Comparison of Sediment Yield in Two Catchments, Northeast Algeria

K. Khanchoul, Y. Spiga
Badji Mokhtar University, Annaba - Earth Science Faculty

M. B. JANSSON
Uppsala University, Sweden - Department of Geography

Résumé : Le présent travail compare les débits solides dans les bassins versants de Saf Saf (322 km²) et de Kébir Ouest (1130 km²) en vue de cerner les différentes modalités de transport des sédiments et les paramètres qui les conditionnent. Le transport des sédiments en suspension a été calculé à partir des prélèvements effectués dans les crues d'une part, et estimés, pour combler les séries ayant un nombre faible de lacunes, à travers une régression des débits et des concentrations de la crue. Ces deux résultats précédents ont servi à confectionner une courbe d'étalonnage des sédiments suivant la méthode des classes de débits pour évaluer les concentrations des crues n'ayant pas de prélèvements.

Le débit solide moyen annuel pendant les périodes de crues sur une durée de 22 ans (1975/76-1996/97) était de 461 T km^{-2} dans le bassin versant de Saf Saf et 247 T km^{-2} dans le bassin de Kébir Ouest. Bien que le bassin versant de Saf Saf avait de faibles précipitations et écoulements de surface, l'érosion était plus élevée. Le débit solide élevé durant les saisons hivernales et printanières du bassin versant de Saf Saf pourrait être expliqué par un taux faible de recouvrement végétal des versants et des cultures sur des sols marno-limoneux - argileux en pentes dépassant 12%. Les impacts négatifs de cette forte mobilité des sédiments sont directement ressentis dans le barrage de Zardézas qui collecte les écoulements du bassin versant de Saf Saf et qui, par conséquent, a vu sa capacité se réduire.

Pour les crues à grandes amplitudes pendant l'hiver et le printemps, l'oued Saf Saf présente des graphes en pic très accentuées des débits et des concentrations ce qui implique un fort approvisionnement en sédiments à cause de la végétation clairsemée. En revanche, l'oued Kébir Ouest présente des graphes plus larges et comparativement des concentrations faibles.

Mots clés : érosion – débit solide – bassin versants – nord-est algérien

Abstract : The present work compares the sediment yields in the Saf Saf (322 km²) and Western Kebir (1130 km²) catchments in order to get a better comprehension of the different sediment transport conditions and the parameters that govern them. The suspended sediment transport of sampled storms were calculated using measured concentration samples and additional estimated concentrations from a regression of the storm in question, to reconstruct the series having a low number of missing suspended sediment concentrations. These two previous results were used to develop a sediment rating curve with the discharge class method to calculate the concentrations from storms with no or few suspended sediment samples.

The mean annual sediment yield during flood events of the 22-year period (1975/76-1996/97) was 461 T km^{-2} in the Saf Saf drainage basin and 247 T km^{-2} in the Western Kebir basin. Although the Saf Saf drainage basin had lower rainfall and runoff, the erosion was higher. The high sediment yield in the Saf Saf basin could be explained by poorly vegetated hillslopes in the winter and spring seasons, and cultivation on steep slopes exceeding 12% on marly-silty-clayey soils. The negative impacts of this enhanced sediment mobility are directly felt in the Zardézas reservoir which collects the flows of the Saf Saf catchment and is consequently highly reduced in its capacity.

In storms of high magnitude during the winter and spring seasons, the Saf Saf wadi presents greatly peaked graphs of water discharge and sediment concentration which implies high sediment supply because of sparse vegetation, while the Western Kebir wadi presents broad graphs of discharge and comparatively low concentrations.

Key words: erosion – sediment yield – catchments – northeast Algeria

1. Introduction

Recent published studies of suspended sediment transport in northeastern Algeria are extremely limited and those that have been carried out have been based on determining some overall transport rate on an annual basis. The works by Demmak (1981) and Bourouba (2003) have treated the phenomenon of erosion in a number of catchments including the Western Kebir catchment, during the 7-year period 1972/73-1978/79. Their work was based on measured data of concentration and water discharge in order to evaluate sediment yields in these catchments. The importance of the sediment discharge in the Saf Saf catchment has been underlined in a study of erosion by Amirèche (1984). He introduced studies published by Heusch & Lacroix (1971) and Sogreah-Sogetha (1969) and used empirical formulas to quantify the gross erosion in the basins of the Maghreb and the irrigated areas in Algeria.

Facing this situation, it seemed tempting to introduce a new method developed by Jansson (1997), never used in Algeria, that permits the quantification of the fluxes of sediment in the wadis of Saf Saf and Western Kebir to get a better comprehension of the sediment transport phenomena. This method tries to reconstruct missing suspended sediment concentrations from measured concentrations of the period 1975/76 – 1996/97. High and medium high storms were mainly studied. The loads during low flow and small storms were estimated as a complement to get the total suspended load. The present study will focus on the analysis of erosion factors to understand the variations in suspended sediment transport and its relation to rainfall and runoff.

The Saf Saf and the Western Kebir catchments have been chosen because of their geographical proximity. Each one offers particular topographic, lithologic and vegetational conditions for sediment supply by runoff.

The collection of the hydro-climatic data and suspended sediment concentrations was possible with the collaboration of the different services of the National Agency of Hydraulic Resources (ANRH) of Annaba and Constantine. Daily and annual rainfall data come from five stations of a 22 year period (1975/76 - 1996/1997), viz. Azzaba (elevation of 96m), Ain Cherchar (34m), Bouati Mahmoud (156 m), Zardézas (189 m) and Ouled Habeba (980 m).

2. Characteristics of the study catchments

2.1 Morphometry

The Saf Saf catchment is located on the ridge of the Tell Mountains, 6 km upstream of the Zardézas dam. This catchment, which has an area of 322 km² at the gauging station Khemakhem, has an elongated shape oriented E-W (Fig. 1). The name of the Saf Saf wadi is applied from the junction of the Khemakhem wadi of SE-NW direction and Bou Adjeb of SW-NE direction (Fig. 2). The Saf Saf basin shows a greatly dissected landscape dominated by a high relief with steep slopes (Table 1). The steepness and the high drainage densities (Dd > 3.30 km^{-1}) of the Bou Adjeb, Khemakhem and Khorfan subcatchments affect the soil stability and contribute to gullying and mass wasting (bank erosion, mudflows and landslides).

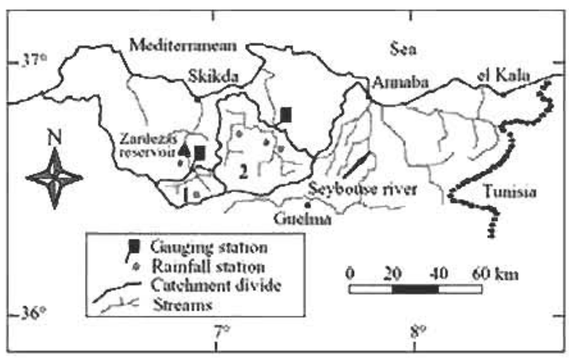

Fig. 1 Location of the study area. 1- Saf Saf catchment; 2- Western Kebir catchment.

The Western Kebir wadi at Ain Cherchar drains an area of 1130 km² and presents a very elongated and triangular shape with an orientation E-W parallel to the coastline (Fig.1), that gives the southern hillslopes an exposure to the north (Bourouba, 2003). The drainage system is formed by the union of the Hammam and Emchekel wadis (Fig. 2). The latter stream of E-W direction traverses a set of highly dissected mountains. The Hammam wadi of SW-NE direction, drains the southern part of the catchment with steeper slopes (71% of the area > 10%) and high drainage density (Dd = 3.28 km^{-1}).

