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Hycham Abdesslam Kazi Tani, Abderrazak Bouanani, Kamila Baba-Hamed, Jean-Luc Probst. The Dynamics of Suspended Particulate Matter in the Oued Nachef (Tafna Basin, Algeria): Typology of Flood Events and Contribution to Sediment Transport. *Journal of Geological Resource and Engineering*, 2020, 8 (5), 10.17265/2328-2193/2020.05.002 . hal-03092202

HAL Id: hal-03092202

<https://hal.science/hal-03092202v1>

Submitted on 1 Jan 2021

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The Dynamics of Suspended Particulate Matter in the Oued Nachef (Tafna Basin, Algeria): Typology of Flood Events and Contribution to Sediment Transport

Kazi Tani Hycham Abdesslam¹, Bouanani Abderrazak², Baba-Hamed Kamila² and Probst Jean-Luc.³

1. Laboratory N° 25, Dpt. Hydraulic, Institute of Science and Technology, Maghnia University Center, 13300, Maghnia, Algeria

2. Laboratory N° 25, Dpt. Hydraulic, Faculty of Technology, University Abou Bakr Belkaid, 13300, Tlemcen, Algeria

3. Laboratory of Functional Ecology and Environment, University of Toulouse, CNRS, Toulouse INP, University Toulouse 3-Paul Sabatier (UPS), Toulouse 31062, France

Abstract: This article focuses on the study of sediment transport during flood events in the Oued Nachef watershed that feeds the Mefrouche dam. To understand the sediment dynamics in this watershed, ANRH data on instantaneous water discharges and the respective concentrations of suspended particulate matter were used. This enabled the selection of some of the largest flood events over a 24-year period in order to establish the log-log relationships between sediment load (concentration and flux) and water discharge. However, the discharge-concentration relationships revealed hysteresis phenomena that enabled a flood typology to be established and classified into seven categories, thus showing very different transfer dynamics in relation to flood events. The results showed that Category 6 floods presenting hysteresis in the form of a figure of eight exported almost 44% of the suspended particulate matter load while representing just 29% of the flow discharge.

Key words: Algeria, Oued Nachef, suspended sediment transport, flood, hysteresis, typology.

1. Introduction

In semi-arid zones characterised by very irregular and often intense rainfall, climatic factors have considerable influence on the removal of particles from the ground and *in fine* on mechanical soil erosion. These particles are transported to wadis primarily by surface runoff. They can then be deposited temporarily along the course of the wadi or as sediment behind the barrages and dams, causing them to silt up. Some of these eroded soil particles will reach the Mediterranean Sea, accompanied by various pollutants that are adsorbed or complexed by the suspended particulate matter, thus contributing to the pollution of coastal areas. Research undertaken on mechanical soil erosion and sediment transport in

rivers shows that the specific erosion of the Maghreb's watersheds is significant, ranging from 1,000 to 5,000 tonnes per km² per year [1]. Erosion varies considerably from one basin to the next and can reach up to 7,200 t/km²/year, as in the case of the Oued Agrioun in Algeria [2]. As a consequence of this significant erosion in watersheds in Maghreb countries, the discharge of sediments carried on average every year to the Mediterranean Sea is estimated to be 100 million tonnes [2]. In these Mediterranean regions, mechanical soil erosion and the transport of sediment in rivers are mainly controlled by extreme climatic events, generally of considerable intensity and short duration, that generate significant surface runoff on watershed soils and sometimes intense flood flow in the wadis [3-13]. It is important to study these flood periods because they play a key role in terms of evaluating the export of particles and also obtaining a better understanding of

Corresponding author: Kazi Tani H. A., PhD, associate professor, research field: surface hydrology.

Probst J.L., PhD, CNRS research director, research field: hydrology and biogeochemistry.

particle transfer processes from the soil to surface water and their dynamics during transport in a river environment. These periods therefore represent hot moments, whose dynamics and contributions need to be understood more fully today, but also allow a better understanding of hot spots on a regional scale, notably the highly erodible areas liable to supply particles to surface water. Furthermore, there needs to be improved understanding of these contributory zones, which also play a key role in the flow of exported suspended particulate matter, to ensure that they are managed more effectively in terms of physical soil erosion and production of fluvial sediment. Hence, in this investigation of the dynamics of the transfer of suspended sediment transported by the Oued Nachef in north-western Algeria, it was decided to focus on a detailed study of flood event episodes. The aim of this study was also to contribute to improved quantification of the flow of sediment exported by this wadi and liable to be deposited behind the Mefrouche dam.

2. Presentation of the Study Zone

2.1 Geographical Location and Geomorphological Characteristics

Located on the Terni plateau at an altitude above

1,000 m, the watershed of the Mefrouche dam is part of the large Tafna watershed (Fig. 1) located in north-western Algeria, south-east of the city of Tlemcen. It drains a surface area of 89 km² between latitudes 34°45' to 34°52' N and longitudes 1°15' to 1°25' W.

Rectangular in shape and with a Gravelius coefficient of 1.37, the basin is oriented north-east to south-west. Its main watercourse, the Oued El-Nachef, is 14.25 km long, has its source in Aouinet Dejaj and ends at the Mefrouche dam, the capacity of which is 15 Hm³. The Mefrouche watershed is a peneplain and therefore offers very little potential for erosion. The physical and geomorphological characteristics of this watershed are summarised in Table 1.

2.2 Hydroclimatology

Variability in the amount of rainfall has been the subject of several studies in Algeria [14-17]. The monthly distribution in terms of percentage of rain in relation to the average interannual mean over a 44-year period and the monthly percentage of flood events in relation to the total number of flood events over a 25-year measurement period in the Mefrouche watershed are illustrated in Fig. 2.

