Statistical modelling of suspended sediment transport in the Cherf drainage basin, Algeria

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Abstract

This work deals with the main topic of the assessment of the Cherf drainage basin sediment yield based on available water discharge and suspended sediment concentration observations, and on the application of general and multivariate models. This study is also part of a broader effort aiming to predict reservoir siltation and future reliability. The 19 years of available sediment concentration data (1975/1976-1993/1994) is used to predict suspended sediment loads. From 1994, this drainage basin has shown a construction of a reservoir at its outlet (Cherf dam) for civil and industrial use. From that date, only monthly water volumes are used to estimate sediment yield in the reservoir. The methodology involved in this study is developed by a conventional sediment rating curve and a multiple regression model. The former method is investigated with the mean discharge classes derived from the recorded suspended sediment concentrations and water discharges for the Cherf drainage basin (1710 km²), prior to the reservoir construction. The later is based on rock type erodibility, mean annual runoff and basin area variables, and which is applied for the ungauged reservoir basin of 1735 km². For the rating curve model, a regression analysis is made between the instantaneous suspended sediment concentration (C) and the instantaneous water discharge (Q) based on all recorded data and seasonal ratings. Optimization of rating curve method is validated by comparing the predicted against observed values on scatter plots.

INRODUCTION

Many river systems in the Algerian regions continue to experience severe and uncontrolled environmental degradation. This has resulted into enhanced soil erosion in the catchments, thereby causing a range of problems from considerable loss of soil fertility and eventual desertification to accelerated river, reservoir sedimentation and flooding (Haregeweyn et al., 2006). In the case of Cherf River, the declining watershed resources have put considerable pressure on the agricultural land and reservoir to support households.

Considering the principles of river material extraction and transported sediments by river flow in design of river structures, study of various methods to predict river sediment transport rate seems to be necessary. Various sediment yield models have been reviewed (e.g. Jansson, 1997; Khanchoul et al., 2007).

The lack of information about the suspended sediment concentration can result in substantial errors in estimates of the total load. For this reason, a longer record of sediment loading is needed to better define the natural condition and the response of sediment yield to human disturbances. The historical hydrometric records of the Moulin Rochefort gauging station might provide temporal and spatial records of sediment load, and offer revealing information about sediment yielding processes and their controlling factors. Assessments of methods for estimating loads have been carried out using data from different sampled rivers, or using simulated data. One of these methods, widely used when and where measurements are not available (Horowitz, 2003; Khanchoul & Jansson, 2008), uses empirical models. They are referred to rating curves and are usually based on the linear relationship between suspended sediment concentration and water discharge.

Although some studies have focused on the water quality and river discharges in Cherf River, the sediment transport and its impact on the Cherf dam has received scant attention. It is our objective to explore the variability of water discharge and sediment load of the Cherf River, the upper fluvial system of Seybouse River, and relate the interannual supply of sediment yield to the geomorphic conditions of the drainage basin. The assessment of the Cherf sediment yields is based on available water discharge and suspended sediment concentration observations (period of 1975/1976-1993/1994), and on the application of a multivariate model to predict sediment load in the reservoir that will serve to protect this structure from sediment flux deposition.

STUDY AREA

The Wadi Cherf is one of the largest fluvial system in Seybouse and originates from headwaters in the Ain Babouche Aptian limestone at an elevation of 1635 m. From 1994, the Moulin Rochefort gauging station

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of this basin has disappeared because there has been a construction of a reservoir (Cherf Dam), with a capacity of 155 million cubic meters and an area of 1735 km^2 (Fig. 1). This station, located upstream of the Cherf River and considered as an outlet of the study Cherf drainage basin, was controlled by the National Agency of Hydraulic Resources (ANRH) from where water discharge and suspended sediment concentration data were collected.

The climate over the basin is semi arid to arid, with dry summers and rainfalls concentrated mainly in fall and spring periods. The average annual rainfall is equal to 290 mm with an abundance rainfall occurring from March to May (mean values ranging from 30 to 41 mm), conversely to the dry season from June to August.