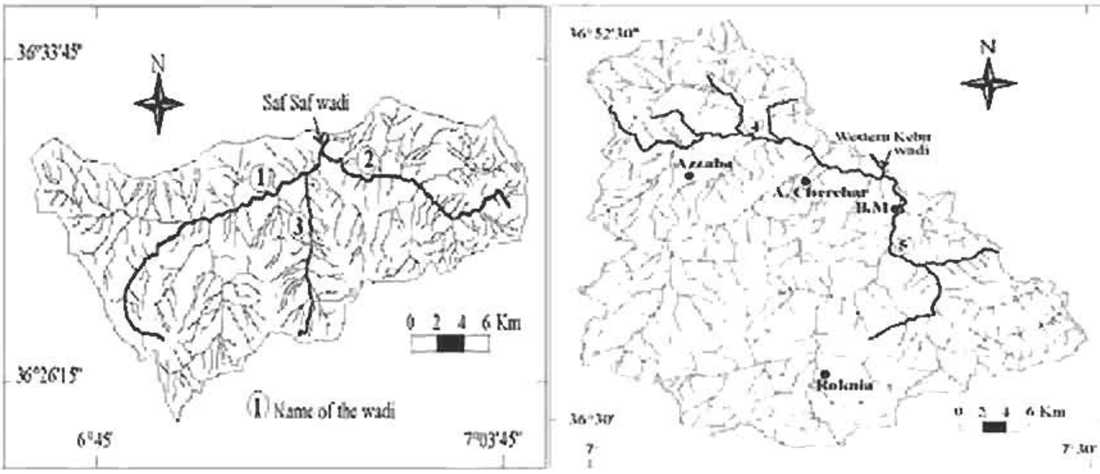

Fig. 2 Drainage networks of the Saf Saf and Western Kebir catchments. 1- Bou Adjeb wadi; 2-Khemakhem wadi; 3- Khorfan wadi; 4- Emchekel wadi; 5- Hammam wadi.

Table 1. Morphometric characteristics of the study catchments.

Morphometric parameters	Saf Saf wadi	Western Kebir wadi
Area (km²)	322.00	1130.00
Perimeter (km)	81.00	137.00
Minimum elevation (m)	206.00	25.00
Maximum elevation (m)	1220.00	1220.00
Mean elevation (m)	628.00	278.00
Drainage density (km^{-1})	3.60	2.51
Stream frequency (km^{-1})	7.61	6.49
Main stream length (km)	24.00	58,00
Compactness coefficient	1.27	1.15
Time of concentration (hours)	5.00	17.00
Orographic coefficient	823.00	62.00
Mean slope of the catchment (%)	23.79	15.00

2.2 Geology

The Saf Saf catchment has 22% of its area covered by erodible soils on geologic formations like marly limestone of Senonian, gypseous and sandy clay of continental high Miocene and the under-numidian clay of Oligocene (Fig. 3). Geologic formations with highly erodible soils have symbols with lines in Fig.3. Landslides appear largely in the gypseous clay provoked mainly by bank erosion at the stream base of the Bou Adjeb and Khemakhem rivers.

The mudflows, sometimes associated with sandstone boulders are especially visible at the sandstone outcrop foot of Ouled Habeba and at marly limestone foothills (Fig. 3). In the northeast, erodible soils are found on the facies belonging to the sandy-clayey flysch (lower Cretaceous) and to the micaceous sandstone (Eocene).

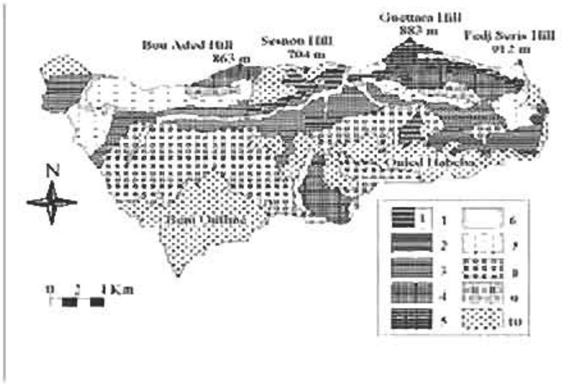

Fig. 3 Lithology of the Saf Saf catchment. 1- quaternary formations (scree deposits and alluvium[1]) ; 2- under-numidian clay (Oligocene) ; 3- gypseous clay (high Miocene) ; 4- marly limestone (Senonian) ; 5- micaceous sandstone (Eocene) ; 6- micro-breccias flysch ; 7- calcareous and clayey sandstone (Cretaceous) ; 8- conglomerate (Mio-Pliocene) ; 9- limestone (Miocene) ; 10- numidian sandstone (Oligocene).

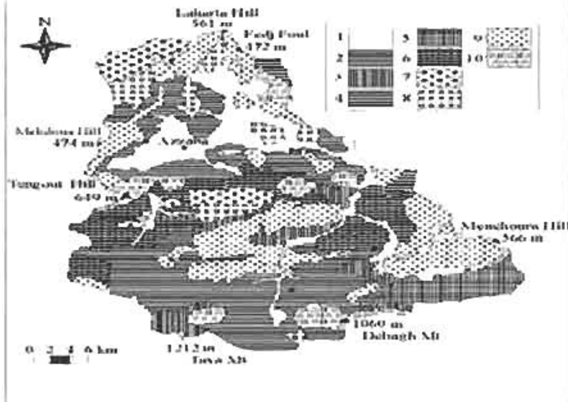

Fig. 4 Lithology of the Western Kebir catchment. 1- quaternary formations; 2- under-numidian clay (Oligocene); 3- marl and shaly marl (high Cretaceous and Eocene); 4- clayey-shaly sandstone (low Cretaceous); 5- marly limestone (Senonian); 6- micaceous sandstone (Nummulitic); 7- metamorphic rocks (schist of Paleozoic); 8- conglomerate (Oligocene); 9- numidian sandstone (Oligocene); 10- limestone (Cretaceous and Senonian).

The landscape of predominantly resistant rocks includes sandstone (Oligocene) and Neritic limestone (Fig. 3). The sandstone, which covers the most extended area of the basin (34% of the area), is subjected to tectonic accidents and highly dissected rocks are found on slopes steeper than 16%. The conglomerate formation of the continental Miocene is distributed on nearly 19% of the basin surface. This substratum, greatly affected by folds and faults show a dense drainage network often in conformity with the geologic structure.

The Western Kebir catchment is characterized by the presence of extended areas of rocks with highly erodible soils (clay, marl, marly limestone and micaceous sandstone) that are estimated to cover almost 50% of the basin (symbols with lines in Fig. 4). The clayey material of the alluvial plains of Azzaba, Roknia and Bouati Mahmoud (B.M) covers part of the Numidian sandstone and can give rise to bank erosion by the Emchekel wadi. In the southern part of the Western Kebir basin, marl and marly limestone of folded structure and clay cover a great part of the Hammam subcatchment. The fragile nature of these rocks allows them to be periodically dissected by gullies and moved away as landslides or mudflows. In limestone domes, the rock formation belongs to the neritic Aptian, and provides high summits with very steep hillslopes (Taya Mountain).

The north of the basin is composed exclusively of sandstone and under-numidian clay of the Oligocene, conglomerate (Oligocene), metamorphic rocks and limestone (Jurassic) which are usually broken up into small hills. The southern part shows a set of mounds with steep hillslopes (> 15%) in particular facing north. Sandstone and the metamorphic surfaces present aggressive stream downcuttings in conformity with the direction of fractures.

2.3 Vegetation

The forest and bushes of the Saf Saf catchment cover 30 % of the basin area. The forest that occupies 11% of that total surface, is found on hilly sandstone slopes of the numidian sandstone of Oligocene (Fig. 3). Dense bushes are observed on the numidian sandstone of Ouled Habeba and spreads to the north on clayey-gypseous rocks and to the southwest on marly limestone surfaces (Fig. 3). Damaged bushes occupy 4% of the basin. The rest of the land is used as grazing land and for cultivation, mainly of cereals and fruit trees.

The vegetation cover of the Western Kebir catchment is composed of permanent forest and bushes that occupy the majority of the northern Emchekel subcatchment. The forest of oak cork and oak zeen species, is distributed mainly in the north (Laharta Hill).

