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VARIATION IN SEDIMENT CONCENTRATION AND WATER DISCHARGE DURING STORM EVENTS IN TWO CATCHMENTS, NORTHEAST OF ALGERIA

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ABSTRACT

The relation between concentration and discharge is not normally homogenous during the storm event, often producing hysteretic loops. In this study relations between sediment concentration and water discharge for hydrologic events are studied by analyzing temporal graphs (discharge and concentration versus time) in terms of spread and skewness. The hysteresis types of the discharge and concentration of 170 storm events have been analyzed to identify the relations between hysteretic loops and the associated controlling factors in the Saf Saf and Kebir West basins. Surveys of suspended sediment concentration and water discharge are being carried out at gauging stations. The selected storm events are based on samples having many sediment concentrations at water discharges. Comparing C/Q ratios at a given discharge on the rising and falling limbs of hydrographs is providing a consistent, reliable method for analyzing C-Q relations. Four common classes of such relations are determined such as single-valued line, clockwise loop, counterclockwise loop and figure eight. The plot of points has exhibited a hysteresis loop which is explained by the variability of sediment concentrations during storm events and seasonal effects. The most frequent floods at Saf Saf and Kebir West rivers are clockwise and single-valued line (62% and 59% of floods respectively) that have brought 73% and 81% of the total sediment flux. Intra-annual variability is very high. Over 31-years, the three biggest floods at each Saf Saf and Kebir West rivers have cumulated 97% and 68% of the total sediment flux and are of two classes.

KEYWORDS

Loop hysteresis, Suspended sediment concentration, Storm events, Temporal variability, Catchment.

1. INTRODUCTION

Rainfall and runoff, the main erosion agents, provoke both the detachment and transportation of the surface soil materials to surrounding rivers. Sediment transport is becoming an important issue involving in sustainable development of water resources system. Estimates of temporal variations of suspended load with discharge are needed for the assessment of aquatic ecosystems, estimates of contaminant export from catchments, and the prediction of stream water quality [1-6]. The behavior of suspended sediment in watercourses is often a function of energy conditions, i.e. sediment is stored at low flow and transported under high discharge conditions. However, sediment transport rates are also a function of sediment availability [7]. Group researchers reported that soil temperature and moisture exert a strong control on soil aggregate stability, and thus on soil erosion intensity [8]. The changes in sediment availability result in so-called hysteresis effects.

Hysteresis loops are a feature of plot-scale and catchment-scale sediment transport [9]. Several studies investigated the factors and processes responsible for these loops in order to explain the distribution of sediment sources within a catchment [10-13]. The difficulty of interpretation at these scales is that there are complications arising from spatial and temporal variability in geomorphic conditions such as climate, soil types, land use, topography, and catchment connectivity [14-17]. Hysteresis behaviour patterns are generally seen as complex and their interpretation is not straightforward [18,19].

Some group researchers have shown models that reflect the relationships between suspended sediment concentration (C) and water discharge (Q), and have introduced the notion of hysteresis into the Rother River Basin (England) and five sub-basins of the Wallagaraugh River (Wales) [20,21]. Storm events were also studied at three gauging stations on the Pejibaye River (Costa Rica) by Jansson [22]. The author has made a considerable contribution to the explanation of the phenomenon of hysteresis. The relationship between discharge and sediment concentration is also available for different catchments and rivers [23-30]. Hysteresis effects generate variability in the relationship between river discharge and suspended sediment transfer [6, 31, 32]. This hysteresis has been an obstacle when the temporal variations of suspended sediment concentration and discharge have been modeled simultaneously, and much research relevant to this topic has been performed [33].

Depending on the variation of water discharge (Q) and suspended sediment concentration (C) versus time, different hysteretic concentration-discharge curves can be generated such as clockwise, anti-clockwise, and figure eight. In Algeria, there were essentially studies who have shown the temporal variability of C and Q, respectively characteristic of the semi-arid basin of the Wahrane River (Chelif) and the sub-basins of the Tafna River [34,35].

Understanding of the catchment transport pathways activated during storm events can be also enhanced by studying the changing relationship between discharge and water quality parameters during an individual storm event [6]. These storm events can generate significant transport of nutrient fraction sand sediment in catchments. The use of data describing hysteretic responses to examine hydrological flow paths is, however, more recent despite its potential to elucidate which flow paths might be dominant during different periods within rainfall events [30, 36].

Few published studies of the relationship between suspended sediment concentration and stream dicharge are available in Algeria. Most of the existing studies have focused on determining the total suspended sediment yield for rivers. Although most of these studies have used storm events to determine the magnitude of sediment yield in rivers channels, they did not highlight the pattern of behaviour of sediment concentration during storm runoff over given periods.

The purpose of the study attempts to identify and classify the major types of the single-event C-Q relations through a series of storm events. The analysis to be conducted is oriented much more towards the graphic explanation that would give the chronological order of C and Q and would show the variation that exists in the concentration of suspended sediment relative to changes in river discharge during storm periods. This is a method that would improve understanding this relationship at the local level. The scatter of points is a very important feature that, along with other characteristics related to the appearance of the graphs, makes it possible to perform combinations related to the phenomenon. In fact, it is necessary to discuss the graphical results by examining the related physiographic and/or hydrological factors that contribute to these variations.

2. STUDY AREA

The Saf Saf and Kebir West catchments are located in the northeast of Algeria. Both of the catchments, which constitute a Mediterranean domain where different forms of erosion are highly distributed, belong to the Coastal basins of Constantine. of northern Algeria [37]. The Saf Saf catchment is located on the ridge of the Tell mountains, 6 km upstream of the Zardézas dam and has an area of 322 km^2 at the gauging station of Khemakhem (Figure 1). The name of the Saf Saf River is applied from the junction of the Khemakhem and Bou Adjeb rivers [38]. The Kebir West catchment at Ain Cherchar gauging station drains an area of 1,130 km^2 (Figure 1). The drainage system is formed by the union of the Hammam and Emchekel rivers.

