, it seems from Table 1 that the application of the discharge class technique has given lower errors in annual sediment load estimates.

Table 1: Rating curve estimates of measured and calculated sediment loads from the continuous record.

Sediment load (SL)	SL ($\times 10^6$ tonnes)	Error (%)	Corrected SL ($\times 10^6$ tonnes)	Error (%)
Continuous concentration record	11.22			
Single rating : one regression line	9.48	-15.45	10.38	-7.46

In addition, the calculation of the EF has also provided information about the predictive capabilities of the model. The EF value is equal to 0.54 for the single regression model (corrected concentration dataset). Threshold values to indicate a model of sufficient quality have been suggested between $0.5 < NSE < 0.65$. Moriasi and others suggest that a EF of greater than 0.50 is satisfactory in catchment models [32].

4.2 Suspended sediment load Variation

In the following discussion, we are going to explain the variations in suspended sediment load in the Saf Saf catchment. The total suspended sediment load during 39 years is 5989.57×10^3 tonnes, corresponding to a mean annual sediment yield of $476.95 \text{ T/km}^2/\text{year}$. The annual suspended sediment load vary significantly from one year to another (Figure 4). For example, during the two years 1984 and 1985, streamflow and sediment load are much higher than average, represented by $\bar{Q} = 1.483 \text{ m}^3/\text{s}$ and

$\bar{SL} = 153.58 \times 10^3$ tonnes, due to exceptional rainstorms in January (154 mm), February (234 mm), December (318 mm) 1984 and January (114 mm), March (134 mm) 1985; during which 3032.35×10^3 tonnes of suspended sediment are transported in the Saf Saf River. These two years have contributed in sediment transport with 50.63% of the total sediment load.

Figure 4: Variation of annual water discharge and sediment load in the study catchment.

Surprisingly, during the years 2011 and 2013, which are wetter than average, only 1% of the 39-year sediment load are carried out of the Saf Saf basin, mainly due to a low sediment supply into the river or a few sediment sampling during these years. Overall, this observation can be generalized on the period after the year 1996, where there is a dramatic decrease in sediment supply and/or sediment sampling, giving a priori less information on sediment long-term trends.

The study of seasonal distribution of sediment load indicates that 4652.03×10^3 tonnes are transported during the winter season from December to February, which is 77.67% of the total sediment load (Figure 5). The spring season, represented by March, April and May, is the second highest sediment load occurred during this season a load reaching 1168.94×10^3 tonnes, i.e. 19.52% of the total sediment load. The major contrast between the winter and other seasons depends on the intensity of rainstorms [33]. Early in the wet winter season, rainstorms are able to supply great volumes of suspended sediment (Figure 5), because this delivery is certainly due to the fact that the highest sedimentation rates are located in agricultural and arable lands on steep slopes. This is probably due to the influence of tillage practices on soil loss because they increase soil erosion rate and sediment losses.

During great floods or when floodplain and hillslope vegetation (with sparse grassland and shrubs) do not stabilize this sediment, large quantities may be flushed from the system. Such cycles of rapid bank erosion or gully and subsequent healing and deposition are common in this basin. Despite higher discharges in January and February, sediment loads fail to rise to the loads observed in December, indicating less sediment supply due to the following explanation: when frequent precipitation occurs, easily erodible soil is detached and transported during the first few storms (in November and December), leaving less erodible soil for subsequent storms. This can result in decreasing erosion rates from rain event to rain event [34]. Also, it is seen from Figure 5a that the storms in December transport the highest monthly sediment load of 2112.92×10^3 tonnes and mean sediment concentration equal to 7.67g/l at high rainfall amounts (Figure 5b).

Figure 5: Variation of: (a) monthly suspended sediment loads and monthly mean discharges; (b) monthly mean suspended sediment concentrations, monthly mean discharges and monthly mean rainfalls.

Nevertheless, during storms, the surface runoff is sufficient to wash sediment from slopes and the flow is sufficient to provoke bank erosion and landslides along the Bou Adjeb and Khemakhem rivers and their tributaries (Figure 6). During December to February, high sediment concentrations contribute to the high sediment loads (Figure 5b). Later in the spring season concentration is lower but the discharges are fairly high (Figure 5b) resulting in substantial load (Figure 5a).

Figure 6: Photographs showing bank erosion and landsliding in the Bou Adjeb and Khemakhem rivers.

The suspended sediment load of the autumn months is higher in November with 132×10^3 tonnes (Figure 5a). This value is mainly represented by the rise of rainstorms, runoff and sediment concentration in November 1976, 1982, 1986, 1990 and 2012 with daily values in sediment loads, sediment concentrations and water discharges that vary as : 3159-19516 tonnes, 1.30-8.58 g/l, 6.1-27.32 m³/s respectively. The summer months from June to August are often dry and the evapo-transpiration is high. The basin has the lowest sediment supply in this season where the loads do not exceed 2.45×10^3 tonnes.

5. CONCLUSION

By studying the suspended sediment dynamics at the outlet of the Saf Saf catchment, the relationship of water discharge and sediment concentration is determined to assess sediment load over 39-year period. The remarkable observed scatter of the suspended sediment concentrations underlines the importance of including suspended sediment rating curves that is developed by least square regression on logged means in discharge classes, and which has produced satisfactory estimations of sediment load. In fact, the high sensitivity of SSC to local sources in the Saf Saf basin is responsible for the complexity of the Q-C relationship, which cannot be adequately characterized using a simple rating curve.

Sediment loads have shown significant decreasing trends from the 1997 to 2015. The prevailing climatic conditions may have significant control over the water flux and suspended sediment load patterns in the Saf Saf basin. However, the other possibility is that data sources are either missing or are not available, which makes the estimation of sediment load less reliable. The mean annual suspended sediment yield during different rainstorm events of the 39 years is equal to 477 T / km²/year, a rather high value for the environment caused by steep slopes. The study basin is showing a substantial high annual variability of the sediment loads and mean concentrations.

Suspended sediment load during the winter season accounts for 78% of the total suspended sediment load during the study period and is caused by the impact of heavy rainstorms during a season with fairly low vegetation cover and tillage activity in the agricultural fields, and by the fact that the vulnerable lithological formations that are easily supplied to streams due to steep slopes.

In the winter, the existence of mass wasting such as landslides and bank erosion are mainly triggered by natural events like flooding and change in soil moisture. These erosive processes may lead to produce high sediment load. During the spring, runoff and sediment loads fail to rise to the loads observed in the winter, because of more plant cover and land use that can explain a large part of the hydrological and erosive variability in this basin. The mean monthly concentration and rainfall are highest in December after the long summer-fall dry period, the mean monthly load is also high.

The present study provides a great opportunity to continue the research and further develop and refine the methodology. Sediment concentration is a critical parameter that can provide an opportunity to evaluate the seriousness of potential environmental impact and serve as an accurate description of erosion and transport processes.

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