In the southeast part of the Emchekel basin on metamorphic and sandstone rock there is forest on 9% of the surface against bushes on 37% (Fig. 4) of which dense bushes are observed on numidian sandstone and micaceous sandstone. Grazing lands and cultivation substitute to a certain extent the forest and bushes and occupy the floodplain of Azzaba - Ain Cherchar and the clayey-micaceous sandstone and marly limestone terrains. Sparse bushes predominate in the southern Hammam subcatchment.

2.4 Rainfall

The two catchments belong to a temperate and humid climate of the Mediterranean type with a slightly fresh winter and a hot summer. Based on recorded daily rainfall of the 22-year period in the study catchments, the Saf Saf catchment is characterized by irregular annual precipitations with a mean annual rainfall of 617 mm and a mean annual temperature of 20°C (Fig. 5). The temperatures vary between 7°C in January and 29 °C in August.

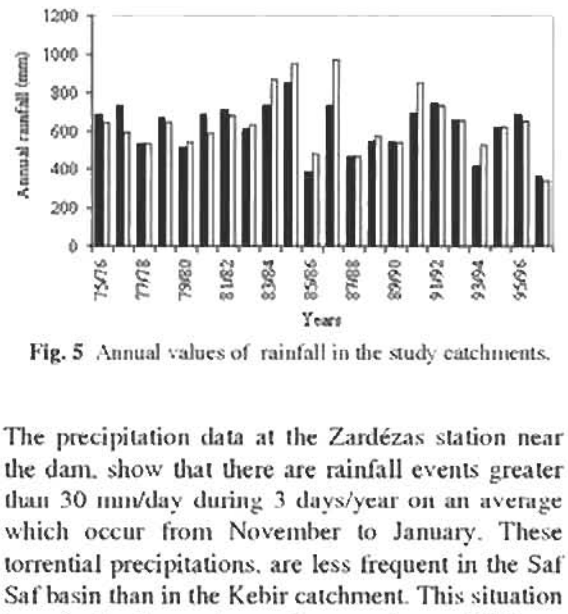

Fig. 5 Annual values of rainfall in the study catchments.

The precipitation data at the Zardézas station near the dam, show that there are rainfall events greater than 30 mm/day during 3 days/year on an average which occur from November to January. These torrential precipitations, are less frequent in the Saf Saf basin than in the Kebir catchment. This situation is probably due to the southern sandstone hillslopes that stand as an obstacle to the humid winds coming from NW to NE. Nevertheless, the violent character of the torrential rains of frequent intensities greater than 100 mm/day may generate high flood events capable of accelerating erosion processes.

In both catchments, the number of days of medium high rains between 19 and 29 mm/day is relatively high, ranging from 5 to 6 days/year.

Low rainfall intensities always constitute a great part of the annual rainfall. The torrential and medium high rains are responsible for most of the flood events calculated in this study.

The Western Kebir catchment is characterized by a mean annual precipitation, recorded at the three rainfall stations of 640 mm (Fig. 5). The mean annual temperature is 17°C with a minimum of 8°C in January and a maximum of 28°C in August.

The thunderstorms recorded at Azzaba and Ain Cherchar stations are most frequent from October to April and are present 4 days/year as a 22-year average, frequent in November, December and February. Within this basin, the torrential rains are frequent in the northern part of the catchment and are less abundant in the southern mountainous part (BNEDER, 1995).

3. Methods

3.1 Suspended sediment measurements and analysis

Surveys of suspended sediment concentration and water discharge are carried out in the two streams Saf Saf and Western Kebir. The gauging stations are controlled by ANRH which also performs the water sampling of surface water using one liter bottles, and the analysis of the samples. The water samples, which are taken in various conditions of stream flows, are filtered using a filter of Laurent type (Ø = 32 cm). The filter and the mud contained in the bottle is weighed after drying in a special oven during 30 minutes to eliminate the organic matter at a temperature of 110 °C.

The instantaneous values of concentration of storm flows are sampled in variable time intervals. The samples are often more numerous in periods of flood peaks with short time intervals (from half an hour to two hours), whereas in low flow or when the water discharge is constant during the day, a minimum of sampling is done (1 to 2).

For storm events with few or no concentration samples, sediment concentrations were calculated with a sediment rating curve at water discharges with small time intervals e.g. one hour when the water discharge rises or falls quickly and two hours or more when the water discharge rises or falls slowly. It was considered important to calculate the sediment load of each small time increment and to sum up the loads of all the increments of the high-water event.

3.2 Sediment rating curves

Before developing sediment rating curves, it was necessary to reconstitute the missing concentration values of the measured storm events using relationships between concentration and instantaneous water discharge (Fiandino, 2003) for the best among the following solutions:

- linear formula : $y = ax + b$;
- power formula : $y = ax^b$ (by log-transformation)
- or exponential formula : $y = a\ e^{bx}$

The purpose of using these relationships was to get smaller time increments for the load calculation of the measured storm events, and to increase the number of data on an equal time basis of the events to get relevant data for the individual discharge classes when sediment rating curves were constructed for the whole period. The developed regressions gave coefficients of correlation exceeding 0.82.

When too many suspended sediment concentration data were missing of a flood, sediment rating curves must be used describing relationships between concentration and water discharge such as $C = f(Q)$. As can be judged from Fig. 6, there is no single relationship between the two variables because of the differences in the level of concentration for different highwater events and of different hysteresis relationship for each event (Jansson, 1996). For this reason, it is essential to introduce a method that permits to establish valid sediment rating curves. The chosen method applied in this paper has been developed by Jansson (1985, 1997).

The data set used to develop the sediment rating curves of the Saf Saf stream consists of 1962 measurements of instantaneous suspended sediment concentration including the extra concentrations calculated for each measured flood event and the corresponding water discharge data, and 1805 water and sediment data of the Western Kebir wadi. The procedure started by sorting the data that include measured and the extra calculated values, and by regrouping them into distinct classes of water discharge. The definition of the width of each class interval depends on the data base in question. To the low discharge values, the class interval can be narrow and may contain 70 values in a discharge class. This class interval becomes progressively wider as the data base becomes small at high water discharges. The mean sediment concentration of the measurements in every class is computed and introduced in a plot to determine the change in direction of the sediment rating curve and to check the goodness of fit of the developed regression (Fig. 6). On the basis of this analysis, it seems that the relationships between the two variables are not always simple. In the same set of high water discharge, we can have different magnitudes of concentration. These relationships are influenced mainly by rainfall associated with other factors such as nature of the soil, land use and topography of the area where the rain occurs.

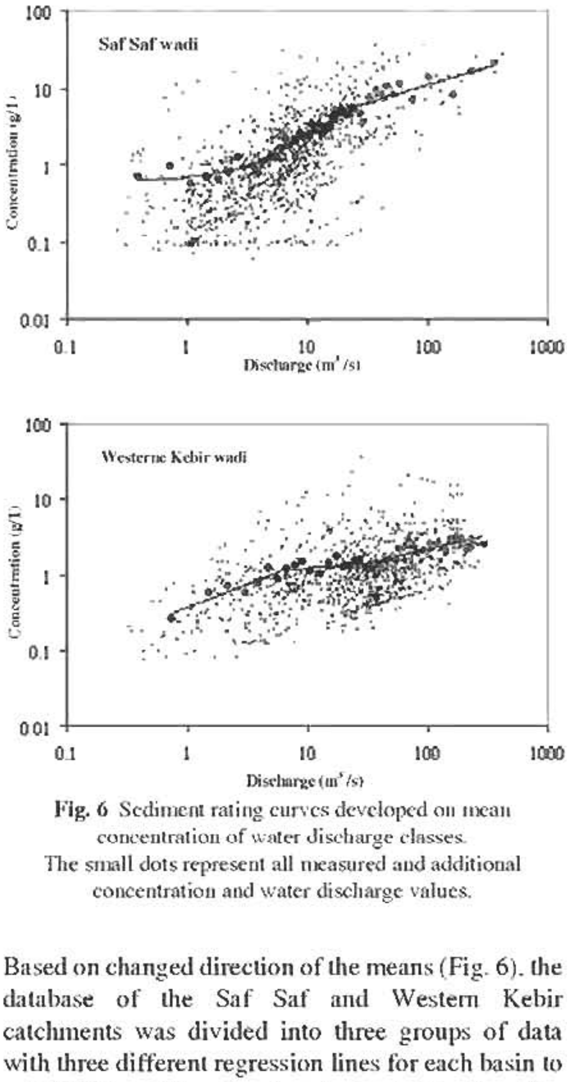

Fig. 6 Sediment rating curves developed on mean concentration of water discharge classes.
The small dots represent all measured and additional concentration and water discharge values.

