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Continuous Monitoring of Suspended Sediment Load in Semi-arid Environments

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1. Introduction

Sediment transport in water courses is an indicator of soil eroded from agricultural land, and the intensity of the phenomenon provides a measure of land degradation and the associated reduction in the global soil resource. Suspended sediment load is a useful indicator for assessing the effects of landuse changes and engineering practices in watercourses.

The investigation of the trend in the sediment loads has different constraints in terms of available data. Sediment load data are lacking for rivers in many areas of the world, particularly in developing countries where changing sediment yields might be expected (Walling & Fang, 2003).

Continuous river monitoring is essential to effectively measure suspended sediment loads during storm events and to accurately describe the sediment transport dynamic. The paper focuses on the application of technologies for continuous monitoring of suspended sediment concentration in rivers in semi-arid environments.

In the first part of the paper, methods for measuring suspended sediment concentration are reviewed. Technologies to continuously monitor suspended sediment overcome traditional methods requiring routine collection and analysis of water samples. Among the available instruments, based on optical principles, pressure difference and acoustic backscatter principles, the optical technology largely spread as turbidity is considered a good "surrogate" for suspended sediment (Gippel, 1995; Lewis, 1996; Lenzi & Marchi, 2000; Seeger et al., 2004;) and particularly suitable for high suspended concentrations (López-Tarazón et al., 2009; Gentile et al., 2010). It provides reliable data when the point measurements can be correlated to the river's mean cross section concentration value, the effects of biological fouling can be minimized, and the concentrations remain below the sensor's upper measurement limit (Gray & Gartner, 2009).

In the second part of the paper the continuous monitoring of the suspended sediment concentration in a semi-arid watershed is used to analyze the sediment transport dynamics. In semi-arid areas the seasonality of the hydrological processes and the strong interannual variation in precipitation rates enhance the role of infrequent flood events (Soler et al., 2007). As a consequence suspended sediment concentrations in rivers are generally high, as they compensate for the infrequency of runoff in producing high annual unit sediment yields (Walling & Kleo, 1979; Alexandrov at al., 2007; Achite & Ouillon, 2007). In these areas suspended sediment transport provides problems for water-resource management where channels are impounded as high rates of sedimentation occur in reservoirs.

High sediment yields in semi-arid environments can be explained in terms of the interaction between erosive energy and vegetation density even if climatic seasonality, relief, basin lithology and the extent of human activity combine to influence the global pattern of erosion processes. The estimation of the sediment transport during the events is necessary for the calculation of long-term sediment yields from basins, as one single event may represent the transport of several 'normal' years (Wolman & Gerson, 1978).
A measuring station in the Carapelle torrent (Northern Puglia – Southern Italy) was established in 2007 to continuously monitor suspended sediment concentration. The station was set up at Ordona bridge and delimits a catchment area of 506.2 km^2. It is equipped with a dual function infrared sensor (turbidity/suspended solids), a remote data acquisition system and an ultrasound stage meter for water level monitoring. The sensor was laboratory tested and a field calibration stage was carried out (Gentile et al., 2010).
High temporal resolution data, recorded over a 3-year period (2007-2009), were then analysed to investigate the relationships between suspended sediment concentration (SSC) and discharge (Q) in flood flows. During intense flood events the concentrations of sediment are high, more than 20 g/l. The concentration of suspended sediment varies hysteretically with water discharge and there are group-types of response. The SSC-Q curves revealed that in the Carapelle stream clockwise, counterclockwise, mixed loops and also no hysteresis are possible and can be related to the event intensity and to the sediment availability. The unsteadiness of the flow mainly influence the sediment transport capacity of the rising and falling limb of the hydrograph. Sediment load generally closely depends on flood volume while the maximum suspended sediment concentration is correlated with peak discharge.