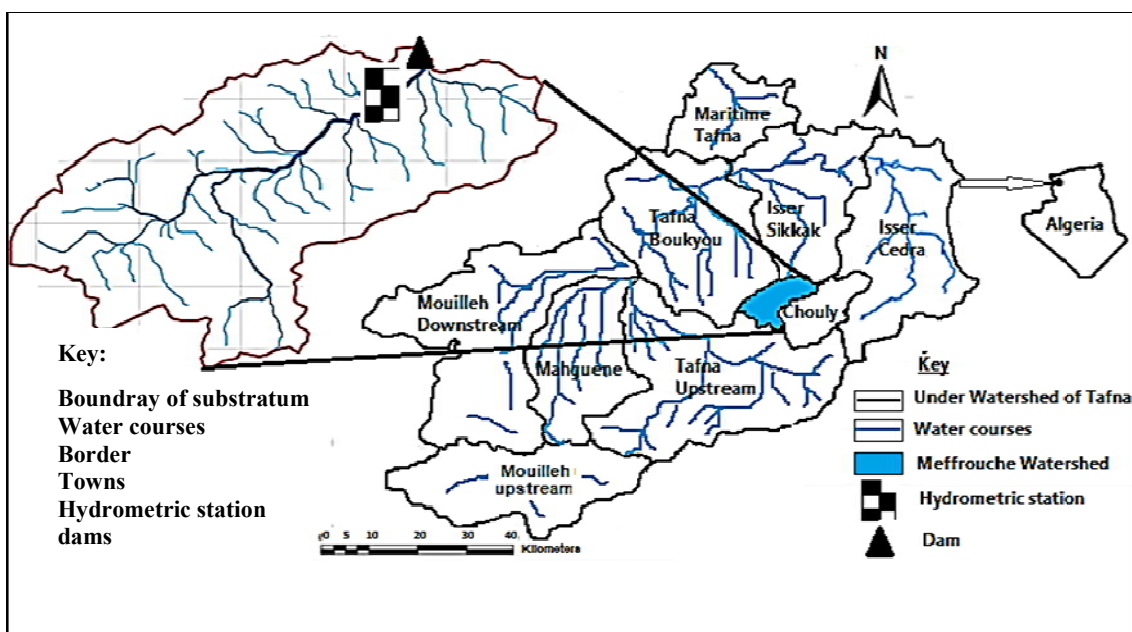


Fig. 1 Geographical location of the Mefrouche watershed.

Table 1 Physical and geomorphological characteristics of the watershed.

Characteristics	Values
Equivalent rectangle length (km)	18.28
Equivalent rectangle width (km)	5.07
Compactness coefficient KC	1.37
Basin slope Ig (m/km)	18.84
Drainage density D (km ⁻¹)	2.48
Average slope of the watercourse (%)	2.38
Bifurcation ratio (RC)	3.72

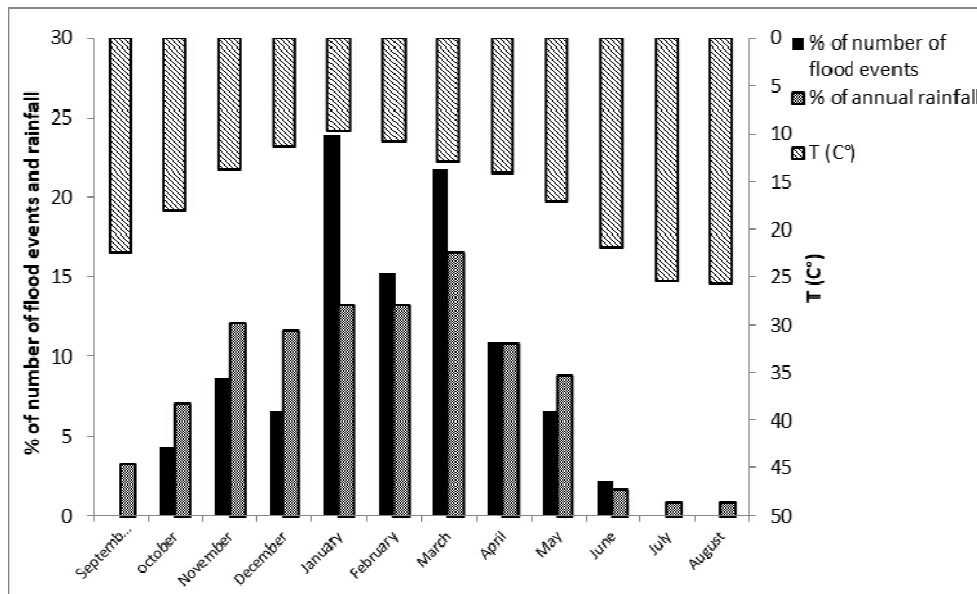


Fig. 2 Average monthly variations in air temperature (averages for the period 1970-2007), contributions in % of rainfall in relation to the annual total (average for 1970-2010) and the number of flood events in relation to total flood events (1990-2014).

The Mefrouche dam reservoir is in asemi-arid climate zone [18, 19]. Fig. 3 shows that rainfall begins in the month of September with a monthly total of 19 mm, i.e. 3.3% of annual rainfall, as temperature starts to fall. The first flood events start to occur in October due to the intensity of the monthly rainfall, with the number of flood events per month reaching its maximum in January at 24%, i.e. 11 flood events on average that month, and rainwater runoff of 79 mm. In February, there is a clear drop in the number of flood events. This phenomenon is explained by the start of the rise in monthly temperatures (seasonal change), but also by the refilling of aquifers and absorption of rainwater by growing local vegetation. In March, a rise in rainfall is recorded that increases the average number of flood events to around ten. Beyond that,

from the month of April, the frequency of flood events reduces in relation to the intensity of rainfall, temperatures rise and the dry season begins.

3. Data and Methods

3.1 Classification of Flow Rates and Concentrations

This study was based on values corresponding to instantaneous measurement of the concentration (*C*) of suspended particulate matter (SPM) and flow discharge values (*Q_L*) measured by the Algerian National Agency of Hydraulic Resources (ANRH) during the period 1990-2014 at the Sidi Hafif hydrometric station (coordinates lat. 36.09; long. 0.40; alt. 1,134 m) located upstream of the Mefrouche dam. The flow discharge values were obtained from the rating curve of water levels recorded on a limnometric

scale. With regard to the concentrations, for each water level reading a sample of untreated water was taken on the bank from the surface of the wadi using a 500 mL bottle. The collected samples were stored in a coolbox at 4 °C, then transported to the laboratory. The separation of SPM was performed by filtration using pre-weighed filter paper with a porosity of 10 µm. These filters rapidly became clogged with the suspended particulate matter and the filter’s porosity very quickly tended towards the standard porosity (0.45 µm) classically used to filter SPM. This matter was then oven dried at 105 °C for 30 min and the dried filter containing SPM weighed again. The weight of SPM was the difference between the pre-weighed amount and the weight after drying, before being returned to the volume of filtered water and expressed in g/L. Fig. 3 shows the variation in concentration in different categories of flow rate during a 24-year measurement period.