Based on changed direction of the means (Fig. 6), the database of the Saf Saf and Western Kebir catchments was divided into three groups of data with three different regression lines for each basin to establish the sediment rating curve. As log-transformation was used to develop the regression equations the re-transformed equations were corrected for bias. Miller (1984) proposed a correction factor (CF) of a regression of natural logarithms.

This factor is defined by the following formula:

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

σ^2, C_i and C'_i are the variance, the measured and estimated concentration respectively.
For base-10 logarithms the correction factor according to Hald (1952), Jansson (1985) and Ferguson (1986) is:

$$CF = 10^{1.1513\sigma^2} \qquad (2)$$

where σ^2 is the variance in base-10 logarithms.

3.3 Suspended sediment discharge, load and yield

The sediment discharge (Qs) of the sampling occasion is:

$$Qs\ (kg/s) = Q\ (m^3/s) \times C\ (g/l) \qquad (3)$$

Sediment load of flood events was calculated down to low flow conditions. The computation of the sediment load (SL) of each storm event is given by the general formula:

$$SL\ (tonnes) = \frac{\sum Q(m^3/s) \times C(g/l) \times T(seconds)}{1000} \qquad (4)$$

where T is the duration of time between concentration values, measured or computed.
As two basins of different sizes were to be compared there was a need to calculate sediment yield. For each month of the year, the sediment loads of flood events were summed and divided by the basin area (A). The sediment yield (SY) is:

$$SY\ (tonnes/km^2) = \sum_{i=1}^{n} SL\ (tonnes)/A\ (km^2) \qquad (5)$$

where i is flood event

The annual sediment yield becomes equal to the sum of the monthly yield values. The mean annualsediment yield corresponds to the sum of the annual sediment yield values divided by 22 years.

4. Results and discussion

The use of the discharge class method to develop sediment rating curves provided good results as the sum of sediment discharges with measured concentration values were close to the sum of those calculated with concentrations predicted with sediment rating curve technique (Table 2).
The calculated loads comprise 202 high, medium high, and low floods but not very small floods in the Saf Saf wadi and 204 floods in the Western Kebir wadi. In the following discussion, attempts will be made to explain the variation in sediment yield between the two drainage basins by looking at sediment yield on an annual, a seasonal, and a storm basis.

4.1 The annual sediment yield

The mean annual sediment yield in the Saf Saf catchment was 461 T km^{-2} compared with 247 T km^{-2} in the Western Kebir drainage basin. That means that the sediment yield was almost two times greater in the Saf Saf basin than in the Western Kebir catchment (Table 3). The three years 1983/84, 1984/85 and 1992/93 with the highest annual loads in the Saf Saf wadi gave 63% of the total sediment load of the 22-year period (Fig. 7). The Western Kebir drainage basin did not have years with such extreme sediment yields as the Saf Saf wadi. In the Western Kebir catchment the sediment transport of the three years 1983/84, 1984/85 and 1990/91 represent 45% of the total 22-year sediment transport.
Considering the hydrologic conditions of the storm events, it appears that the Western Kebir catchment behaves as a highly efficient runoff generating unit (Fig. 7) with nineteen annual runoff coefficients of the storm events down to low flow ranging from 11% (1975/76) to 64% (1983/84). The stream flow response becomes less pronounced when the runoff efficiency of the Saf Saf wadi is examined, where annual runoff coefficients greater than 10% are obtained only for sixteen years, with a maximum of 37% (1984/85). The low runoff coefficients of storm events, observed mainly in the Saf Saf wadi, may be attributed to higher evapo-transpiration in grazing and cultivation areas, and more infiltration and transmission losses that reduce the total discharge, especially downstream, where losses increase in proportion to the increase in ephemeral channel width and the texture of the sediments (Jordan, 1977, Wallace & Lane, 1978, and Belmonte & Beltran, 2001).

Table 2. Corrected equations and the sum of sediment loads calculated from measured concentrations [(1)] and from sediment rating curves [(2)].

	Equations	R^2	σ^2	CF	Corrected equations	Sum of Qs (10^3 tonnes)	
						Measured [(1)]	predicted [(2)]
Western Kebir catchment	$C = 0.3714\ Q^{0.614}$ $C = 0.8927\ Q^{0.1429}$ $C = 0.405\ Q^{0.369}$	0.84 0.22 0.55	** 0.004398 0.008358	** 1.002202 1.004190	$C = 0.3714\ Q^{0.614}$ $C = 1.002202 \times 0.8927\ Q^{0.1429}$ $C = 1.004190 \times 0.405\ Q^{0.369}$	869.15	844.57
Saf Saf catchment	$C = 0.5868\ e^{0.1591Q}$ $C = 0.3925\ Q^{0.8276}$ $C = 1.3186\ Q^{0.461}$	0.80 0.85 0.64	0.006478 0.002666 0.014213	1.003244 1.001334 1.007132	$C = 1.003244 \times 0.5868\ e^{0.1591Q}$ $C = 1.001334 \times 0.3925\ Q^{0.8276}$ $C = 1.007132 * 1.3186\ Q^{0.461}$	590.02	546.85

**: number of water discharge classes insufficient to establish a bias correction.

Table 3. Mean annual rainfall, runoff, water volume, sediment concentration and sediment yield during storm events in the two study catchments.

Variables	Saf Saf wadi	Western Kebir wadi
Number of storm events	202	204
Mean annual rainfall (mm)	337.52	394.12
Mean runoff (mm)	62.90	103.26
Mean volume ($10^6 m^3$)	20.23	113.42
Mean concentration (g/l)	7.33	2.46
Mean sediment yield (t/km^2/year)	461.00	247.00

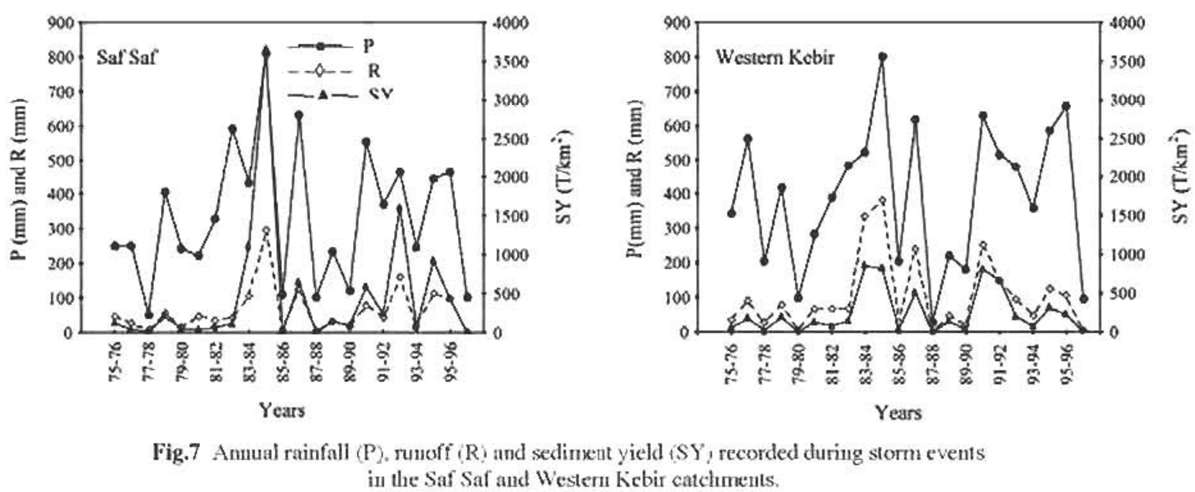

Fig.7 Annual rainfall (P), runoff (R) and sediment yield (SY) recorded during storm events in the Saf Saf and Western Kebir catchments.