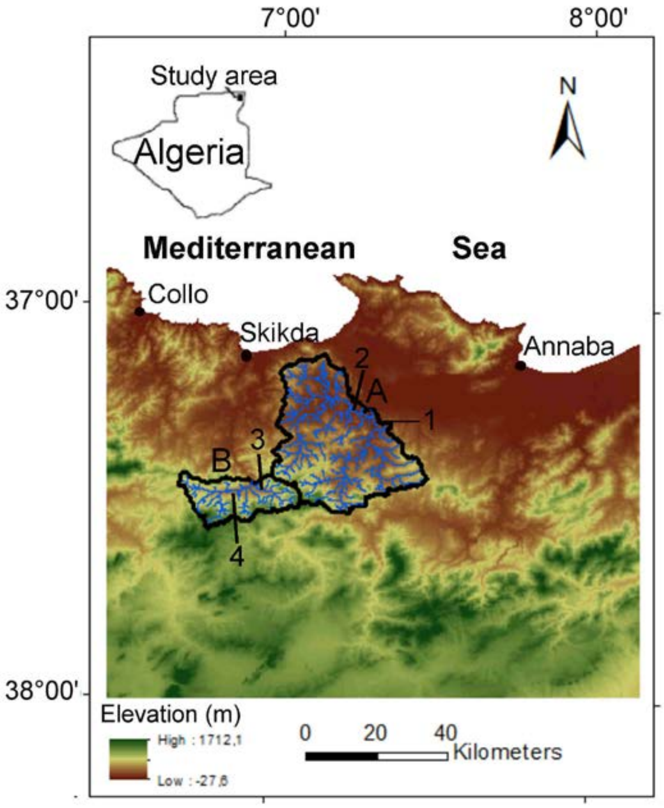


Figure 1: Location map of the study catchments. A: Kebir West catchment; B: Saf Saf catchment; 1: Hammam River; 2: Emchekel River; 3: Khemakhem River; 4: Bou Adjeb River.

The Saf Saf catchment has 44% of its area covered by weathered or un-consolidated geologic formations that generate very erodible soils viz. marly limestone of Senonian, gypseous-sandy clay and clayey conglomerate of continental Miocene age and the Numidian clay highly dissected by gullies. Conglomerate formations, with 19% of the basin area, have been greatly affected by folds and faults that have generated a dense drainage network. In the north of the basin, unconsolidated flyschs are less distributed. The landscape formed on predominantly resistant rocks including Cretaceous limestone and Oligocene sandstone (with 27% of the basin), is made up of high hills which are highly dissected. The floodplain is poorly developed in the Saf Saf basin and occupies a narrow area along Bou Adjeb and Khemakhem rivers. The stream beds are gravelly, stony and blocky with some sand [38]. Fluvial bank erosion of the low terrace remnants occurs.

The Kebir West catchment has extended areas of clay, marl, marly limestone, micaceous sandstone, clayey conglomerate and gypsum clay, which generate highly erodible soils and a landform type of modest to low hills. The hills, which are lower than 300 m in the northern part of the basin and lower than 800 m in the south, are often dissected by rills and gullies on slopes exceeding 10%. The gully erosion in areas with marl and marly limestone of folded structure and clay has created a badland-like landscape with bare rock areas [38]. The less distributed metamorphic and sandstone areas (19% of the basin area) present deeply incised streams and show a set of modest hills with steep hillslopes. Sandstone is susceptible to disintegration and a deep regolith has developed at the foothill slopes and may mask the more impervious clay. Limestone displays the highest and steepest mountains and covers only 6.3% of the basin area. Extended alluvial plains are developed in the regions of Azzaba and Roknia, with low to high terraces. The clayey alluvium of the floodplain covers mainly clay and sandstone formations. Contrary to the Saf Saf catchment, the lower and middle terraces in the Kebir West basin are extensive. These terraces 4–5 m above the stream bed, are subjected to bank erosion during severe storm events [39].

The natural vegetation that protects the soil is usually disturbed by man. In the Saf Saf catchment 66% of the basin area is cultivated with wheat and barley, and fruit trees with smaller areas. In the Kebir West catchment only 31% is agricultural land with cereals, wine and fruit trees. Forest and shrubs cover 30% of the Saf Saf catchment. Forests are found mainly on poorly developed soils on sandstone and conglomerate on slopes exceeding 20%. Shrubs (Oleo-lentiscus and Erica europa) with an open canopy covering 7% of the Saf Saf area are damaged by livestock and fires during the summer season. Overgrazing is observed in pasture and open shrubland. Dense forests are less distributed in the Kebir West catchment. Because of the frequent fires in summer, the forest areas are generally more open, with bare soils exposed to erosion. Large areas with reforestation exist in the Emchekel sub-catchment [40]. Dense shrubland occupying 37% of the basin area are mainly found on poorly developed soils on sandstone formations. Open shrubland damaged by fires and overgrazing is found in southern part of the basin.

The northeastern part of Algeria's climate is a humid temperate climate. The two catchments are dominated by a coastal temperate climate. The precipitation data shows that there are rainfall events greater than 30 mm/day during an average of 3 days/year from November to January. These torrential rains are less frequent in the Saf Saf basin than in the Kebir catchment. Nevertheless, they sometimes have intensities greater than 100 mm/day. Torrential rains recorded in the Kebir West catchment are frequent from October to April and occur 4 days/year, mainly in November, December and February. Within this basin, the torrential rains are found mainly in the northern part of the catchment and are less abundant in the southern mountainous part [40].

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. The Kebir West and Saf Saf catchments are characterized by mean annual precipitations of 640 mm and 617 mm respectively. The mean annual water discharges range between 1.40 m^3/s in the Saf Saf River and 4.67 m^3/s in the Kebir West River. The runoff coefficient is fairly greater in the Saf Saf River (RC = 22%) than in the Kebir West River (RC = 20%).

3. MATERIALS AND METHODS

3.1 Sampling

Surveys of suspended sediment concentration and water discharge are being carried out in the two Saf Saf and Kebir West rivers. The gauging stations are controlled by the National Agency of Hydraulic Resources (ANRH) which also performs the water sampling of surface water using one-liter bottles, and the analysis of the samples [38]. The water samples, which are taken in various conditions of stream flows, are filtered using a filter of Laurent type (ϕ = 32 cm). The filter and the mud contained in the bottle are weighed after drying in a special oven for 30 minutes 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 during low flow or when the water discharge is constant during the day, a minimum of sampling is done (1 to 2). Suspended sediment monitoring started from 1975 to 2005. Due to technical problems, this monitoring is interrupted at the end of December 2005.