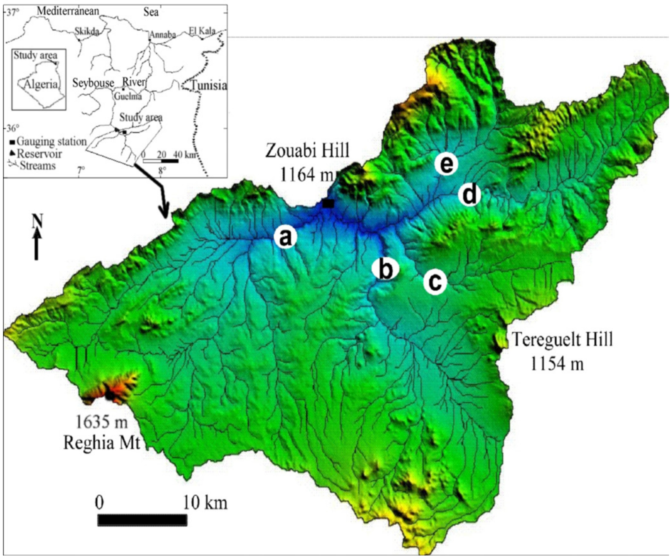

Fig. 1. Location map of the Cherf drainage basin and drainage network presentation with: a- Settara River, b- Trouch River, c- Snob River, d- Hamimine River, e- Crab River

The mean annual water discharge (1975 to 1994) is equal to 0.59 m^3/s and the highest monthly values of out-flows are recorded in January and February, with mean values not exceeding 1.20 m^3/s.

For the most part, the basin is composed of quaternary deposits and calcareous crusts that represent as much as 73% of the total basin area. The rest of the lithologic formations are Aptian limestone, Mio-Pliocene conglomerate, Oligocene sandstone, Cretaceous marl and marly limestone, and some Triassic outcrops composed of marl and clay. In this study area most of the rivers, mainly Crab, Trouch, and Settara rivers, are adapted to the geologic structure with the main arteries that are consistent with the synclinal axis and tributaries.

Slopes steeper than 3% represent only 24% of the basin area. The steep slopes (over 10%) occupy the resistant rocks, and the moderately resistant rocks distributed mainly in the north-west and north-east and along the conglomerate formations of the upper part of Cherf River. Land use is characterized by forest (Aleppo pine) associated with sparse shrubs and grasslands as steppe of Alfa (Stipatenacissima) that occupy 16% of the basin area. Cultures and associated grasslands are the dominant land use cover of the basin. The frequent use of cultivation techniques such as up and down tillage triggers rill/ gully erosion and mass wasting processes that, in turn, can generate severe erosion forms such as badlands on sandy-clay slopes.

MATERIALS AND METHODS

Meteorological and hydrological data have been monitored routinely for years by the ANRH. The Moulin Rochefort hydrometric dataset includes: (1) discrete data of suspended sediment concentration (C) and corresponding water discharge (Q), (2) records of daily water discharge, and (3) instantaneous water discharge (based on river stage) during floods. Water samples were taken for measurement of suspended sediment concentration several times a year, which make 801 hourly data sets in 19-year period (1975-1994). Data on monthly streamflow for the Cherf reservoir are obtained from the National Agency of Dams, but information is not available for that period on the sediment transport component.

In the absence of actual suspended sediment concentration (SSC) measurements, a regression analysis is made between the daily suspended sediment discharge (Qs) and the daily water discharge (Q). The most commonly used sediment rating curve is a power function:

$$Qs = aQ^b \qquad (1)$$

where a and b are regression coefficients. It has been demonstrated that improvement of the log transformation regression formulation can significantly reduce the bias introduced in the calculation (Cohn, 1995).

This regression analysis has provided a moderate coefficient of correlation (r = 0.78) and the Qs-Q data show a scatter distribution mainly at low and medium values, with an underestimation of sediment loads at high flows (Fig. 2). The regression line has underestimated the true sediment load by 37%. Due to this underestimation of sediment load, a further interesting prediction about the suspended sediment transport can be extracted from the following technique between sediment discharges and their water discharges.

An attempt has also been made by subdividing the data set into winter, spring, summer, and fall periods and by determining whether or not the plotted Qs-Q indicated a change in inclination of an imagined line through the plotted values. Optimization of rating curve method is validated by comparing the predicted against observed values on scatter plots. 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.