Despite the fairly low amounts of water discharge during floods, the sediment transport of the 202 storm events in the Saf Saf catchment has revealed that it is subject to high erosion (Table 3). In fact, other physical conditions than runoff may play a major role in this high erosion in the Saf Saf basin such as:

- a higher orographic coefficient than that of the Western Kebir catchment. A general steepness of the topography and a higher drainage density excellent for the delivery of sediment (Table 1).
- a dominance of slopes greater than 10% that occupy 97% (310 km²) of the Saf Saf catchment area against only 68% (730 km²) of the Western Kebir catchment.
- a small percentage of forest and bushes in the Saf Saf basin.
- soils along the river banks along the reaches upstream of the gauging station are prone to landslides and slumps.

The annual average suspended sediment concentrations of flood events are consistently higher in the Saf Saf wadi than in the Western Kebir stream (Table 3).

4.2 Relationships of annual sediment yield versus rainfall and runoff

After the presentation of the annual sediment yields, it would be interesting to understand the hydrologic work and search for a relationship between the net erosion, i.e. the sediment yield, and the main erosion factors: rainfall, and stream flow.

The obtained results are as follows:

- The correlation coefficient of the relationship between annual rainfall of storms and annual sediment yield during flood events is 0.86 in the Saf Saf catchment and 0.95 in the Western Kebir catchment at a significance level of 5% (test of Spearman) (Fig. 8).
- The two catchments present more complex relationships between annual mean concentrations and annual rainfall/annual runoff. An important part of the concentration values are dispersed widely around the regression line of which the coefficient of correlation doesn't exceed 0.58. This scatter in the rainfall plot probably reflects an oscillation in the conditions of the stream flow including the groundwater flow conditions, and in rainfall intensity leading to periods of high sediment transport alternating with periods of more clear runoff. Thereby, the factor of rainfall alone remains insufficient to explain the variations in sediment fluxes.
- The correlation coefficients of the relationships between annual flood runoff and sediment yield of the flood events in the two catchments are very high (r > 0.96) and significant at 5% (Fig. 8). The flow régime is characterized by extremes with humid years associated with active erosion and by low flow years insufficient to conduct high erosion and produce great quantities of suspended sediment load.

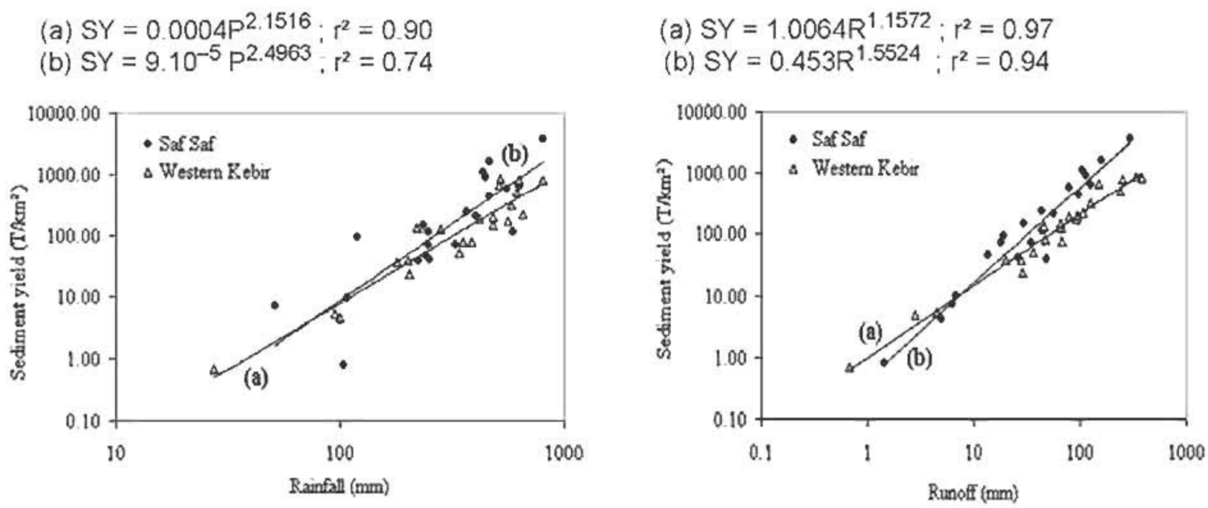

Fig. 8 Relationships of annual values: rainfall (P) versus sediment yield (SY) and runoff (R) versus sediment yield.

4.3 The seasonal sediment yield

The mean monthly sediment yield values of flood events during the study period are higher in the winter and spring seasons and the high monthly values are more abundant in the Saf Saf wadi. Indeed, the sum of the mean monthly sediment yields of January-March represent almost 85% of the mean annual sediment yield, whereas in the Western Kebir wadi only 67% are transported during these three months.

Monthly relationships between stream flow and sediment yield show a considerable rise of the coefficient of correlation of the rainy months related to the winter and spring seasons of the year. This coefficient is greater than 0.98 in both catchments. In addition, the relationships of monthly rainfall versus sediment yield also show an important rise of the coefficient of correlation which exceeds 0.91.

4.3.1 Fall season

The rainfall and hydrometric characteristics of the two catchments in the autumn months September to November can be illustrated as follows :

- the mean monthly rainfall of the flood events is high in November with 39 mm in the Western Kebir catchment (Table 4). However, the two catchments show seasonal quantities of rain of 52 mm in the Saf Saf catchment and 69 mm in the Western Kebir catchment.
- the mean monthly runoff coefficients range between 2.3% and 7% in the Saf Saf catchment and between 6% and 18% in the Western Kebir catchment.
- a low seasonal flood runoff of about 3 mm in the Saf Saf wadi basin, and about 9 mm in the Western Kebir wadi basin.
- a seasonal mean concentration of 3.86 g/l in the Saf Saf wadi and 3.64 g/l in the Western Kebir wadi.
- the mean sediment yield of this season is three times higher in the Western Kebir catchment with 32 T km^{-2} than in the Saf Saf catchment with 10 T km^{-2}. The autumn sediment loads make up 13% of the mean annual loads of the study period in the Kebir stream and 2.2% of the loads in the Saf Saf stream.

Table 4. Mean monthly rainfall, runoff, runoff coefficient, concentration and sediment yield during storm events in the two catchments.

a- Saf Saf catchment

	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
P (mm)	-	17.95	33.52	47.08	86.98	55.09	55.09	33.02	9.57	-	-	0.63
R (mm)	-	0.41	2.22	4.94	23.81	11.81	11.70	6.51	1.02	-	-	0.48
RC (%)	-	2.28	6.62	10.49	27.37	21.44	21.79	19.71	10.66	-	-	76.19
C (g/l)	-	2.48	4.12	5.50	11.11	6.72	3.97	4.25	3.82	-	-	5.35
SY (T/km²)	-	1.02	9.14	27.18	263.49	79.33	46.45	27.65	3.91	-	-	2.55

b- Western Kebir catchment

	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
P (mm)	2.20	28.48	38.55	69.49	87.24	70.34	58.89	26.69	11.20	1.06	-	-
R (mm)	0.15	1.71	6.93	10.77	27.95	25.35	18.93	9.73	1.73	0.01	-	-
RC (%)	6.82	6.00	17.98	15.50	32.04	36.04	32.14	36.46	15.45	0.94	-	-
C (g/l)	1.37	2.20	4.04	2.18	2.34	2.49	2.42	2.11	2.58	0.51	-	-
SY (T/km²)	0.20	3.75	27.93	23.49	65.55	54.57	45.11	22.59	4.12	0.01	-	-