The selected storm events are based on samples having many sediment concentrations at water discharges with short 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. Moreover, the water samples are also collected during rainfall–runoff events in 1975–1990, at intervals of 15 minutes or 30 minutes to several hours. In the case of the highest rate of water level changes, the highest frequency sampling is used. Since manual sampling was used, it was not possible to collect samples during all the discharge waves that occurred over the monitoring period and during the whole time of wave evolution, particularly on the falling limb overnight [25].

3.2 Identifying C-Q relationship classes

The dispersion of the points of C and Q is a very important feature which, together with other aspects related to the shape of the graph, it becomes possible to perform combinations, in association with the hysteresis phenomenon [34]. For this purpose, the discussion of the physico-geographical and hydrological parameters of each storm event class is necessary, especially when it comes to locate the source of sediment transport. In this study 170 events belonging to the Saf Saf and Kebir West catchments are analyzed in detail based on the following criteria:

- Production of complete and simple hydrographs,
- Taking into account strong and moderate floods.

The process of realizing C-Q relations is taking place in two stages:

- The water discharge (m^3/s) and suspension concentration (g/l) data are plotted on the ordinate axis and the corresponding time (hour) is plotted on the abscissa axis,
- The data of the two variables C-Q of each flood event are related, in the form Q = fct (C), in order to determine the hysteresis phenomenon and to discuss the hydro sedimentary behavior of the events.

The different temporal graphs with their widths, symmetries/asymmetries reveal 04 classes of relation C-Q (Table 1). Each class is characterized by a simple, objective and reliable mathematical criterion, once both time graphs are available [23]. This criterion is the ratio C/Q at arbitrary times during the rise and fall of C and Q. It is fundamental in the identification of hysteresis loops.

The first step of the analysis is to select a time during the rise of Q, read the corresponding values Q1 and C1, and calculate the ratio C1/Q1. The second step is to locate the same value of Q1 on the graph of Q, read the concentration associated with the flow at the same time and determine the ratio C2/Q1. These two ratios will be qualitatively compared according to the equality or the superiority of one over the other, which facilitates the determination of the class. The shape characteristics provide also details regarding the width and orientation of the loop.

3.2.1 Class I

This class represents the simplest C-Q relationship. Its main feature is that the C/Q ratios are equal for Q values whether it is rising or falling (Table 1). This model indicates that the suspended concentrations must increase or decrease in perfect synchronization with water discharge [35]. In this class, the straight line appears when both graphs C and Q have simultaneous peaks and identical widths and symmetries.

In addition, a curved single-valued C-Q relation can be obtained when both temporal graphs have simultaneous peak, identical skewness and height, but different amounts of spread [23]. If the spread of the graph C is smaller than that of the graph Q, the curve bending upward prevails; however; if the spread of the C-graph is greater than that of the Q-graph, the C-Q curve is becoming bending downward (Table 1).

Table 1: Classes of relations C-Q

Class	Relation	C/Q Ratio	Reference
I	single-valued line A- Straight line B- Slope increases with Q curve bending upward C- Slope decreases when Q increases curve bending downward	$(C/Q)_1 \approx (C/Q)_2$ - Slopes of the two subsections (1, 2) are equal - Slopes of the two subsections (1, 2) are unequal - Slopes of the two subsections (1, 2) are unequal	[20]
II	clockwise loop	$(C/Q)_1 > (C/Q)_2$ for all the values of Q	[37]
III	counterclockwise loop)	$(C/Q)_1 <$ (C/Q) for all the values of Q	[38]
IV	Figure eigh	- $(C/Q)_1 > (C/Q)_2$ for one range of Q values - $(C/Q)_1 < (C/Q)_{2\ 2}$ for other range of Q values	[39]

The degree of concavity is less when the spread of the two-time graphs of C and Q are almost identical (the spread of the graph C is slightly larger or smaller than the spread of the graph Q). The concavity becomes more pronounced when the spread of one is considerably larger or smaller than the other.

3.2.2 Class II

This is the clockwise loop class. If the peak of the suspension concentration (C) reaches the hydrometric station before the peak of the water discharge (Q), the value of C during the flood rise is higher than that during the recession, with the same value of the flow (Table 1). Discharge from which the ratio C1/Q1 (C of rising limb/Q of rising limb) at any chosen time is greater than that of C2/Q1 (C of falling limb/Q of rising limb).

The orientation axis of the C-Q loop is close to 45° to the horizontal, when the spread of C (L_C) is almost equal to that of Q (L_Q). If $L_C < L_Q$, the axis of the loop has a substantially vertical orientation. However, if $L_C > L_Q$, the axis becomes approximately horizontal. This class is attributed to two main causes namely:
- Exhaustion of available sediment supply in the basin or stream before peak flow or a subsequent reduction in erosive rain effect [20, 44-46]. The increasing proportion of basal flow during the recession is also to be considered [20, 44, 47].
- The formation of an armoured layer prior to the occurrence of the discharge peak [43].
The clockwise loop tends to occur more at the beginning of the torrential rainy season [48]. This is due to the availability of sediments produced by previous floods, compared to lack or decreased sediment stored later in the season.

3.2.3 Class III

This class represents a counterclockwise or anti-clockwise loop. This is a situation where the C peak arrives later than the Q peak. As a result, the values of C on the rising limb are lower than those during the recession (falling limb) and therefore the C1/Q1 ratio on the rising stage is lower than the C2/Q1 ratio on the falling stage (Table 1).

The loops of this class result from three causes: one possible cause is the travel time of the flood wave and the sediment flux, particularly because of the distance downstream from the stream, located between the flood source and the gauging station [49]. This velocity is generally faster than the average velocity of flow. Since the suspended sediments tend to move at a rate close to that of the mean flow, the sediment flux tends to lag behind the flood wave. The delay in the arrival of the C peak at the station is accentuated in watercourses with irregularities that prevent the movement of sediment relative to that of water. The second cause of this type of loops is the significant soil erodibility associated with prolonged erosion during the rainstorm [23]. The third cause is the variability in the seasonal distribution of rainfall and sediment production in the catchment.

3.24 Class IV

This class corresponds to the form of eight "figure eight" which combines parts of class II and class III. However, under certain conditions a loop of eight develops independently of the peaks of the variables C and Q. The two parts of the eight figures are sequentially directed in opposite directions.

The models show lower ratios C1/Q1 in the lower part of the rising limb than those of the falling limb (C2/Q1), with the same value of the discharge flow (Table 1). The data of C and Q, for low values of Q, describe a loop in the opposite direction of the clockwise. On the contrary, in the upper part, the ratio C1/Q1 is higher than that of C2/Q1, and this for the same value of Q. The data of C and Q, with high values of Q, provide a loop in the clockwise.