Fig. 3 shows a wide range of average concentrations for different flow rate categories. The interval of variation in concentrations was large for the lowest categories of flow rates, varying between 0.01 and 10 g/L for flow rates between 0.003 and 0.01 m³/s, and between 0.02 and 31.64 g/L for between 0.01 and 0.03 m³/s. This concentration variation interval reduced as the flow rates increased. This

phenomenon can be explained by the fact that during the slowest flow rates there is a combination of flows with SPM coming from different sources, whereas with the fastest flow rates the contribution of surface runoff and mechanical soil erosion from slopes becomes predominant and the SPM concentration therefore tends towards 1 g/L, as has already been suggested by Refs. [20-22] for different rivers around the world. With regard to the fastest flow rate categories (between 30 and 100 m³/s), the measurements were generally taken in the spring and the sediments being transported were mainly due to linear erosion in the watercourse from the banks and the riverbed.

3.2 Flood Event Selection Criteria

The study of flood events was based on instantaneous measurement pairs of concentration and flow (C_i, Q_i) at time t_i , representing 1,540 pairs of values in this study. These measurements were taken during flood events over a 24-year period from 1990 to 2014 and with a variable duration of T hours. In the present study, 446 pairs of values were selected that represented 45 representative flood events in total. The selection criteria for these flood events were:

- a distinct and straightforward flood hydrograph (rise and fall);

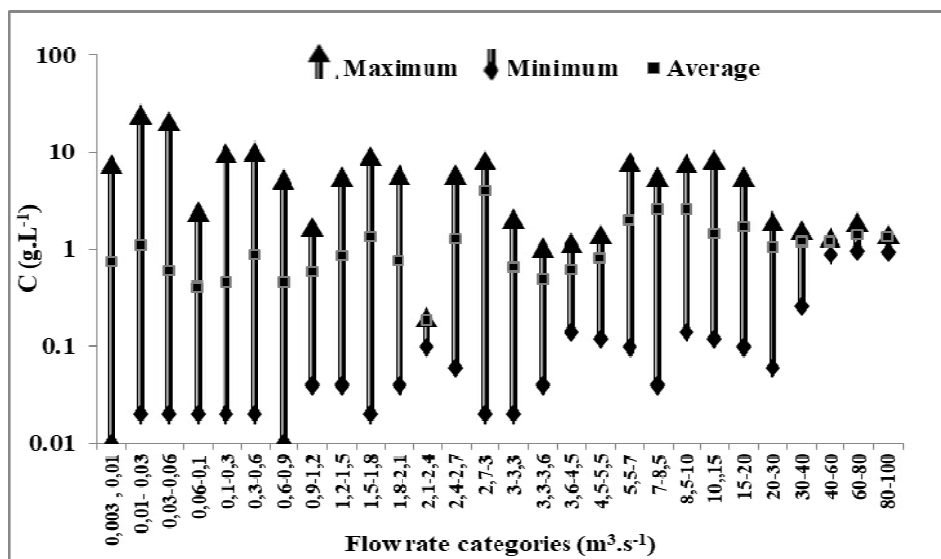


Fig. 3 Variation in SPM concentration for different flow rate categories (averages for the period 1990-2014).

- a flood peak above the average annual flow;
- a variation curve of SPM concentrations without null values.

3.3 Concentration-Flow Relationship

Generally, the most widely used regression between instantaneous measurements of concentrations of suspended particulate matter in relation to flow rate is the log-log model [23-25].

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

where parameters a and b are regression coefficients. Although the appropriateness of this approach has been debated by Ref. [26], its application appears suitable in several case studies and for different aims [27]. It is based on the transformation of values into logarithms to reduce the polarisation presented in calculations [28, 29].

Another empirical relationship, known as the curve of solid transport [30] that links sediment discharge with flow discharge has classically been used [31-36]. Its calculation offers the best adjustment and allows daily values of sediment discharge flow Q_s to be evaluated from the flow discharge Q observed, and the study of flow/sediment discharge relationships and the influence of flow discharge on sediment transport over different timescales: annual, monthly and seasonal [37-44]:

$$Q_s = aQ^b \quad (2)$$

where exponent b is a function of the physical, climatic and hydrological characteristics of the watersheds [45, 46] or the hydraulic conditions of the flow in the watercourse [21]. It generally varies between 1 and 2. Refs. [47, 48] suggest that exponent b and constant a reflect the characteristics of the watershed, whereas Ref. [49] considers that the constant represents an index of soil erodibility.

3.4 Calculation of Solid and Liquid Inputs

The suspended sediment input A_s is calculated by integrating the product of suspended sediment discharge over time. By considering the linear variation in sediment discharge over time, the average

sediment input for the period between times t_i and t_{i+1} is given by the relationship:

$$A_s = \sum_1^N (t_{i+1} - t_i) Q_i C_i \quad (3)$$

where:

A_s : annual solid input (t/year);

Q_i : flow discharge rate (m³/s);

C_i : concentration of sediments at time t_i .

The arithmetic total of the basic sediment inputs for a given period (month, season, year or flood) provides the sediment input for this period. The specific tonnage or specific input expressed in t/km²/year is obtained by dividing the total annual input by the surface area of the watershed.

Similarly, the corresponding liquid input A_L expressed in m³ is given by the relationship:

$$A_L = \sum_1^N (t_{i+1} - t_i) Q_i \quad (4)$$

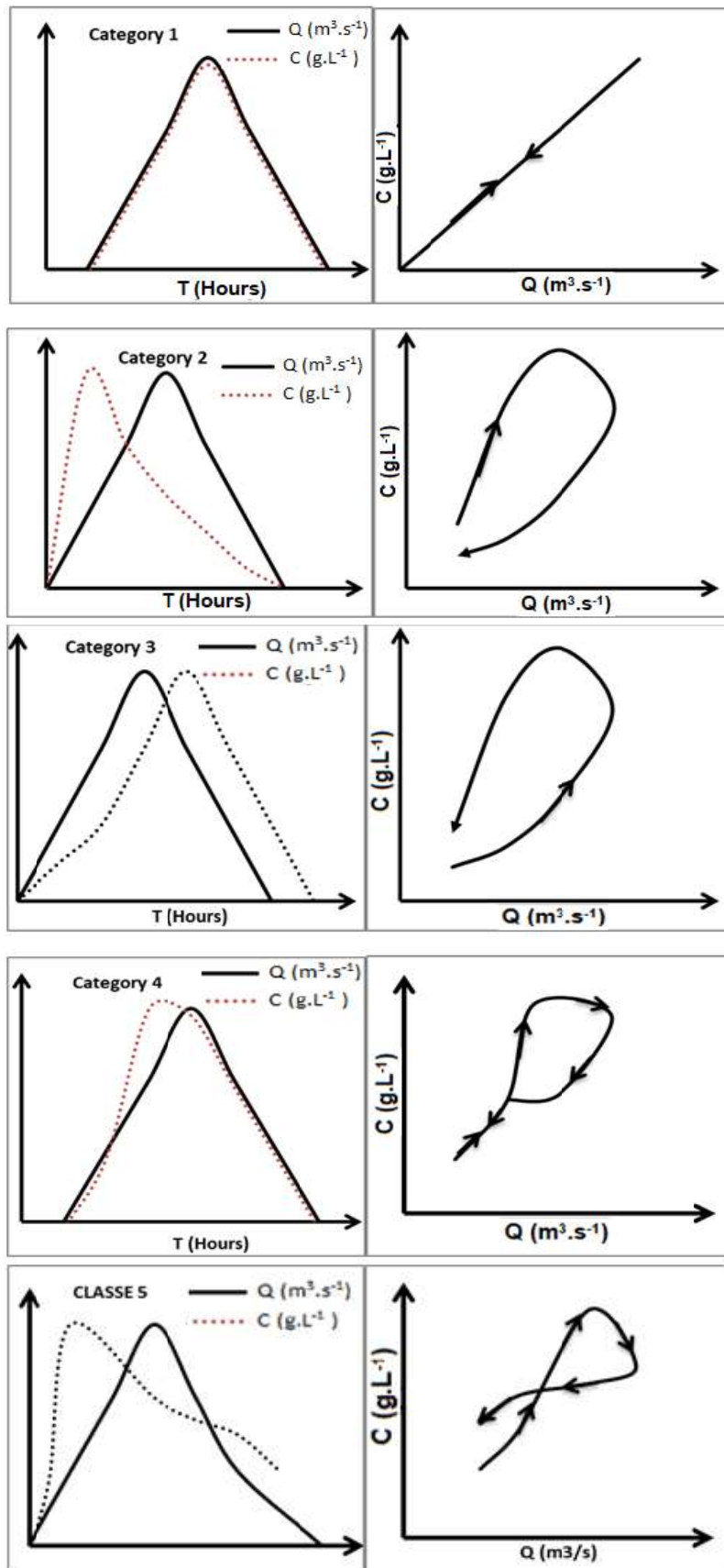
3.5 Hysteresis

The study of sediment transport by event can allow the origin of the transported sediments to be determined by analysing the relationships between SPM concentration and flow discharge, notably when these relationships form hystereses. The analysis of this hysteresis is considered an interesting approach towards acquiring a better understanding of SPM dynamics in a watershed. Most research is currently based on the study of hysteresis loops to identify the different sources of sediments in a watershed [50-56]. It is therefore possible to distinguish between different forms of hysteresis, which can be grouped into seven categories (Fig. 4):

Category 1: linear form where the rise of the curve is parallel to the descent of the curve;

Category 2: open loop with a chronology of sampling points going in a clockwise direction (dextral hysteresis) from the start to the end of the loop, maximum C in SPM comes before maximum Q ;

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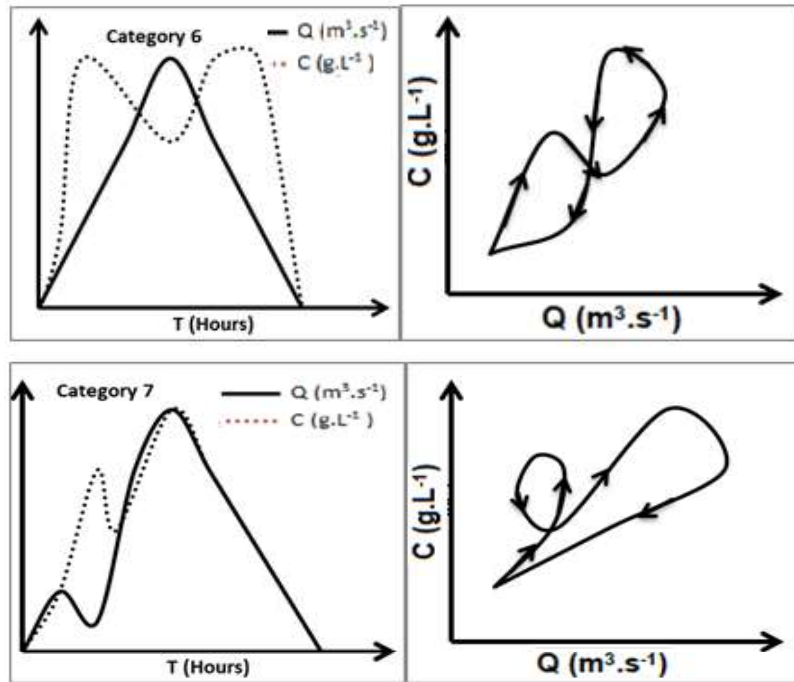


Fig. 4 Different categories of hysteresis in relationships between SPM concentration and flow discharge.

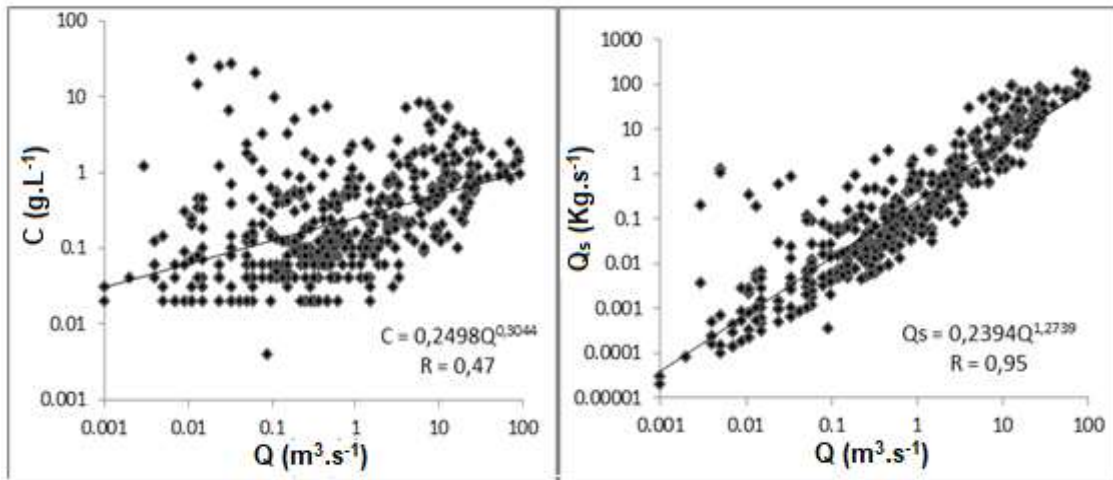


Fig. 5 Relationships between concentration-flow discharge (left) and sediment-flow discharge (right) for the period 1990 to 2014.