4.3.2 Winter season

The winter months December to February are essentially characterized by rains of polar and cold air masses. These rains often cover large areas and are continuous with moderate to high intensity (rains > 30 mm/24 hours). They produce more runoff than those of the autumn. Indeed, the winter period is characterized by mean monthly runoff coefficients that vary from 11% to 27% in the Saf Saf wadi and from 16% to 36% in the Western Kebir wadi. This coefficient can exceed 80% in particular at times of exceptional floods in the Saf Saf stream. This fact indicates a high percentage of surface runoff in certain cases. The mean seasonal hydrological and sedimentological characteristics of the two catchments are:

- the mean seasonal rains are higher in the Western Kebir catchment, but the winter rains of the two catchments make up about 60% of their mean annual rainfalls (Table 4).
- a winter runoff of flood events of 64 mm in the Western Kebir basin representing 61% of the mean annual flood runoff, and a flood runoff of only 41 mm in the Saf Saf basin which is 65% of the mean annual runoff.
- the mean concentration of flood events of the season is 9.14 g/l in the Saf Saf catchment against 2.37 g/l in the Western Kebir basin.
- a higher winter sediment yield of flood events in the Saf Saf catchment with a mean seasonal sediment yield of 370 T km^{-2} that constitutes about 79% of the mean annual sediment yield. This is almost 2.6 times higher than the sediment yield in the Western Kebir catchment.

Although the rainfall and runoff is lower in the Saf Saf catchment the sediment yield is higher than in the Western Kebir basin. This can be explained by other factors such as higher steepness of the basin slopes, erodible soils close to the main river channel near the gauging station (Fig. 3), higher percentage of the area with poor vegetation and more human activity in the Saf Saf catchment which altogether can cause a high percentage of surface runoff out of the total runoff during winter floods.

4.3.3 Spring season

This season has a mean sediment yield of 78 T km^{-2} in the Saf Saf catchment and 72 T km^{-2} in the Western Kebir catchment, thus supplying less sediment than the winter season (Table 4).

The reasons of this decrease in sediment load compared with the winter season can be explained by:

- the existence of a seasonal plant cover capable to reduce the mobility of sediment materials from hillslopes.
- a reduction of flood events generated by high intensity rains compared with the winter season, especially the number of high torrential rains that lead to excessive surface erosion and rapid mass-movements.

As is shown in Table 4, the Western Kebir river shows higher runoff and runoff coefficient of the season, about 1.5 times higher than the Saf Saf wadi. The high runoff in the Kebir basin may be caused by higher groundwater flow at the end of the wet season.

The Saf Saf wadi has a mean seasonal concentration of the storm events of 4.1 g/l against only 2.3 in the Western Kebir wadi. A high relative relief within its basin and a sub-humid climate coupled with sparsely forested areas and cultivation on fairly steep hillslopes are major reasons for this intense erosional activity in the Saf Saf catchment. In addition, rocks with highly erodible bare soils are exposed more or less in large portions of the Saf Saf catchment.

4.3.4 Summer

The summer months from June to August are dry and the evaporation is high. The runoff coefficient is low in the Western Kebir wadi, with 1% in June (Table 4). On the other hand, the Saf Saf stream presents a high runoff coefficient, of 76%, mainly related to one torrential rainfall and an instantaneous runoff due to a rapid overland flow on dry soils. The low water volumes flowing in this season reflect the low sediment transport. Nevertheless, the Saf Saf catchment shows a mean monthly sediment yield in August of 2.55 T km^{-2} (Table 4).

4.4 Selected storm events

4.4.1 Flood in November 1982

The sampled flood of 11-12 November in both catchments shows that in the Saf Saf wadi, Q and C had simultaneous peaks (Fig. 9) but the falling limb had an increase in sediment concentration, leading to a counterclockwise loop of the Q-C relationship (negative hysteresis).

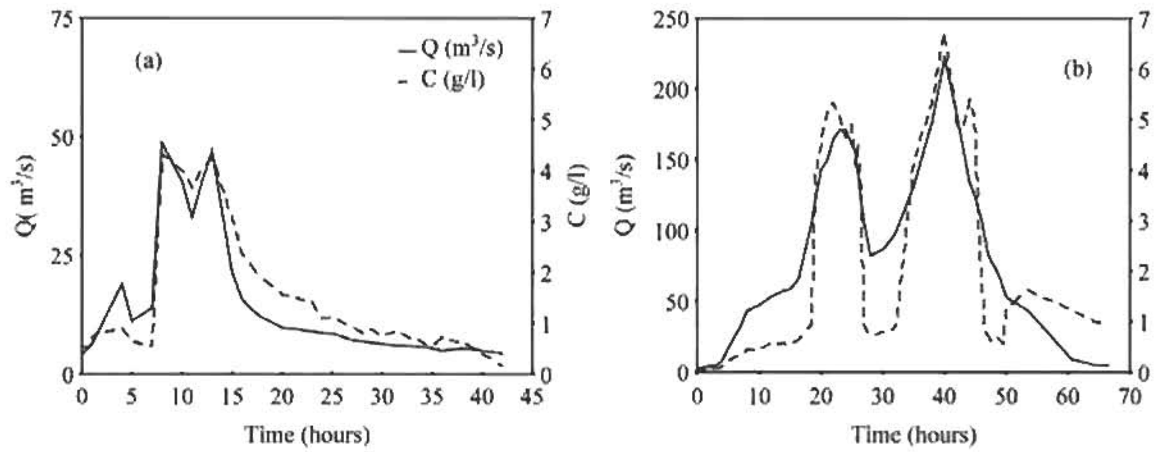

Fig. 9 Floods in the autumn. (a) 11-12/11/1982 in Saf Saf ; (b) 10-13/11/1982 in Western Kebir.

Although, the Saf Saf catchment received more rainfall (123 mm) during this flood than the Western Kebir catchment, it shows low runoff and low sediment concentration (Table 5). Consequently, despite more or less sparse and low permanent vegetation, the dry soils after a hot and dry summer season prevented much sediment to be washed away, and the soils were not humid enough to provoke landslides. The total sediment load produced is then estimated at 5.3×10^3 tonnes, which represents about 15% of the annual sediment yield of the flood events in 1982/83.

Table 5. Water discharge and sediment discharge variations during storm events in the study catchments. 1, Saf Saf wadi ; 2, Western Kebir wadi.

Storm events	November 1982		December 1990		March 1985	
Catchments	1	2	1	2	1	2
Rainfall (mm)	123.00	79.15	101.60	142.50	95.50	104.35
Runoff (mm)	6.70	17.28	17.67	45.20	76.30	57.99
Volume (10^6m^3)	2.16	19.53	5.69	51.07	24.57	65.53
Mean discharge (m^3/s)	14.27	79.19	21.08	186.67	71.09	195.72
Mean concentration (g/l)	2.46	3.55	14.53	3.17	4.81	1.50
Peak discharge	48.70	222.07	94.11	321.45	345.33	316.81
Peak concentration	4.31	6.72	36.13	3.40	39.62	2.81
Sediment load (10^3 tonnes)	5.30	69.39	82.69	162.10	118.17	98.08
Sediment yield (T/km^2)	16.46	61.41	256.81	143.46	366.98	86.80

The sediment load of the same event in the Western Kebir catchment, was 69.4×10^3 tonnes which represents 42% of the annual sediment yield in 1982/83. This event resulted from a total rainfall 79 mm and produced a peak discharge of 222 m^3/s and a peak concentration of 6.7 g/l (Fig. 9).
The relationship between Q and C of the first hydrograph shows a marked positive hysteresis because of re-erosion of sediment in the channel before the water discharge had peaked.

The second hydrograph shows C-Q graphs with simultaneous peaks and somewhat higher concentrations than the Saf Saf wadi. As the Western Kebir basin area is about 3.5 times larger than the Saf Saf basin area, the scale of the Q axis is nearly 3.5 times greater.