4. RESULTS AND DISCUSSION

4.1 Annual and seasonal variation of runoffs and sediment loads

The total water volume during the flood events over the study period (1975–2006) is 321.24 Mm^3 in the Saf Saf catchment and 739.18 Mm^3 in the Kebir West catchment, yielding a mean annual water volume of 10 Mm^3 and 23 Mm^3 in the Saf Saf and Kebir West basins respectively.

The annual floods have shown of general downward trend from 1985 in both catchments (Figure 2). The maximum water volumes are observed during the period 1981-1985; however, their mean is at maximum during the period 1986-1990 in the Kebir West, and this is because of the greater number of floods during the previous period with 25 against only 12. The water yield at the Saf Saf river outlet equal to 1.00 Mm^3/km^2 (321.24 Mm^3) is fairly higher than that at the Kebir West River outlet (R = 0.65 Mm^3/km^2 or 739.18 Mm^3). The water volumes of the study floods vary between 0.07 Mm^3 and 17.86 Mm^3 and between 0.28 and 65.61 Mm^3 in the Saf Saf and Kebir West catchments respectively.

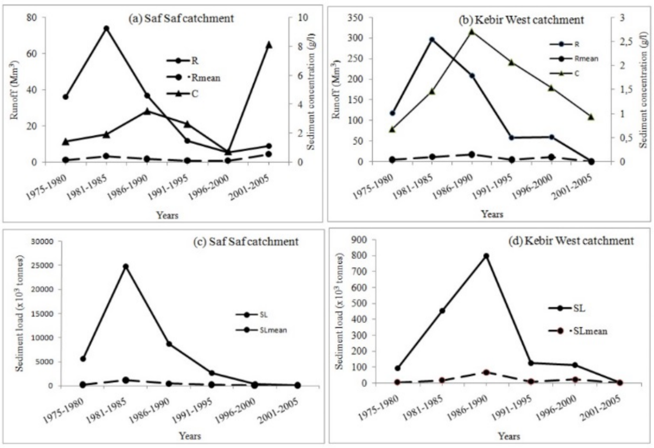


Figure 2: Trends of annual hydrosedimentolgical fluxes at the Saf Saf and Kebir West catchments. (a, b) Runoff and sediment concentration, and (c, d) Sediment load.

The sediment flux estimated for the whole floods in the Saf Saf basin recorded during the study period (1975–2005) is estimated at 41879.52x10^3 tonnes, giving a mean value of 444.38x10^3 tonnes, which corresponds to a sediment yield of 4195.50 T km^{-2} yr^{-1} (Tables 2). Meanwhile, the total sediment load of the Kebir West basin is equal to 1576.57x10^3 tonnes with a mean sediment load of 20.74x10^3 tonnes, corresponding to sediment yield of 45.01 T km^{-2} yr^{-1} (Table 3).

Table 2: Main hydro-sedimentological data of recorded storm events according to hysteretic classes in the Saf Saf catchment

Class	Season	F	T (days)	$\bar{C}$ (g/l)	$\bar{Q}$ (m^3/s)	R (Mm^3)	SL (x10^3 tonnes)	$\overline{SL}$ (x10^3 tonnes)
I	Autumn	6/26	6.13	1.99	5.16	3.68	201.11	33.52
	Winter	16/26	24.00	1.97	5.46	15.67	4662.12	291.38
	Spring	4/26	10.00	2.37	6.82	6.72	1921.17	480.29
	Summer		-	-	-	-	-	-
	Total		40.13	2.04	5.60	26.07	6784,40	260.94
II	Autumn	4/32	2.80	2.97	3.24	0.88	65.15	16.29
	Winter	18/32	28.40	2.20	13.49	49.16	19355.01	1075.28
	Spring	11/32	22.3	2.73	9.93	22.19	4395.38	399.58
	Summer		-	-	-	-	-	-
	Total		74.20	2.47	11.06	72.23	23815.5	721.68
III	Autumn	3/17	3.60	3.90	8.26	3.25	373.37	124.46
	Winter	9/17	14.5	1.90	7.32	12.90	1824.92	202.77
	Spring	5/17	7.90	1.47	7.85	6.76	1061.12	212.22
	Summer		-	-	-	-	-	-
	Total		26.00	2.13	7.64	22.91	3259.41	191.73
IV	Autumn	1/19	1.30	4.70	8.45	0.94	104.78	104.78
	Winter	13/19	27.10	2.13	6.95	19.61	2761.73	212.44
	Spring	3/19	5.10	3.84	53.63	22.39	4942.88	1647.63
	Summer	1/19	1.20	2.83	24.83	2.59	210.78	210.78
	Total		34.70	2.60	15.80	45.53	8020.17	445.56
	Autumn	14/94	13.83	2.87	5.51	163.25	744.41	53.17

Table 3: Main hydro-sedimentological data of recorded storm events according to hysteretic classes in the Kebir West catchment.

Class	Season	F	T (days)	$\bar{C}$ (g/l)	$\bar{Q}$ (m^3/s)	R (Mm^3)	SL (x10^3 tonnes)	$\overline{SL}$ (x10^3 tonnes)
I	Autumn	3/22	3.71	2.05	77.73	17.35	64.59	21.53
	Winter	8/22	19.79	1.18	37.26	57.24	92.67	11.58
	Spring	11/22	32.15	1.01	37.26	100.65	119.82	10.89
	Summer		-	-	-	-	-	-
	Total		55.65	1.21	42.78	175.24	277.08	12.59
II	Autumn	5/23	14.72	4.97	45.85	62.01	432.66	86.53
	Winter	10/23	32.24	1.25	74.58	212.00	428.53	42.85
	Spring	8/23	23.75	1.02	43.18	108.94	140.57	17.57
	Summer		-	-	-	-	-	-
	Total		70.71	1.98	57.41	382.95	1001.76	43.56
III	Autumn	4/10	9.85	2.18	15.20	16.48	24.24	6.06
	Winter	4/10	8.40	0.80	20.85	13.66	13.95	3.49
	Spring	2/10	4.46	1.01	23.13	8.07	11.43	5.71
	Summer		-	-	-	-	-	-
	Total		22.71	1.40	19.04	38.21	49.62	4.96
IV	Autumn	4/21	9.67	1.80	20.82	16.11	40.98	10.24
	Winter	13/21	33.18	1.43	35.50	114.18	180.33	13.87
	Spring	4/21	6.21	2.43	19.09	12.49	26.80	6.70
	Summer		-	-	-	-	-	-
	Total		49.06	1.69	29.57	142.78	248.11	11.81
All classes	Autumn	16/76	37.95	2.93	37.91	111.95	562.47	35.15
	Winter	35/76	93.61	1.25	45.39	397.08	715.48	20.44
	Spring	25/76	66.57	1.24	35.11	230.15	298.62	11.94
	Summer		-	-	-	-	-	-
	Total		198.13	1.60	40.44	739.18	1576.57	20.74