2. Measurement of suspended sediments in water courses

2.1 Suspended sediment sampling

Different technologies are available to estimate suspended sediment concentrations in water courses (Garcia, 2008). Sediment measurement can be carried out sampling the water-sediment mixture to determine the mean suspended sediment concentration and the particle size distribution. The different sampling equipments can be summarized in: single-stage, point-integrating, depth-integrating and pumping type samplers.
If the suspended sediment is uniformly distributed within a stream cross section, the suspended sediment concentration can be simply determined by means of a *single-stage* sampler. It consists of a container (isokinetic or not) that is deployed at a specific flow depth and instantaneously collects the samples. This method allows a reasonably estimation of the sediment concentration at the sampled point in small streams and under slow flow conditions. Rooseboom and Annandale (1981) showed that sampling in bottles generally gives concentrations about 25% lower than results obtained from more sophisticated techniques.
Generally suspended sediment concentration in natural streams varies in time and space, from the water surface to the streambed and laterally across the stream. Concentration increases from a minimum at the water surface to a maximum at or near the streambed. In order to take into account this variability *point-integrating* and *depth integrated* samplers can be used.
Point-integrating samplers take the sample over an extended period of time to determine the average concentration at a point. A point integrating sampler has a nozzle that points directly into the streamflow. An electrically valve mechanism is used to start and stop the

sampling process. To eliminate a sudden inrush after opening of the intake nozzle, the air pressure in the bottle is balanced with the hydrostatic pressure before opening of the valve. The time sampling can vary from 1 to 30 minutes.

The *depth integrated* sampler is lowered at a uniform rate from the water surface to the streambed, instantly reversed, and then raised again to the water surface. The sampler continues to take its sample throughout the time of submergence. At least one sample should be taken at each vertical selected in the cross-section of the stream. A clean bottle is used for each sample. This type of samplers collects velocity-weighted samples.

Important storm flows are infrequent and difficult to predict, and when they occur, trained personnel may not be available to collect the required information. As a consequence automated data collection is essential to effectively capture such events. *Automatic samplers* pump a small sample into a series of bottles, at predetermined times and intervals, triggered by predetermined flow (Pavanelli & Bigi, 2005) or turbidity conditions (Lewis, 1996).

2.2 Acoustic backscatter systems

The acoustic backscatter (ABS) instruments transmit high frequency ultrasound beams towards the measurement volume. Suspended sediments scatter a portion of this sound back to the transducer. The strength of the backscattered signal allows the calculation of sediment concentration. Suspended sediments significantly scatter underwater sound at megahertz frequencies (0.5 -5 MHz) and the sediment concentration and the grain size control the backscattered intensity (Thorne & Buckingham, 2004).

The acoustic backscattering method is based on the sonar equation (Medwin & Clay, 1997). Since the acoustic backscatter system is an indirect method of measurement, an inversion algorithm is required for determining sediment concentration with measured backscattered signal strength. The acoustic backscatter equations provide the basis for the development of such an algorithm (Thorne & Meral, 2007).

The backscatter amplitude depends on the concentration, particle size, and acoustic frequency. In recent years, the development of multi-frequency acoustic backscatter systems overcame the uncertainties associated with measurements from single frequency instruments. Several experiments have been made to use the backscattered signal of the Acoustic Doppler Current Profiler (ADCP) for determining the suspended sediment concentrations. The multi-frequencies method using commercial ADCP frequencies is able to investigate concentration and grain size field inside the silt-sand range, with typical acoustic shadow zones (Guerrero & Lamberti, 2008). Similarly, the Acoustic Doppler Velocity Meter (ADV) was used to determine the suspended sediment concentrations.

The acoustic backscatter system requires accurate in-situ calibration and is not suitable for the upper concentration range (>10 g/l). This technique is sensitive to the presence of flocculated materials, air bubbles, phytoplankton and seems to provide less precise results, in terms of concentration, than the optical instruments, when large quantities of fine material are transported (Fugate & Friedrichs, 2002).

2.3 Optical turbidity

Methods for measuring suspended sediments via optical turbidity derive from the pioneering work of Whipple and Jackson around the year 1900 that lead to a candlebased turbidity standard. In 1926, Kingsbury and Clark discovered formazin and improved the consistency in standards formulation (Sadar, 1999). Turbidity measurement standards changed in the 1970's when the nephelometric turbidimeter, or nephelometer, was developed which determines turbidity by the light scattered at an angle of 90° from the incident beam.