Category 3: open loop going in an anti-clockwise direction (sinistral hysteresis), maximum Q comes before maximum C ;

Category 4: closed loop going in a clockwise direction (dextral);

Category 5: hysteresis in a figure of eight, but remaining open;

Category 6: closed figure of eight;

Category 7: complex form where the rise of the curve comprises a knot in a clockwise direction (dextral).

4. Results and Discussions

4.1 Concentration-Flow Discharge and Sediment-Flow Discharge Relationships

After extracting the instantaneous values of C and Q , sediment discharges can be calculated and the log-log type relationships between C and Q and between Q_s and Q established (Fig. 5). The log-log model frequently used then allows parameters a and b to be determined that are specific for each watershed and

watercourse, and gaps filled when there are no measurements by simulating the missing values.

The $C-Q$ regression presented a weak correlation coefficient ($R = 0.47$) for a distribution showing a greater spread of points for average values. These points coincided with flow discharge below $0.8 \text{ m}^3/\text{s}$ and sediment discharge above 1 g/L , values that corresponded to autumn flood events (easily mobilisable sediment). This coefficient increased when a regression was performed for the values of each flood event category (Table 2).

The Q_s-Q relationship however revealed a better correlation coefficient ($R = 0.95$) for the same number of points.

The coefficient was almost identical for the two relationships while parameter b was very different: 0.304 for the $C-Q$ relationship and 1.27 for the Q_s-Q relationship.

The evaluation of the models achieved in hydrology was crucial. The root mean square error (RMSE) was then performed to give a value ranging from 0 to $+\infty$, with the optimum of this value being the minimum:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^N (C_i - C')^2}{N}} \quad (5)$$

C_i : value of the concentration observed (g/L);

C' : value of the concentration calculated by the model (g/L);

N : sample size.

For the $C-Q$ regression, the RMSE gave a value of 1.21 while the Q_s-Q regression was 2.1. These values were reliable and significant. Table 2 shows the

different $C-Q$ regressions for each flood category.

It can be seen that the correlation coefficients for the different categories varied between 0.38 and 0.62. They were close to that of the regression $R = 0.58$ for all floods. The RMSE values varied from 0.33 to 2.45.