4.4.2 Flood in December 1990

This is the most important storm event of the hydrologic year 1990/91, measured from 23 to 26 December in the Saf Saf catchment. The most intense rain fell in December 24 and 25 with 32 mm and 52 mm. The Q and C curves show simultaneous peaks (Fig. 10) and the Q-C relationship presents a plot that corresponds to a linear relationship. The main C peak shows as high a concentration as 36 g/l reached in 29.5 hours (Fig 10, Table 5), provided by a quite high runoff which was capable of eroding and transporting great quantities of sediment toward the outlet. The sediment transport during this flood event was about $83x10^3$ tonnes, representing 44% of the sediment load of flood events in the hydrologic year 1990/91. The recorded flood at the Western Kebir catchment shows a flattened summit of the hydrograph with a highest discharge of 321 m^3/s (Fig. 10). The concentration is very low compared to that of the Saf Saf wadi with a peak of only 3.4 g/l (Table 5). In spite of its fairly high runoff coefficient of 32% and rainfall of 143 mm, this flood transported less sediment load per km^2 compared to the Saf Saf catchment, and contributed with only 18 % of its annual sediment yield of floods in 1990/91 (803 T km^{-2}). The appearance of sediment is not solely dependent on water discharge but can rather be related to other geomorphic conditions. As concentrations are relatively low, there is a limiting factor that appears to be the availability of material because of the higher vegetation cover and litter than in the Saf Saf basin causing less sediment concentration in the surface runoff and less landslides.

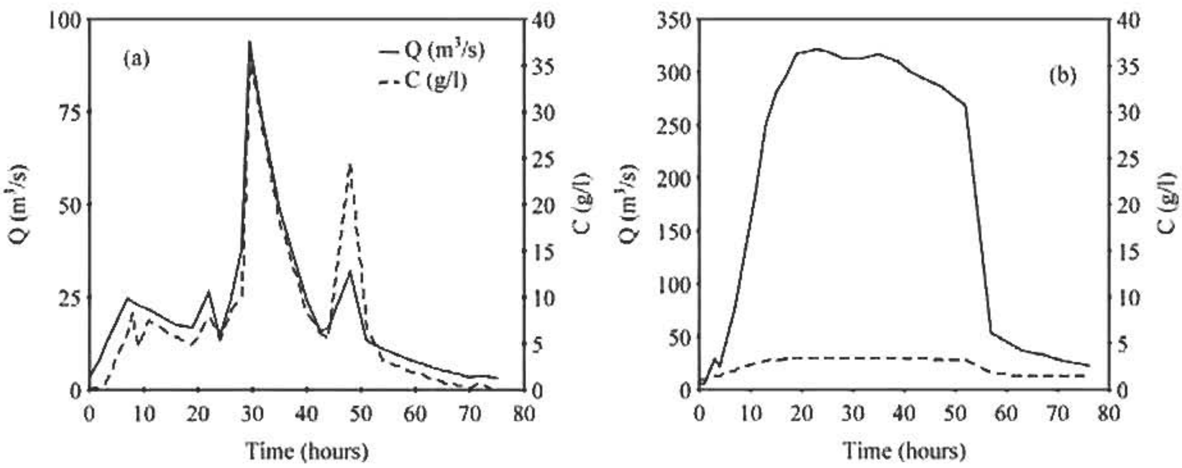

Fig. 10 Floods in the winter. (a) 23-26/12/1990 in Saf Saf; (b) 23-26/12/1990 in Western Kebir.

4.4.3 Flood in March 1985

The floods of this season and in particular those of March can present high runoff and sediment discharge because of the humid period that may prevail, exceeding sometimes the winter moisture. For this reason, a storm event representing the most rainy month of the season has been chosen for discussion.

The flood of 7-10/03/85 is an important event in terms of sediment transport in the Saf Saf catchment that comes after the flood of 29/12/84 - 03/01/85 (3134 T km^{-2}). The total rainfall of this flood event, which represents 71% of the rain in March 1985, shows a rainfall of 96 mm and a runoff of 76 mm (Table 5).

The morphological impact of this flood event are certainly influenced by the saturation of the soils of the weak geologic formations poorly covered by vegetation. The high peaks of water discharge and sediment concentration obtained after 17 hours of the rising limb coincide with the time of concentration of the catchment and will be caused by overland flow (Fig. 11, Table 5).

This situation produced the huge quantity of 367 T km^{-2} of material removed by overland flow and mass wasting on clayey and marly hillslopes and river banks. This sediment load represents about 10% of the sediment transport in 1984/85 which was a sediment transport year of high magnitude.

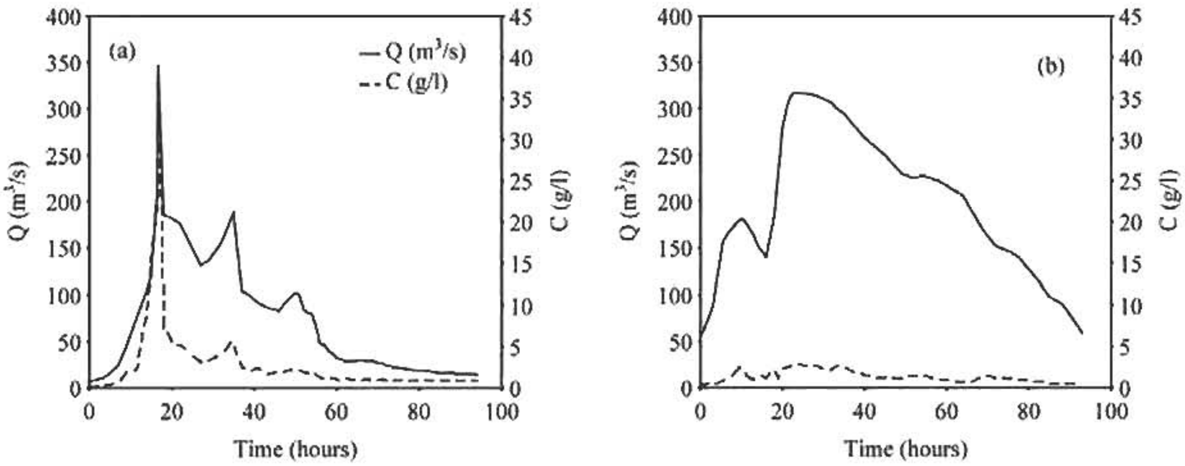

Fig. 11 Floods in the spring. (a) 7-10/03/1985 in Saf Saf ; (b) 7-10/03/1985 in Western Kebir.

The flood 7-10/03/1985 in the Western Kebir wadi shows a broader Q graph but lower runoff than the Saf Saf basin (Fig. 11. Table 5). This broader peak seems to be made up of both overland flow and throughflow. Although this flood event corresponds to somewhat higher rainfall in the Western Kebir basin compared to that of the Saf Saf basin (Table 5), it shows a lower sediment load of 87 T km^{-2} that represents only about 11% of the total sediment transport of flood events during the hydrologic year 1984/85. It is believed that the limited sediment load could be caused by less supply of sediments in the surface runoff water due to more vegetation cover, less steep slopes, and to less erodible soils along the river in the downstream parts of the basin with less slides and slumps near the gauging station, and may also be caused by some sediment accumulation on floodplains.

4.5 Zardézas reservoir sedimentation

Sediment deposition in a reservoir provides an ideal opportunity to study the erosional history of a drainage basin. As previously mentioned, the Saf Saf wadi passes through the Zardézas reservoir. This reservoir constructed in 1945 has since then undergone substantial sediment accumulation. Because of the trap efficiency of the Zardézas dam by the Saf Saf inflow, the initial water capacity of 15 Mm^3 is not as high any more.

The available reports taken from the Agengy of Algerian dams show that during the first 13 years of existence (1945-1958), the sedimentation reached 4.97 Mm^3. The accumulated volume increased to 10.36 Mm^3 in 1982 and 13.30 Mm^3 in 1992.