In recent years the use of the optical technology for river monitoring largely spread as it is considered a good “surrogate” for suspended sediment (Gippel, 1995; Lewis, 1996). These instruments are based on the theory that an incident beam in a mixture is subject to absorption, scattering and transmission caused by the presence of suspended particles. The light source can vary in wavelength and type. The scattered beam can be measured by one or more electronic photodetectors positioned at α=90° (nephelometric scattering), α<90° (forward scattering) or at α>90° (backscattering) to the direction of the incident beam.

These instruments are sensitive to the grain size distribution of the material. This feature has little relevance in small watersheds because they are generally characterised by homogenous pluviometric regimes and erosion times, but can be significant in large watersheds (Lenzi and Marchi, 2000). Variations in grain size distribution, associated with floods, can lead to nonlinear turbidity/suspended sediment concentration relationships. In practice, the degree of curvature is usually very small and linear models perform quite well in estimating loads (Lewis, 2003).

The interferences associated with optical measuring are the colour of the particles and the watery medium, which absorb light in some bands of the visible spectrum, altering the characteristics of the transmissed light. Further interference is caused by the ratio between the size and shape of the particles and the wavelength of the incident beam: particles of a comparable size to that of the incident beam wavelength transmit light symmetrically, whereas larger particles transmit an irregular light in all directions. The scattered light, the density of the particles and the content of dissolved particles such as pollutants and organic matter can lead to errors of measurement since they interfere with the diffusion of light between the particles and the photodetector (Gippel, 1989; Foster et al., 1992; Sadar, 1998). These interferences are minimized by the ratio detection system that uses a combined system of photodetectors and a specific algorithm that calculates the intensity of the scattered light (Sadar, 1999). Another advantage of this system is that it can measure in a broad range of concentrations, therefore it is suitable for suspended sediment monitoring in different environments.

2.4 Laser diffraction

A new generation of systems for measuring the size distribution and concentration of suspended sediments is based on small-forward angle scattering technology, formerly called laser diffraction. At small angles, the scattered light is composed primarily of light diffracted by a particle. Laser scattering instruments direct a laser beam through the water sample, and the suspended particles scatter, absorb and reflect the beam. The scattered laser beam is received by a ring detector that allows measurement of the scattering angle. Particle size and sediment concentration can be calculated using this angle.

These systems replace old technology optical backscatter sensors or single frequency acoustic sensors which suffer from calibration changes with particle size and composition.

The laser scattering and transmissiometry devices measure scattering of light at multiple angles. Inversion of this data leads to sediment concentration and size distribution in 32 size classes. The size classes span a 200:1 range of particles (1.25 to 250; 2.5 to 500; or 7.5 to 1500 microns). In addition, these systems also measure beam attenuation, which is used to de-attenuate measured multi-angle scattering. Thus, these instruments have the

transmissometer function built in. The detailed size distribution of the laser instrument exceeds in information content that offered by the multi-frequency acoustic. These instruments measure sediment concentration in a range of 10 – 3.000 mg/l and are not suitable for high suspended sediment transport.
This technology can be influenced by few compact aggregates that may scatter the light beam as individual entities, altering the actual size distribution of the material (Pedocchi and Garcia, 2006).