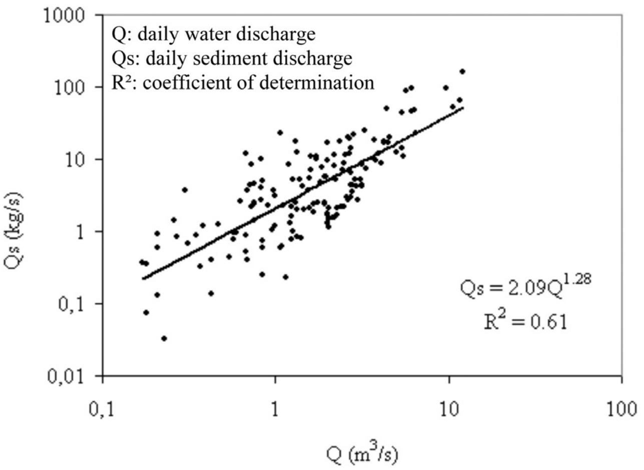

Fig. 2. Suspended sediment discharge versus water discharge (period 1975/76-1993/94)

To test the validation of the sediment rating curve technique, an efficiency factor *EF* of observed and predicted values are estimated for different predictions on validation datasets. The best model is selected based on the EF value approaching one. The model efficiency factor is estimated for all the validation sets using the equation:

$$EF = 1 - \frac{\sum_{i=1}^{n}(C_i - \hat{C}_i)^2}{\sum_{i=1}^{n}(C_i - \overline{C})^2} \qquad (2)$$

where n is the total number of observations, C_i the ith observed value, $\overline{C}$ the mean of observed values, and $\hat{C}_i$ the ith predicted value.

Concerning the application a multiple regression model, available data on suspended sediment transported by rivers in the Maghreb, which have been summarized by SOGREAH (1983), were reviewed for 130 drainage basins (Probst & Amiotte Suchet, 1992). The influences of several factors (precipitation (P) in mm, runoff (R) in mm, drainage area size (A) in km² and rock type (K_{er})) on mechanical erosion and fluvial sediment transport were analysed. A multiple regression model was proposed to estimate the river sediment yields in the Maghreb. Rock type is a qualitative variable, and each lithological formation has been ascribed a coefficient (K_{er}) which represents rock erodibility (Table 1). K_{er} is the ratio between the mechanical denudation rate of a given rock and the denudation rate of granite which is considered to be the most resistant to mechanical erosion (Probst & Amiotte Suchet, 1992).

Table 1. Rock erodibility coefficient (K_{ER}) calculated for the different lithological formations.

Lithology	K_{ER}
Granites	1
Sandstones, limestones	4
Schists/micaschists	10
Shales, pelites, marly sandstones, Marly limestones	27
Marls	50

In Table 2, the lithologic formation and K_{er} of each rock type for the study basin are represented. In this case, the mean weighted K_{er} is equal to 21. Despite the fragility to erosion of the alluvial plain deposits, they have been assigned a coefficient of 10 because their surfaces are not really disturbed by the morphogenesis due to the permeable nature of soils and very gentle slopes.

Table 2. Rock erodibility coefficient (K_{ER}) of the Cherf drainage basin.

Lithology	Area (km²)	K_{ER}
Limestone and sandstone	58	4
Conglomerate	213	10
Alluvial plains	370	10
calcareous sandstone, sandy limestone, marl	33	27
Marly limestone, limestone and marl	95	27
Triasic rocks	36	27
Calcareous crust	589	27
Colluvium and scree deposits	279	27
Marl and sandy marl	37	50
Total	1710	-
Basin K_{ER}		21

The multiple regression equation for the predicted suspended sediment yield (SY), in T km^{-2} y^{-1}, has the following terms:

$$\ln(SY) = 4.79 + (54 \times 10^{-3} K_{er}) + (4 \times 10^{-3} R) - (5.6 \times 10^{-5} A) \qquad (3)$$

The observed suspended sediment yields for the 130 basins are compared with the predicted values obtained. The previous authors have stated that the cluster of points is relatively well centred around the line of regression, even if it is scattered. The model therefore provides a reasonable explanation of the observed values. The performance of equation (3) in the prediction of Cherf sediment yield is used for the period prior to the reservoir construction, and a comparison is done between the multiple regression and the rating curve models.

RESULTS AND DISCUSSION

The sediment rating curves for all available and season suspended sediment discharge data are presented in Figure 3. The best-fit power function line through the data for the stratified single rating has given a low and moderate coefficients of correlation (r = 0.59 and 0.78), but the suspended sediment estimates at the high water discharges are accurately represented. The regression functions for the season ratings have provided coefficients of correlation ranging from 0.57 to 0.99 (Fig. 4).