From the period of 1982 to 1992, the Zardézas reservoir accumulated 2.94 Mm^3 of sediment. The bulk density of the deposits is 1.8 g/cm^3. The bulk density is by implication always the wet bulk density. The dry bulk density of deposits must be known to be able to compare with the sediment calculations at gauging stations. Another reservoir, which is dry some period of time every year, had a measured wet bulk density of 1.4 g/cm^3, and a measured dry bulk density of 0.6 g/cm^3 on the terraces with clayey silt and silty clay, and a wet bulk density of 1.25 and a dry bulk density of 0.4 g/cm^3 in the upper parts of the channel deposits (Axelsson, 1992, p. 93). Therefore we estimated the dry bulk density of the Zardézas reservoir to be about 0.9 g/cm^3. With this dry bulk density the sediment deposited in the reservoir during the period 1982 to 1992 was calculated to be about 2.65 $x10^6$ tonnes. With a mean dry bulk density of 0.8 the sediment deposition would be $2.35x10^6$ tonnes. In fact, some wash load has passed the reservoir.

The suspended sediment load of storm events at the gauging station during this period was shown to be $2.16x10^6$ tonnes. Sediment load during small storms and during low water periods can be estimated to be about $0.06x10^6$ tonnes during this ten-year period. Some of the material in the reservoir is bed load material. A bed load of 10% of the suspended load would give $0.22x10^6$ tonnes of bed load (cf. Lane & Borland, 1951). Altogether the bed load and suspended load at the gauging station during the 10-yr period would be $2.44x10^6$ tonnes. As the sampling used surface water samples this load is too low an estimation of the total load.

In recent years, the Algerian government has given more interest to the problem of reservoir sedimentation and the impact of the development of agriculture on erosion, especially during the drought periods that have touched the country. Thus, decisions were taken to remove the accumulated sediments in the reservoir and to make managements in the drainage basin starting from 1993 by an Algerian society (SONATRAM).

5. Conclusion

The suspended sediment transport was calculated for the Saf Saf wadi with a drainage basin of 322 km^2, and the Western Kebir wadi with a basin of 1130 km^2. In water sampled storms a few additional concentrations were added by using one regression of each storm. For storms with no or few concentration samples, a sediment rating curve was used. The sediment rating curves of the two wadis were developed with the discharge class method. The measured and additionally calculated concentrations of all sampled storms were grouped into water discharge intervals and sediment rating curves were developed by using the mean concentrations and the mean discharges of the discharge classes.

The sediment load for a 10-year period at the gauging station in the Saf Saf wadi before the Zardézas reservoir was estimated to be 2.44x10^6 tonnes, and the deposition in the reservoir including bed load was about 2.35-2.65x10^6 tonnes which implies that the sediment load calculations were of the right order of magnitude.

The mean annual sediment yield during high, medium high, and low flood events of the 22 years of the study period was 461 T km^{-2} in the Saf Saf drainage basin and 247 T km^{-2} in the Western Kebir basin. Although the Saf Saf drainage basin had lower rainfall and runoff the erosion was higher. However, other factors seem to be more important in the erosion dynamics. These erosion factors can be summarized as:

- higher relief energy expressed by the orographic coefficient.
- higher drainage density.
- a greater part of the area having slopes exceeding 12% gradient in the Saf Saf catchment.
- extended cultivation on lands mostly associated with marly silty-clayey materials, often furrowed on slopes exceeding 12%.
- a more important supply of sediment coming from eroded and poorly vegetated hillslopes in the winter and spring seasons.

Especially during high rainfall years there is sediment transport of high magnitude in the Saf Saf wadi. During the 22-year study period three humid years contributed with 63% of the sediment transport in the Saf Saf wadi. The Western Kebir stream had a lower and more even sediment transport within the years and between the years. In this river, 45 % of the sediment load of the 22 years were transported in three years.

The sediment yields are highest in the winter and spring seasons. In storms of high magnitude during these seasons the Saf Saf wadi has highly peaked discharge and concentration graphs which implies high sediment supply with much erosion because of sparse vegetation, while the Western Kebir wadi has broad graphs of discharge and low concentrations implying high amounts of throughflow and upper groundwater flow and better filtering of the sediment of the overland flow by vegetation and litter.

As understood from reservoir sedimentation, it is essential to fight against the erosion and mass movement processes by using different procedures such as reforestation and other soil conservation practices.

Reference

Amirèche H. (1984). Etude de l'érosion dans le basin versant de Zardézas (Tell constantinois. Algérie) - milieux physiques et aménagement rural. Thèse doct. 3ème cycle, Université Aix-Marseille, 240 p.

Asselman N. E. M. (2000). Fitting and interpretation of sediment rating curves. J. Hydrol., 234: 228 – 248.

Belmonte A. M. C., & Beltran F. S. (2001). Flood events in Mediterranean ephemeral streams ramblas) in Valencia region, Spain. Catena, 45: 229 – 249.

Benkhaled A. & Remini B. (2003). Analyse de la relation de puissance : débit solide - débit liquide à l'échelle du bassin versant de l'Oued Wahrane (Algérie). Rev. Sci. Eau, 16 (3): 333 – 356.

Bourouba M. (2003). Etude de la teneur de sédiments en suspension de deux oueds méditerranéens intramontagneux du Tell oriental (Algérie). Z. Geomorph., 47 : 51 – 81.

Bureau National d'Etudes pour le Développement Rural (1995). Etude du Bassin Versant de l'Oued Kébir Ouest (Barrage de Zit Emba). Direction Générale des Forêts, Tipaza, Algérie. Phases 1 et 2.

Demmak A. (1982). Contribution à l'étude de l'érosion et des transports solides en Algérie septentrionale. Thèse doct. Ing., Paris, 323 p.

Ferguson R.I. (1986). River loads underestimated by rating curves. Water Resour. Res., 22 (1) : 74 – 76.

Fiandino M. (2004). Apports de matières en suspension par les fleuves côtiers à l'Etang de Berre (Bouches – du – Rhône, France). Etudes de géographie physique, suppl. n°XXXI. Travaux du BVRE, du Mont – Lazère. UMR6012 « Espace » - équipe G.V.E. Nice.

Hald A. (1952). Statistical theory with engineering applications. – Wiley, New York.

Heidel S. G. (1956). The progressive lag of sediment concentration with flood waves. Trans. Am. Geophys. Union, 37(1): 56 – 66.

Heusch B. & Lacroix A. M. (1971). Une méthode pour estimer l'écoulement et l'érosion dans un bassin – application au Maghreb. Mines et géologie n°33. Rabat.

Jansson M. B. (1996). Estimating a sediment rating curve of the Reventazon river at Palomo using logged mean loads within discharge classes. J. Hydrol., 183: 227 – 241.

– (1997). Comparison of sediment rating curves developed on load and on Concentration. J. Nordic Hydro., 28 (3): 189 – 200.

Jordan P. R. (1977). Streamflow transmission losses in Western Kansas. Journal of Hydraul. Div., Proc. ASCE 103 (HY8): 905 – 919.

Wallace D. E. & Lane L. J. (1978). Geomorphic features affecting transmission losses potential on semiarid watersheds. Hydrol. Water Resour. Ariz. Southwest, 8: 157– 164.

Marre A. (1992). Le tell oriental algérien : de Collo à la frontière tunisienne. Etude géomorphologique. Office des Publications Universitaires, Alger. 624 p.

Miller D.M. (1984). Reducing transformation bias in curve fitting. Am. Stat., 38(2): 124 –126.

Sogreah-Sogetha. (1969). Etudes générales des aires d'irrigation et d'assainissement agricole en Algérie. Dossier Ministère de l'Agriculture et de la Réforme Agraire, Alger, 164 p.

Zavoianu I. (1985). Morphometry of drainage basins. Developments in Water Science, 20. Elsevier, Amsterdam. 238 p.

Used formulas :

Compactness coefficient = $0.282P/\sqrt{A}$

Time of concentration (Giandotti) = $\dfrac{4\sqrt{A}+1.5L}{0.8\sqrt{Hm-h}}$

Orographic Coefficient = Hm x tang φ, where tang φ = Hm – h /A,
With P : catchment perimeter (km); A : catchment area (km^2)
h : minimum elevation (m); Hm : mean elevation (m)
L : main stream length (m)