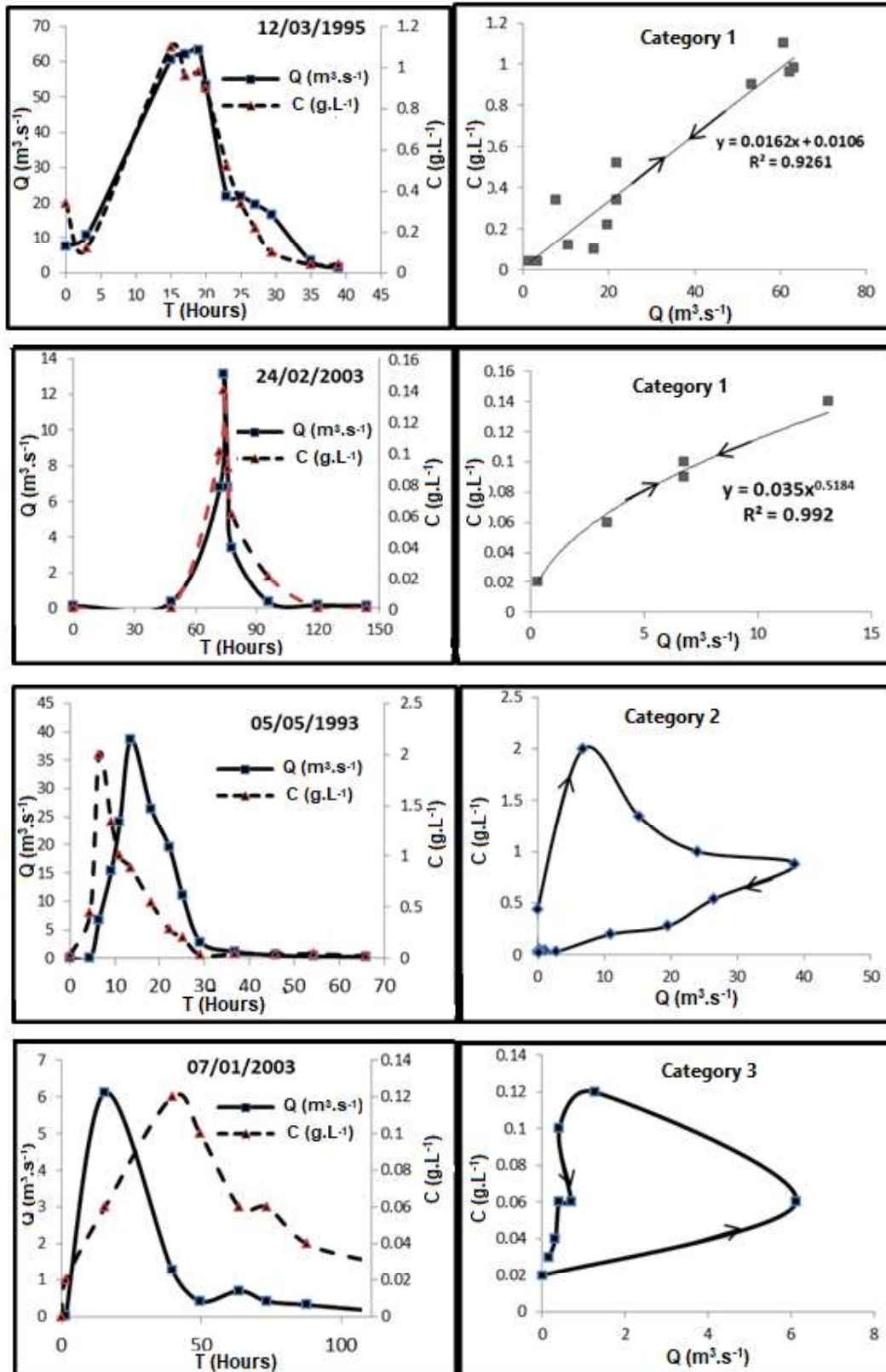
4.2 Study of Flood Events

The term flood event refers to a complete hydrological event with a rise and fall in water level. Of the 45 floods selected in this study over the 24-year period, six were in autumn, 24 in winter, 14 in spring and one in summer. Fig. 6 shows the variations in Q and C observed in some of these flood events, with the temporal variations of these two parameters on the left and the relations between these two parameters, at times revealing hysteresis loops, on the right. Table 3 shows the seasonal distribution of the seven flood categories studied here.

The curves in Fig. 6 present different variants of the $C-Q$ relationships that can be observed for the flood events in Oued El Nachef. These different variants can be grouped together, as mentioned above, in seven categories, with the percentages of each shown in Fig. 7. Thus 22% of the flood events fall into Category 1. This type of flood is characterised by a linearity of the $C-Q$ relationship and generally occurs in winter and spring. The mechanical erosion and transport of suspended sediments is a function of the intensity of rainfall, water saturation of the soil, infiltration capacity and depth of runoff. At this time of the year, the ground is saturated and the level of infiltration is therefore lower, generating surface runoff that causes

Table 2 Log-log models adjusted for each flood category to relationships ($C-Q$) with their RMSE adjustment test.

	Log-log model $C = aQ^b$		Correlation coefficient R	RMSE
	a	b		
Category 1	0.1657	0.3311	0.54	0.51
Category 2	0.1405	0.3695	0.67	0.38
Category 3	0.2038	0.2495	0.46	0.55
Category 4	0.5076	0.2162	0.38	1.37
Category 5	0.2251	0.2900	0.60	0.33
Category 6	0.2754	0.4623	0.62	2.45
Category 7	0.1614	0.4823	0.60	0.72



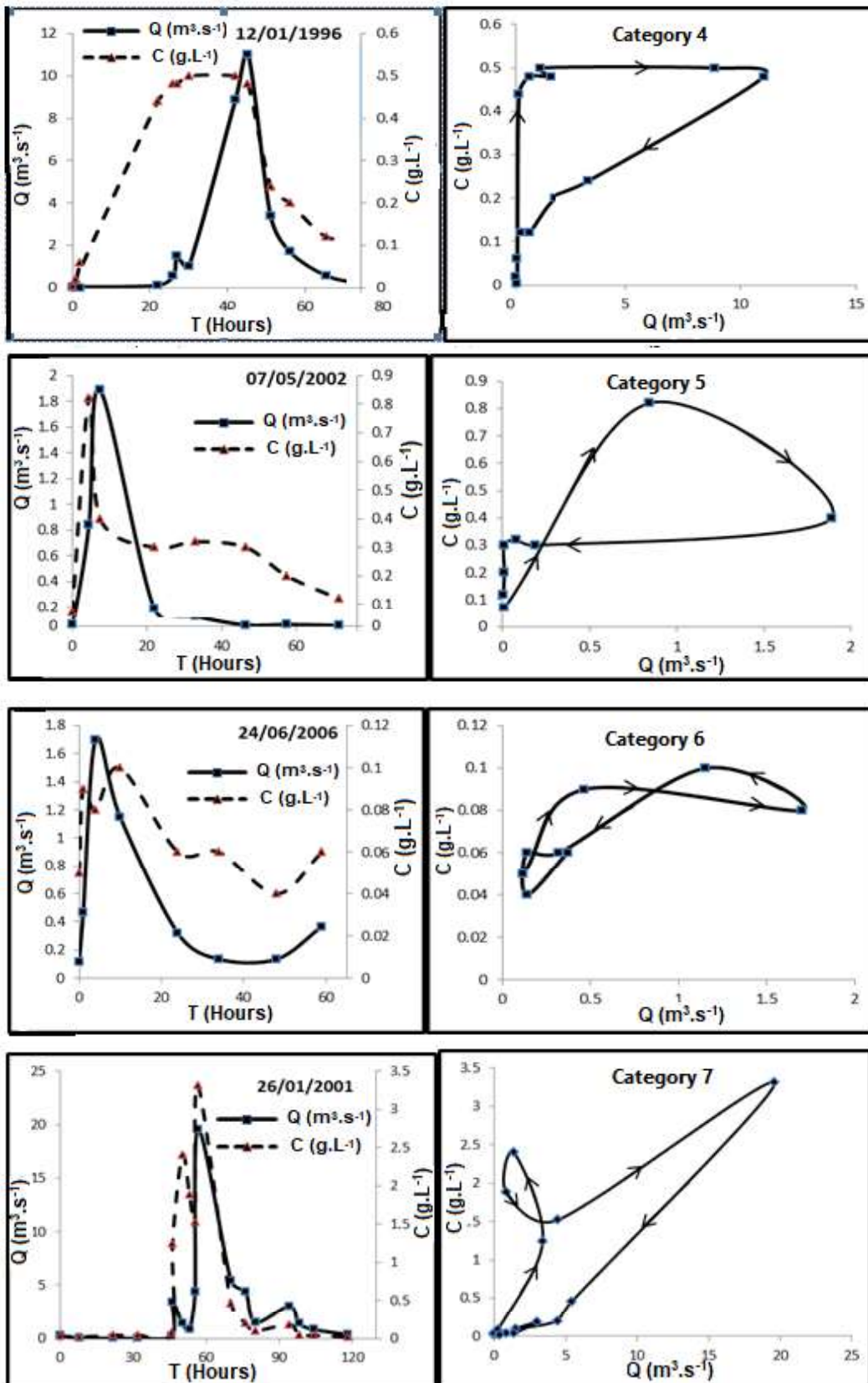


Fig. 6 Temporal developments in SPM concentrations and flow discharge during the selected floods (left) and the C-Q relationship during these floods (right), with arrows showing the dextral or sinistral direction of the hysteresis.