The annual suspended sediment production is shown to vary dramatically giving very high coefficients of variation of 86.20% and 133.45% in Kebir West and Saf Saf rivers. Further, the high values of the skewness coefficients of 1.40 (Kebir West River) and 1.83 (Saf Saf River) can confirm that sediment load for a few years has experienced high values. Indeed, the Saf Saf sediment output for the period 1981-1985 is corresponding to 59% of the whole sediment output during the 31-year floods (Figure 2). The three biggest floods in terms of sediment flux (in winter from 10-15/01/1984, 2-5/02/1984 and in spring from 7-10/3/1985) have brought 97% of the total (Table 4). In contrary, the mean sediment concentration is higher for the period 1986-1990, where 55% of the floods have values exceeding 3 g/l (Figure 2). The Kebir West sediment output is observed during the period 1986-1990 and the sediment load has a contribution of 51% of the total sediment production related to 31 year-period. The three important storm events of 20-24/12/1988, 15- 18/11/1990 and 23-26/12/1990 have produced 68% of the period (Tabl4).

Over the 170 storm events, there are in the Saf Saf catchment 14 have begun in autumn, 56 in winter, 23 in spring and 1 in summer (Table 2). In the Kebir West basin, 16 have started in autumn, 35 in winter and 25 in spring (Table 3). In both catchments, the floods are usually absent or very short in summer, medium in autumn (between 9 and 14 days in average), long in winter (23 days in average) and in spring (between 11 and 17 days in average).

Table 4: Hydrometric parameters and statistics of selected floods

Kebir West River	$\overline{Q}$	$\overline{C}$	R	SL	Q_p	C_p	Class
21-22/01/1981	32.40	1.61	3.38	7.86	59.60	3.93	III
21-24/12/1984	68.21	1.41	19.92	48.39	45.09	2.93	IV
7-10/03/1985	195.96	3.13	65.61	98.22	55.10	2.13	II
27-29/10/1986	15.14	3.36	3.27	12.90	34.67	7.45	IV
23-26/11/1986	62.75	3.53	20.10	312.06	175.07	9.04	II
20-24/12/1988	69.33	1.75	27.95	108.70	274.65	5.09	II
15-18/11/1990	75.92	12.83	20.54	312.06	194.74	35.91	II
23-26/12/1990	195.65	2.48	39.39	124.09	321.46	4.41	II
24-25/11/1995	9.58	4.51	1.07	7.93	23.94	22.97	III
6-7/02/1996	87.51	1.79	13.86	29.58	166.10	4.04	Ib
8-10/02/1996	81.36	1.77	19.92	48.39	202.88	5.14	IV

Saf Saf River							
14-16/04/1979	20.54	3.32	7.37	3664.35	68.30	10.78	II
10-15/01/1984	12.61	2.86	6.13	1089.27	33.48	4.83	IV
2-5/02/1984	120.62	8.27	32.57	18551.95	419.19	27.21	II
7-10/03/1985	141.78	9.59	17.86	4397.64	345.33	39.62	IV
27-29/10/1986	1.91	6.80	0.13	17.23	7.90	26.55	II
5-6/11/1986	0.57	3.38	0.066	4.56	1.26	11.91	Ia
24-25/11/1986	8.45	4.70	0.94	104.78	22.16	12.90	IV
4-7/02/1987	13.36	5.13	3.90	1404.93	56.63	25.53	III
23-26/12/1990	21.62	7.18	5.84	3606.59	94.11	36.13	Ia
4-5/11/1992	9.03	8.41	1.06	196.84	22.00	28.29	III

$\overline{Q}$: mean water discharge (m3/s); : mean suspended concentration (g/l); R: runoff (Mm3);; SL: sediment load (x103 tonnes); Qp: discharge peak (m3/s); Cp: maximum concentration (g/l).