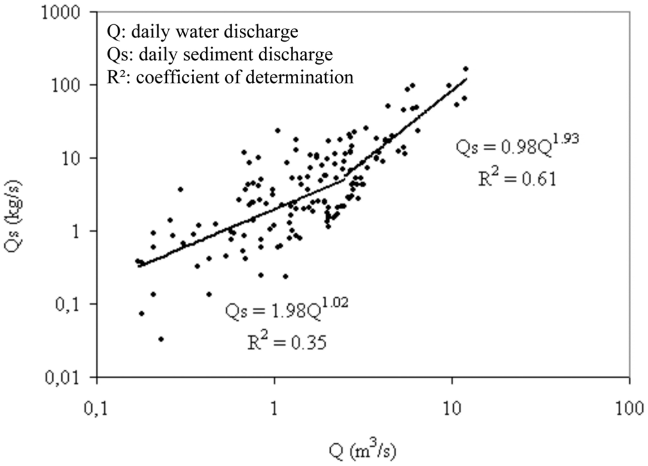

Fig. 3. Stratified regression lines of sediment discharge versus water discharge (period 1975/76-1993/94)

The error in the sum of loads by using the relationship between Qs and Q from 149 datasets and seasons with measurements, demonstrate that sediment loads calculated by using a stratified single rating curve and seasonal ratings have underestimated the load by only 3% and 1.28% after correction for bias (Table 3). Moreover, the *EF* value is equal to 0.78 for the seasonal regression model and is lower for the stratified single ratings (*EF*= 0.64). From the different calculations, the use of the seasonal sediment rating curve has given satisfactory results.

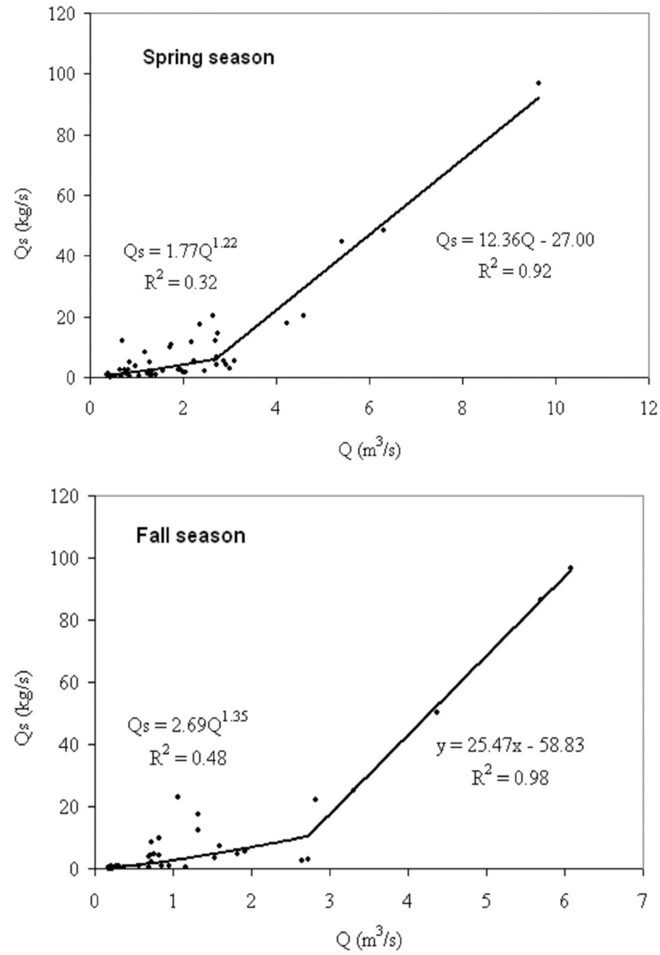

Fig. 4. Examples of Qs-Q relationships according to seasonal ratings (period 1975/76-1993/94)

Based on the seasonal sediment rating curve, the calculated mean annual specific suspended sediment yield in the Cherf drainage basin during the period 1975/1976-1993/1994 is equal to 350 T km^{-2} year^{-1}, which corresponds to an annual sediment load of 11.36 x 10^{6} tonnes.

Table 3. Sediment load computation for the stratified single ratings and seasonal sediment rating curve method.

Sediment load (SL)	SL (tonnes)	Underestimation error (%)	Corrected SL (tonnes)	Underestimation error (%)
Measured SL	131,632	–	–	–
Estimated SL: Stratified single rating	107,196	-18.57	127,513	-3.00
Seasonal ratings	106,934	-18.76	129,953	-1.28

Before using the multiple regression model in the estimation of the sediment load entering the reservoir, a calculation is made with this model for the period 1975-1994 to assess the quality of the estimated sediment load. With a mean annual runoff of 11 mm, K_{er} and basin area of respectively 21 and 1710 km^2, the estimated sediment yield (SY) is equal to 347.23 T km^{-2} year^{-1}. In comparison with the rating curve method, equation (3) has underestimated the sediment yield by only 0.79%. The multiple regression equation has shown a low degree of error, and thereby the model is judged to be sufficiently reliable for the estimation of the sediment yield at the Cherf reservoir.