Table 3 Seasonal distribution of flood events in relation to the total of 45 floods for the different categories.

	Category 1	Category 2	Category 3	Category 4	Category 5	Category 6	Category 7	Total
Flood events in autumn	0	3	2	1	0	0	0	6
Flood events in winter	4	3	5	4	2	4	2	24
Flood events in spring	5	2	1	1	3	1	1	14
Flood events in summer	1	0	0	0	0	0	0	1
Total	10	8	8	6	5	5	3	45
% of total floods	22	18	18	13	11	11	7	100

greater mechanical erosion and linear sediment transport that becomes proportional to the flow discharge of the watercourse. Categories 2 and 3 each represent 18% of all the flood events studied. Category 2 floods (dextral hysteresis) are frequently seen in autumn.

In the case of Category 2 flood events, peak concentration was reached before peak flow discharge. There can be different reasons for this difference. It could be due to:

- significant resuspension of sediment deposited after the previous flood event (“flush” effect);
- a maximum contribution of surface runoff and therefore of mechanical soil erosion from the increase in flow;
- the source of sediments (very erodible material) being close to the gauging station.

Thus, the transported sediment starts to be deposited before the peak flow, meaning that most of the suspended sediment being transported will be exported from the first discharges early on when the water is rising.

The opposite is true for Category 3 flood events (sinistral hysteresis) where the maximum C in SPM occurs after the peak flow. In this study, these flood events generally occurred in winter. The origin of sediment transported in this case is the result of linear hydric erosion and could also come from a source further away from the gauging station.

Category 4 floods represented close to 13% of the flood events studied and generally occurred in winter. The $C-Q$ relationships present dextral, but closed

hysteresis. The first phase of this curve is explained by a resuspension and transport of sediments deposited after the previous flood event (as for Category 2). Then, in a second phase, the linearity describes a phase of transport where the concentration of sediments varies proportionally with the flow discharge.

With regard to Category 5 (hysteresis in an open figure of eight) and Category 6 (hysteresis in a closed figure of eight) flood events, they represent 11% of all the flood events studied. The $C-Q$ relationship, which gives an open figure of eight, related to winter and spring floods. The form of this relationship can be explained by a first phase of transport of sediments already mobilisable in the watercourse, then a second phase of transport of sediments due either to erosion in the drainage channel caused by maximum flow discharge or to a contribution of sediment upstream of the watershed. The processes can be attributed to flood events in Category 6 that are mostly observed in winter. In this case, the second peak in concentration occurs directly after the maximum flow, suggesting a contribution of sediment from erosion of the sides. Finally, Category 7 flood events only represent almost 7% of the flood events studied. These flood events have two phases. The first causes the transport of sediments already in the drainage channel, and then immediately afterwards a reduction in flow discharge is recorded that is accompanied by a peak in SPM concentration C , which provides the knot indicating the inverse proportionality in the increase in the $C-Q$ relationship in Fig. 5.

4.3 Sediment Loads and Water Volumes

The average duration of the flood events chosen for this study was 3.5 days. As shown above, the largest number of flood events corresponded to Category 1 flood events which, as can be seen in Fig. 7, contributed just 8.5% of total sediment transport for a volume of runoff that was nevertheless 22% of the total. The sediment transports of Category 2 and 3 flood events represented 19% and 9% respectively and were proportionate to the volumes of runoff of 17% and 7.5% respectively of the total. For the flood events

in Categories 5 and 6, the contributions to sediment transport diverged completely. The lowest percentage (0.8%) was observed for Category 5 flood events, corresponding to a volume of water of just 1.86%. Conversely, the Category 6 flood events transported 44% of the sediment for a flow discharge of 29% of the total volume of water evacuated by all the floods. Finally, the contributions of Category 4 and 7 flood events were practically the same, with 9.4% and 9.6% of sediment transport and 9.8% and 12.9% of water volume respectively.

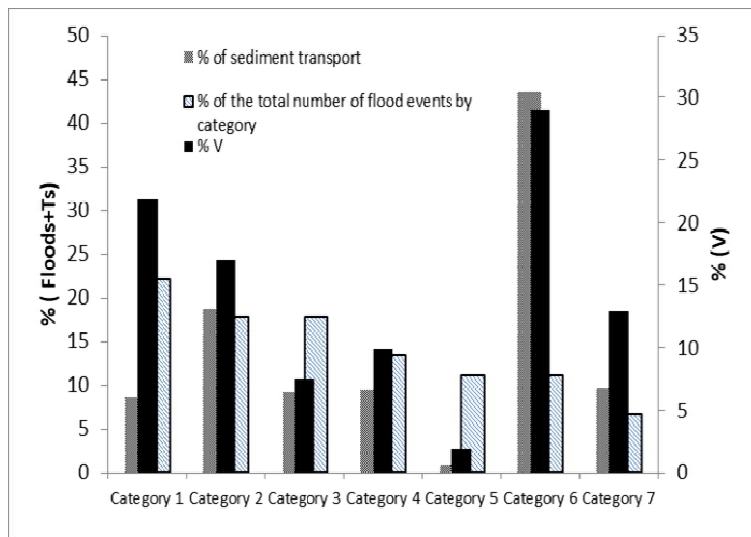


Fig. 7 Distribution (in % of the total) of floods for the different categories and the contribution (in %) of the different categories (1 to 7) of flood events studied between 1990 and 2014 to the volume of water flow (V) in all flood events and to sediment transport (Ts) evacuated by all flood events.

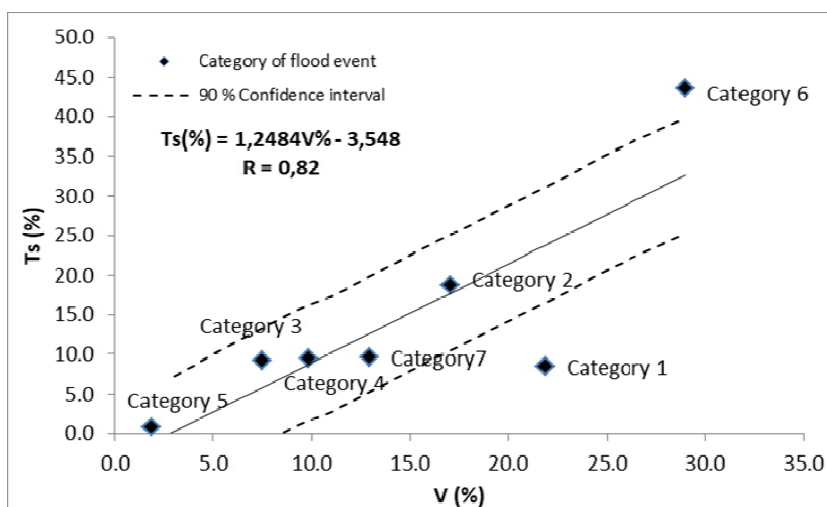


Fig. 8 Relationship between the % of sediment transport and the % of water volume (V) for the flood events studied between 1990 and 2014.