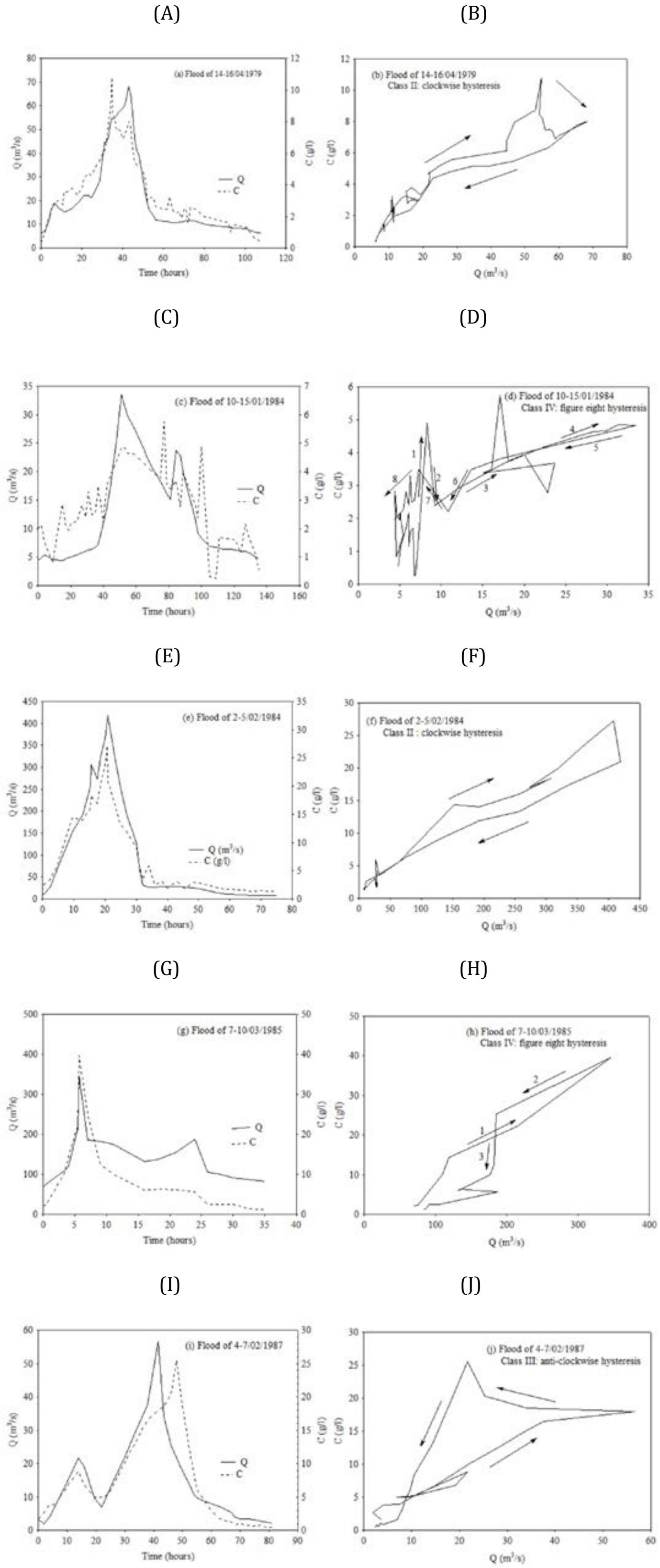
The mean of suspended sediment concentration at the Saf Saf basin is the highest in spring (14.64 g/l over 23 floods), intermediate in winter (8.68 g/l over 56 floods), fairly low in winter (5.51 g/l over 14 floods) and low in summer. However, in the Kebir West basin the mean of suspended sediment concentration is the highest in autumn (3 g/l over 16 floods) due to the start of the rainy season, and low in winter and spring, with 1.25 g/l over 35 and 25 floods respectively. In addition, the variability of the seasonal sediment concentration stays high in both catchments, which varies between 56% (winter in the Kebir West basin) and 135% (spring in the Saf Saf basin).

4.2 Variation of storm event types

The mean annual duration of storm events is 5 days per year for the Saf Saf River and 6.40 days per year for the Kebir West River. The annual average number of flood events is 3 and 2.45 for the previous basins, respectively.

It is known that the form of the hydrograph depends on the temporal structure of the rain storm and on its period of occurrence. In both Saf Saf and Kebir West catchments, class II is the dominant one representing 34% and 30.26% of the total floods and has produced 56.87% (23.82x10^6 tonnes) and 63.16% (0.99x10^6 tonnes) of the total sediment load (Tables 2 and 3). Class I is the second one with 27.66% (6.78x10^6) and 28.95% (0.28x10^6) of the floods in the Saf Saf and Kebir West rivers respectively, but giving a sediment load contribution of only 16.20% and 17.76% . Class IV represents 20.21% and 27.63% of the floods in the Saf Saf and Kebir West rivers, giving 19.15% and 15.90% of the total sediment load (Tables 2 and 3). Class III is the least important in the number of floods and sediment load production.

In both catchments, the class II in mostly represented by the winter season with 18/32 and 10/23 of floods in the Saf Saf and Kebir rivers. The spring comes in the second position with 11/32 and 8/23 for the previous basins respectively. Even though, the autumn season at class II has lesser floods, it has produced the highest sediment concentrations, with mean sediment concentrations of 3 and 5 g/l (Tables 2 and 3). Concerning the winter floods, the one of the period 2-5/02/1984 at the Saf Saf River has shown a clockwise hysteresis and a flood which has carried almost 96% of the total sediment load of this class (Table 4 and Figure 3e,f). The mean water discharge and sediment concentration are also high with 120.62 m^3/s and 8.27 g/l during 75 hours. The peak of sediment concentration (27.21 g/l) has been reached after 20 hours and the water discharge (419.19 m^3/s) at 21 hours. The flood of 23-26/12/1990 at the Kebir West River has shown a clockwise loop where this flood has produced 29% of the sediment load (Table 4 and Figure 4g,h). The mean water discharge and sediment concentration are considered high, giving 171 m^3/s and 2.48 g/l.



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(K) (L)

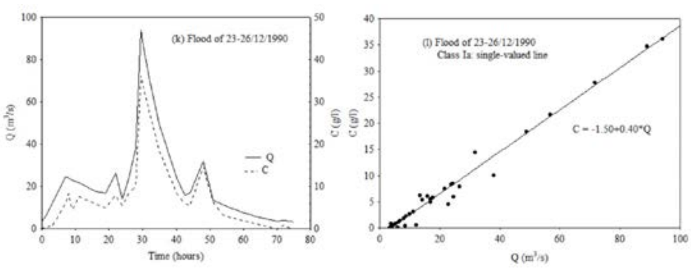
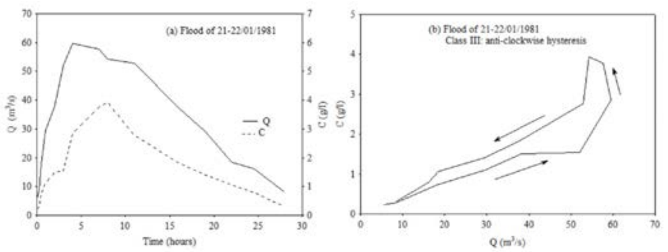


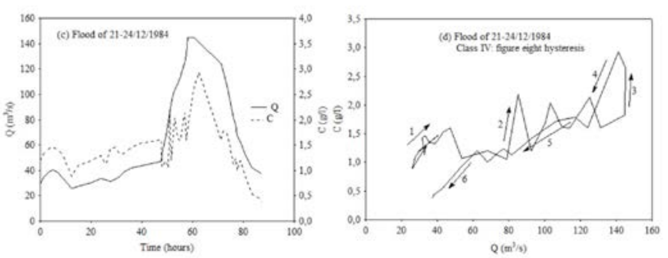
Figure 3: Sediment dynamics during major floods in the Saf Saf catchment outlet. (A) hysteresis plots of water discharge Q against sediment concentration C; (B) Time evolution of the water discharge Q and suspended sediment concentration C.