Corresponding to the Cherf reservoir basin (1735 km^2) for the period 1994/1995 to 2004/2005, we have used a rock type erodibility of 21 and a mean annual runoff equal to 19 mm. The mean annual suspended sediment yield (SY) that entered the reservoir is estimated to 357.81 T km^{-2} year^{-1}; and the total suspended sediment load shows 6.83x 10^{6} tonnes.

Based on some studies undertaken in Algerian reservoirs, we estimated that 20% of the sediment flux passed through the Cherf dam. Taking the same rate, the overall sediments deposited in the reservoir during the 11-year period would be 5.46x10^{6} tonnes. This value is converted to a mass using measurements of sediment density and according to the Agency of Algerian Dams (AAD), the dry bulk density is equal to 0.81 g/cm^3 of the accumulation. The annual rate of sedimentation in the reservoir is therefore equal to 6.74 Mm^3 and according to the initial storage capacity of the reservoir of 155 Mm^3 and the total amount of accumulated sediment in the reservoir, 4.35% of the total designed capacity is lost (an average annual loss in storage capacity of 0.40% y^{-1}).

This study has shown that the Cherf Reservoir has affected more or less considerable sediment budget of the stream by interrupting the normal flux of coarse and fine sediments supplied to the channel network by the upstream drainage basin. Sediments are stored during specific runoff periods, when inflowing loads are relatively large, and then gradually released when the reservoir is drawn down for irrigation water supply.

From the standpoint of long-term use of the reservoir for water supply, continuous water release from the dam is beneficial because it increases reservoir longevity, avoids sediment concentrations and turbidity to be stored continuously for long periods, and helps to ensure a dependable future supply of water.

CONCLUSIONS

Suspended sediment concentrations and flow data for Cherf drainage basin are used to develop sediment rating curves to estimate sediment yield for a 19-year period from 1975 to 1994. Based on the results obtained in this study, the sediment rating curve method has given a reliable prediction of suspended sediment yield. As the reservoir sedimentation survey data are not available, the multiple regression model is used to provide a reasonable approximation of suspended sediment yield estimates.

Results derived from the two empirical models not only have saved time in dealing with the large historical database but also have allowed reconstruction by extrapolation from the history of the sediment load, thereby permitting quantification of drainage basin responses to human disturbances (e.g. dam and agriculture) as well as natural events. Sediment loads have shown fairly increasing trends from the late 1995s. The prevailing climatic conditions have certainly significant control over the water flux and suspended sediment load patterns in the Cherf River.

The 30-year specific sediment transport in the study drainage basin is 18.19×10^6 tonnes. From the point of view of reservoir sedimentation, soil erosion appears to be a major problem in the study reservoir. Hence, an integrated approach needs to be studied to control the erosion and reservoir sedimentation.

REFERENCES

Cohn, T. A., 1995. Recent advances in statistical methods for the estimation of sediment and nutrient transport in rivers. Reviews of Geophysics, 33, 1, 1117–1123.

Haregeweyn, N., Poesen, J., Nyssen, J., De Wit, J., Haile, M., Govers, G., Deckers, S., 2006. Reservoirs in Tigray (Northern Ethiopia): Characteristics and sediment deposition problems. Land Degradation Development, 17, 211–230.

Horowitz, A. J., 2003. An evaluation of sediment rating curve for estimating suspended sediment concentration for subsequent flux calculations. Hydrological Processes, 17, 3387–3409.

Jansson, M. B., 1997. Comparison of sediment rating curves developed on load and on concentration. Nordic Hydrology, 28, 3, 189–200.

Khanchoul, K., Jansson, M. B., Lange, Y., 2007. Comparison of suspended sediment yield in two catchments, northeast Algeria. Zeitschrift für Geomorphologie, 51, 1, 63–94.

Khanchoul, K., Jansson, M. B., 2008. Sediment rating curves developed on stage and seasonal means in discharge classes for the Mellah wadi, Algeria. Geografiska Annaler, 90A, 3, 227–236.

Probst, J. L., Amiotte Suchet, P., 1992. Fluvial suspended sediment transport and mechanical erosion in the Maghreb (North Africa). Hydrological Sciences Journal, 37, 621–637.

Sogreah, 1983. Erosion et transport solide au Maghreb. Analyse bibliographique. Rapport de projet RAB/80/011, PNUD.