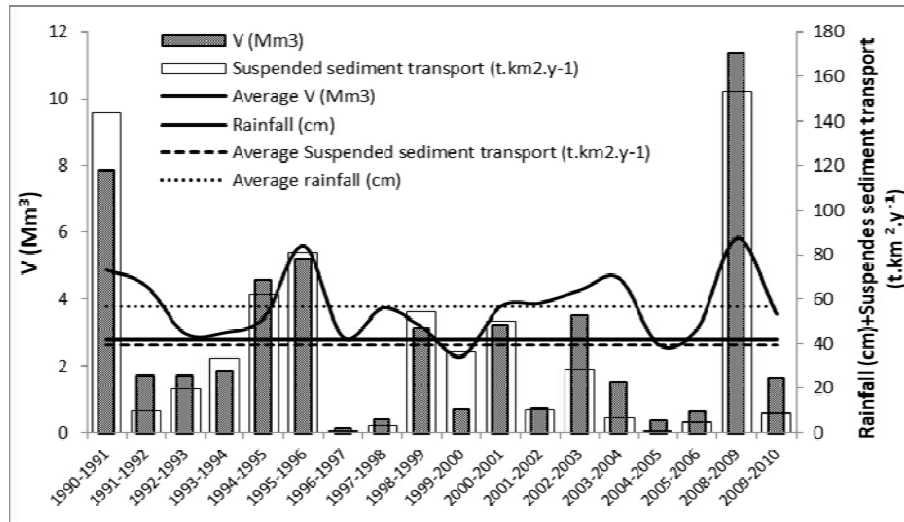


Fig. 9 Interannual variation in water volume and sediment transport (1990-2010).

However, for Category 1 flood events, a sediment transport load could be observed that was distinctly lower than the contribution of volumes of water flow. In general, these flood events occur at a time of year when the ground is covered with vegetation.

Fig. 8 denotes a linear variation in percentage terms between the sediment transport and the volume of water flow for the seven flood event categories. It can be seen that Categories 1 and 6 are some distance from the linear relationship, whereas Categories 2 to 5 and 7 are close to the line and within the confidence interval, which means that for these categories the suspended sediment transport varied proportionately with water flow.

Fig. 9 shows good proportionality between the volumes of water evacuated annually and the annual intensity of specific sediment transport. Annual total rainfall appeared to play a secondary role in these sediment transports, with the distribution, nature and intensity of this rainfall, and as a consequence the nature and intensity of the flood events, playing more of a key role in mechanical soil erosion and sediment transport in rivers. During the 20 years studied, the interannual average of specific sediment transport was in the order of 40 t/km²/year, but some exceptional hydrological cycles such as in 1990-1991, 1995-1996 and 2008-2009 presented sediment transport ranging

from 80 to 160 t/km²/year, corresponding to significant annual volumes of water (5 to 11 million m³).

5. Conclusion

In a hydroclimatic region where flood events play an important role in erosion and river transport, this article focused on the study of flood events and their contribution to suspended sediment transport in the Oued Nachef. A typology of flood events was established based on a study of 45 floods over the past 25 years (period 1990-2014), by examining the relationships between concentrations (*C*) of suspended particulate matter and flow discharge (*Q*). This typology allowed seven flood event categories to be defined, of which one presented linear *C-Q* or log-log relationships while the other six highlighted phenomena of hysteresis between the rise and fall of the flood events that were dextral (Categories 2 and 4), sinistral (Category 3) or complex in a figure of eight (Categories 5, 6 and 7). These phenomena can be attributed to different erosion-transport-sedimentation mechanisms that vary by season and by the nature of the flood events. In total 84% of the floods studied occurred in winter (53%) and spring (31%). With the exception of Category 1, the contribution of sediment transport for each of the categories was proportionate to the percentage of water flow volume. The most

frequent floods (22%) were in Category 1 (winter and spring), flood events where a linear $C-Q$ relationship was observed but with sediment transport of just 8.5% of all the floods, despite significant volumes of water (> 30%). Meanwhile for Category 6 flood events, which only represented 11% of the flood events, the contribution to total volumes of water and sediment transport was significant at more than 43%. These Category 6 floods were mainly observed in winter (four floods) with a single flood in spring. They generally consisted of two phases, one of remobilisation and transport of sediment previously deposited on the wadi bed and a second of erosion and transport of sediments from the sides. On an interannual level, the assessment of sediment transport showed that the intensity of this transport was proportional to the volumes of water flow during the year. Thus the years 1990-1991, 1994-1995, 1995-1996 and 2008-2009 which had annual volumes of water above 4 million m^3 (> 7 in 1991-1992 and > 11 in 2008-2009) exported the highest specific tonnages of sediment (60 to 160 $t/km^2/year$), while in the other years the volumes exported were generally below 4 million m^3 with sediment transport below 60 $t/km^2/year$. In semi-arid Mediterranean regions, flood events play a key role in the export of sediments. The study of these events is vital to obtain a thorough understanding of the mechanisms of erosion-transport-sedimentation on a watershed scale as well as to accurately assess the annual tonnages of sediments evacuated by the watercourse. In this understanding of transfer mechanisms, it is evident that a flood event typology based on relationships between SPM concentrations and flow discharge is unquestionable of benefit.

Acknowledgments

The authors thank all the staff of the National Agency of Hydraulic Resources (ANRH), who participated in the field measurements at Terni Hydrometric Station. They also thank the anonymous

and the associate editor for their comments and suggestions. The authors are grateful to the CNRS for the stay of Pr. Kazi Tani in the Laboratory of functional Ecology and Environment

Author Contributions

All authors contributed equally to the paper. Jean Luc Probst was responsible for revising the article; and all authors read and revised the final manuscript.

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