Always with the hysteresis class II, the spring has to be considered in terms of sediment supply. The flood of 14-16/04/1979 at Saf Saf River has yielded 83% of the class sediment load (Table 4 and Figure 3 a, b). For 108 hours, the means of water discharge and sediment concentration are estimated to 20.54 m^3/s and 3.32 g/l. At the Kebir West River, the flood of 7-10/03/1985 is the most important spring one; it has given almost 70% of the sediment load's class II. The water discharge and sediment concentration values are the highest ones, corresponding to 196 m^3/s and 3.13 g/l (Table 4 and Figure 4e, f).

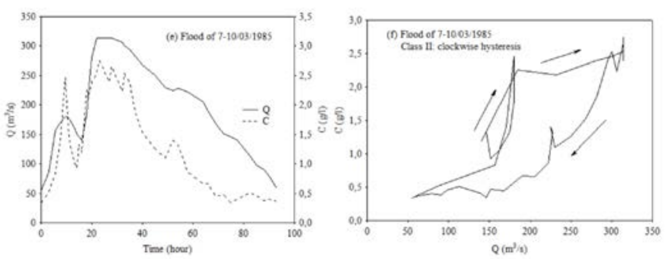
(A) (B)



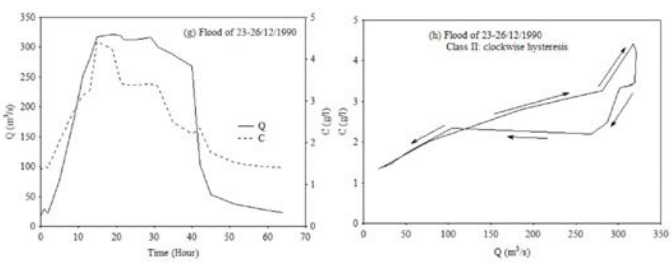
(C) (D)



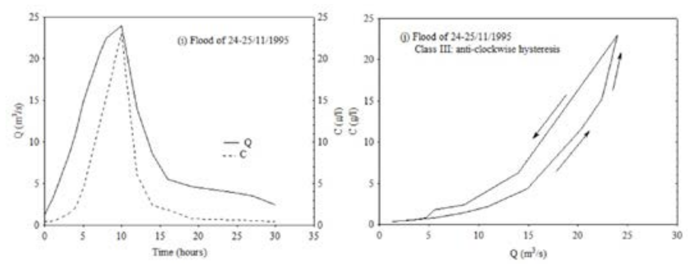
(E) (F)



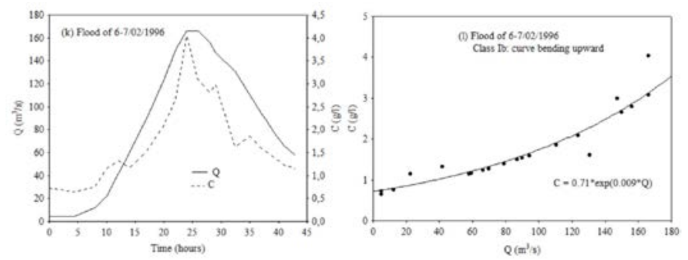
(G) (H)



(I) (J)



(K) (L)



(M) (N)

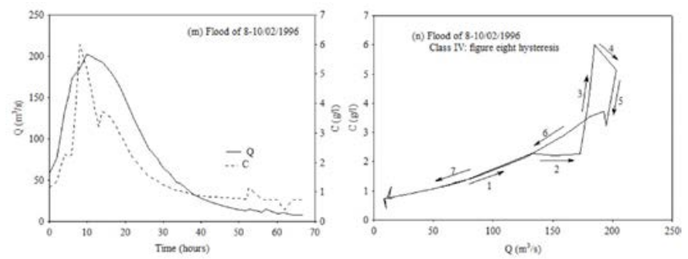


Figure 4: Sediment dynamics during major floods in the Kebir West catchment outlet. (A) hysteresis plots of water discharge Q against sediment concentration C; (B) Time evolution of the water discharge Q and suspended sediment concentration C.

The Class I winter floods at Saf Saf River represents 68.72% of this class sediment load and 11.13% of the total sediment load during the 31-year period (Table 2). The Kebir West's class I is distinguished by a high spring sediment load which represents 43.24% of the class sediment load and 7.60% of the whole sediment load (Table 3). Nevertheless, the winter season can't be neglected because it has produced 33.5% of the class sediment load. For both seasons mean sediment concentrations didn't exceed 1.2 g/l. The biggest floods of this class are represented by the floods of 23-26/12/1990 at Saf Saf River and 6-7/02/1996 at Kebir River. The first flood has produced total sediment load of $3.61x10^6$ tonnes, representing 53.16% of the sediment load of its class I. The water volume and mean sediment concentration are the highest ones, with 77.36 Mm^3 and 7.18 g/l. The second flood related to the Kebir West River has produced $29.58x10^3$ tonnes, which has given a contribution 10.68% of the total sediment load of the class (Tables 3 and 4, Figures 3k,l and 4k,l).

The winter is the dominated season related to class IV with 68% and 62% of floods, corresponding to Saf Saf and Kebir West rivers respectively (Tables 2 and 3). The sediment load of this season corresponds to 6.59% and 1.14% of their total sediment loads. Looking to their sediment concentrations, this season has the lowest mean values compared to the other seasons. At the Saf Saf River, the floods of 10-15/01/1984 and 7-10/03/1985 have brought 71.22% ($5.49x10^6$ tonnes) of the winter and spring sediment loads or 68.41% of the sediment production of class IV (Table 4 and Figure 3c,d,g,h). In addition, their water runoffs contribute to 57% (24 Mm^3) of total water volume of the two seasons. The floods of 21-24/12/1984 and 8-10/02/1996 attributed to Kebir West River have generated 32% ($79.38x10^3$ tonnes) of the total sediment load of class IV (Table 4 and Figure 4c,d,m,n). In fact, the highest runoffs of the season estimated at 149.57Mm^3 and medium sediment concentration supply of 1.58 g/l in average have produced this yield.

Class III is the less flood type occurrence, it has given 18 % (17/94) in the Saf Saf catchment and 13% (10/76) in the Kebir West basin. The most productive in terms of sediment is the flood of 4-7/02/1987 (Saf Saf River) which has generated 43.10% of the class sediment (duration: 3.37 days) (Table 4 and Figure 3i,j), and those of 21-22/01/1981 and 24-25/11/1995 (Kebir West River) which have produced 31.82% of suspended sediments related to class III, with durations of 1.21 and 1.29 days (Table 4 and Figure 4a,b,i,j).

5. DISCUSSION

The sediment transport in rivers is mostly related to the capacity of the stream to transport the available material. However, the availability of material from hillslopes and the presence of temporary storage of sediment in the stream system cause an extent scattering between water discharge and suspended sediment load. Therefore, the C–Q pattern is more related to the abundance of sediment supply and distance from available sediment sources to the basin outlet.

In Algerian environments such as in northeast of Algeria, where sediment transport is high, the question arises as to how significant the availability of sediment load during the different seasons is and understanding sediment behaviour during hydrological events. This study conducted in two Saf Saf and Kebir West rivers over 31 year-period of record has brought partial answers.

The sediment load has shown showed seasonal variations associated to different types of storm events. In autumn, high suspended sediment concentration is linked to a large contribution of different sediment sources within the catchment area (like in October and November 1986 and November 1992 at the Saf Saf River, October and November 1986 and November 1990 at the Kebir West River; see Tables 2, 3 and 4). The high suspended sediment concentration is mainly related to intense rainstorms, to flushing of sediment accumulated during the dry summer period with low soil moisture and to poor vegetation cover, especially in the Saf Saf basin. The autumn surface runoff has washed away fine particles from hillslopes (silt/clay) and organic matter produced in. The most frequent forms of floods observed in autumn are single-value line (6/96), followed by clockwise (4/96) and counter-clockwise (3/96) in the Saf Saf basin, and by clockwise (5/76) and counter-clockwise with eight form type (4/76) for each in the Kebir West catchment.

The instantaneous C-Q rising peaks in both basins, that are not only frequent in autumn but also in winter and spring (at Kebir West River), could be associated with a continuous inflow of fine sediments during storms and/or the availability of mobilisable sediments from the dry season. The clockwise hysteresis, which is abundant in winter and spring, may be related to the availability of hillslope sediments rapidly transported to the channel or by remobilization of fresh deposits in the channel system [44]. Appreciable quantities of fine sediment deposited under low streamflow conditions may be available to subsequent flood events for evacuation within the stream. This phenomenon is produced when one flood occurs immediately after another and is enhanced during short floods that may occur in autumn and even in winter since rainfall is irregular and therefore the soils stay less saturated with water. Moreover, the existence of cultures during the spring season is considered not enough as a vegetation cover to protect the agricultural soil from sheetwash and gullying. This is mainly observed in the Saf Saf catchment where bank erosion is added intensively to the later geomorphic processes.

It may arrive that during the rising stage, there is a low sediment exhibition, but during the falling stage a short anticlockwise appears. the case is observed in 14/17 and 6/10 during winter (mainly in February) and spring (less significant) seasons in the Saf Saf and Kebir West rivers, respectively (Tables 2 and 3). The hysteresis may result from the travel time of the flood wave and the sediment flux, particularly because of the distance downstream from the stream, located between the flood source and the gauging station [49]. This velocity is generally faster than the average velocity of flow. Since the suspended sediments tend to move at a rate close to that of the mean flow, the sediment flux tends to lag behind the flood wave. The delay in the arrival of the C peak at the station is accentuated in watercourses with irregularities that prevent the movement of sediment relative to that of water. Also, the cause of this type of loops can be the significant soil erodibility associated with prolonged erosion during the rainstorm or the existence of large groundwater contribution where under high moisture conditions, the mechanisms of erosion operate locally [23].

According to the eight-shaped floods, produced mostly in winter for both catchments, a fast-contribution from sediment stored in the channel network or derived from slopes in proximity of stream-flow can be hypothesized for the first clockwise loop, whereas the anti-clockwise trend occurring near the flood peak could be referred to bank collapse. The clockwise and/or counter-clock hysteresis situations have contributed to the emergence of an erosive dynamic on the hillslopes and the existence of a mobilizable paving layer formed on the stream bed prior to the flood. This pavement, mainly observed in the Kebir West River between 1975 and 1985, has seen an increasing of its thickness at the hydrometric station to 50 cm and one meter in 2000. The silting of the Zerdezas dam, located downstream of the Saf Saf River, is another aspect of the sediment availability during floods that is carried along by the water flow into the reservoir.

6. CONCLUSION

The graphical procedure has been applied in this paper to: (1) provide a clarifying explanation of the relationship between C–Q hysteresis types and sediment sources within the two study catchments, by using models; and (2) estimate the contribution of distinct sediment sources at event scale. Its application has allowed to better understand the dynamics of sediment fluxes during the storm events in order to try to reduce their social and economic impacts. The sediment yield delivered at the outlet of the Saf Saf catchment is considerably greater than that at the outlet of the Kebir West basin; it is 4196 T km^{-2} yr^{-1} against only 45 T km^{-2} yr^{-1} throughout the 31 year-period. The specific geomorphic conditions and the hydrographical network should be the ones that have governed the production of those considerable sediment amounts.

Several pairs of successive clockwise and anticlockwise floods are observed in the study rivers. At the start of the rainy season, hillslope material is considered as a major contributor to sediment discharge when the intensity of rainfall is relatively high. The long and fairly high sediment concentration floods in winter and spring are mainly of class II and class I. They are on one hand the high availability of sediments after a dry season where the soil is particularly weakened, and the appearance of suspended concentrations is rapid, and on the other hand an instantaneous erosion and a continuous supply of sediments during the flood. Nevertheless, these effects have induced lower sediment fluxes than those in autumn related to hillslopes or re-suspension of fresh deposits.

The most frequent floods are clockwise and single-valued line (60 % of floods in the Saf Saf River and 59% in the Kebir West River) that have brought 73% and 81% of the total sediment flux for each previous basin, respectively. The 18% to 13% of the least floods are anticlockwise which have produced less than 8% of the sediments.

Over 31-years, the five biggest floods have cumulated 65% of the total sediment flux in the Saf Saf River and the six biggest floods has generated 40% of the load in the Kebir West River of two classes, the most dominant storm events.

From the practical purposes for more reliable prediction of suspended sediment transport, mainly during storm events, which are significant with respect to the total suspended sediment load, it is necessary to improve understanding of the role of the controlling factors on suspended sediment dynamics. The potential interrelations of the variables such as precipitation intensity and areal distribution, runoff amount and rate present a formidable challenge for predicting the type and magnitude of C-Q relation for a particular site.

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