3. Suspended sediment transport in semiarid watersheds

Semi-arid climate describes regions receiving low annual rainfall, having nutrient-poor soils and short-grass or shrublands vegetation. Climate is characterized by extreme variability in precipitation and is subject to droughts and infrequent rainfall periods and subsequent flooding. In these areas actual evapotranspiration represents an important feature and it is recognised as the main hydrologic loss (50-60 % of mean annual rainfall).
In the semi-arid climatic zone hydrological processes are largely variable both in time and space due to the high variability of rainfall regime, in addition to the influence of topography and the spatial distribution of geology, soil and land-use. Suspended sediment load is generally high and it reaches maximum values at the beginning of the flood season and after dry periods.
In semi-arid environments (if gully erosion is not active), sheet erosion is the main source of sediments. In the western United States sediment load of rivers is derived mainly from semiarid watersheds (Wilcox & Wood, 1989).
Vegetation influences soil erosion and agriculture likely represents the dominant cause of catchment disturbance and accelerated erosion in most areas of the world (Walling & Fang, 2003).
About 40% of Spanish territory is seriously affected by erosion. One of these areas, the central Ebro valley in northeast Spain, provides a case-study of climate and human impact on soil erosion. The occurrence of convective storms coupled with the high erodibility of the soils gives rise to very fragile agrosystems in which soil essentially constitutes a non-renewable resource (Navas et al., 1997).
The River Isábena in the Ebro valley drains areas of highly erodible sediments (badlands) that occupy a small portion of the basin but are the main source of sediment. This leads to intense suspended sediment transport during most flood events. Thirty-four flood were monitored using a turbidity probe and different hydrological and sedimentary responses of the cachment to similar rainfall were observed. This variability can be attributed to the sediment availability and to the antecedent soil moisture conditions (López-Tarazón et al., 2010).
In the Eshtemoa basin (Israel) vegetation is sparse, small areas are cultivated for growing winter wheat and the steeper hillslopes are used for grazing. The Yatir forest covers a portion of the basin. An automatic sampling programme was esthablished in the period 1994-1998 and 9 flood events were monitored in the winter seasons. The range of suspended sediment concentration in the Eshtemoa basin covers similar orders of magnitude of other semi-arid and arid-zone drainage basins (Alexandrov et al., 2003). Distinct seasonal differences are identified and related to the prevalence of cellular, convectively enhanced storms in autumn and spring and frontal storms in winter (Alexandrov et al., 2009).
In northwest Algeria Megnounif et al. (2007) investigated the variability and seasonality of suspended sediment transport in the Wadi Sabdou collecting water samples during 19 flood

events (1988-1993). They distinguished two periods of active erosion and high sediment yield. The first in autumn due to the sediment accumulated during the dry summer and the second in spring, at the end of the wet season, when the collapsing of the river banks contributes to increase the sediment transport. During the wet period of winter and spring the relationships between sediment and discharge produces hysteresis mainly in the form of mixed loop.
An attempt to explain the relationship between sediment concentration and discharge was carried out by Benkhaled & Remini (2003) monitoring 13 flood events in the Wadi Wahrane (Algeria). The high intensity and the variability of concentration of sediments is due to seasonal effect and hysteresis.
A summary description of the basins monitored in semi-arid environments is reported in table 1.

River	Basin area (km^2)	N° events	Q_p (m^3/s)	SSC_{max} (g/l)	References
Eshtemoa (Israel)	119	9	0.24-84.4	15.5-186.0	Alexandrov et al. (2003)
Isábena (Spain)	445	34	1.52-78.7	0.1-90.0	López-Tarazón et al. (2010)
Sabdou (Algeria)	256	3*	29.2-106.0	22.5-115.0	Megnounif et al. (2007)
Wahrane (Algeria)	270	13	0.9-200.0	63.0-250.0**	Benkhaled & Remini (2003)
*For three events of the total 19 monitored SSC_{max} and Q_p are available. **The event Q_p=1 m^3/s, SSC_{max}~500 g/l was excluded from the dataset					

Table 1. Basins monitored in semi-arid environments.

4. Monitoring suspended sediment in Southern Italy

The experimental station measuring suspended sediment concentration (fig. 1; tab. 2) is located in the Carapelle torrent (Ordona-Castelluccio dei Sauri bridge). The torrent originates from flyschoid formations of the Daunia Mountains and develops into the alluvial fan of the Tavoliere plain. The plain and the low hilly areas are mainly used for cereal cultivation and olive growing, whereas the higher slopes are occupied by woods and pasture. The climate is typically Mediterranean, with rainfalls ranging from 450 to 800 mm/year and average temperatures ranging from 10 to 16 °C.
The station is equipped with a remote data transmission ultrasound stage meter and a stage recorder. In addition, an infrared optic probe (Gentile et al., 2010) was implemented for the measurement of the suspended sediment concentration (fig. 2). The instrument is housed in a shelter tube through a pulley, a float and a counterweight group. The housing device, anchored to a bridge pier, protects the instrument from the impact of any flowing coarse material and prevents any potential measuring errors caused by incident radiant energy straying into the infrared field. Solar infrared radiation decreases of approximately 63% below 50 mm of clean water, and this information is important particularly in regard to surveys carried out near surface level. The instrument is controlled through a data acquisition system that is power supplied by solar panels.

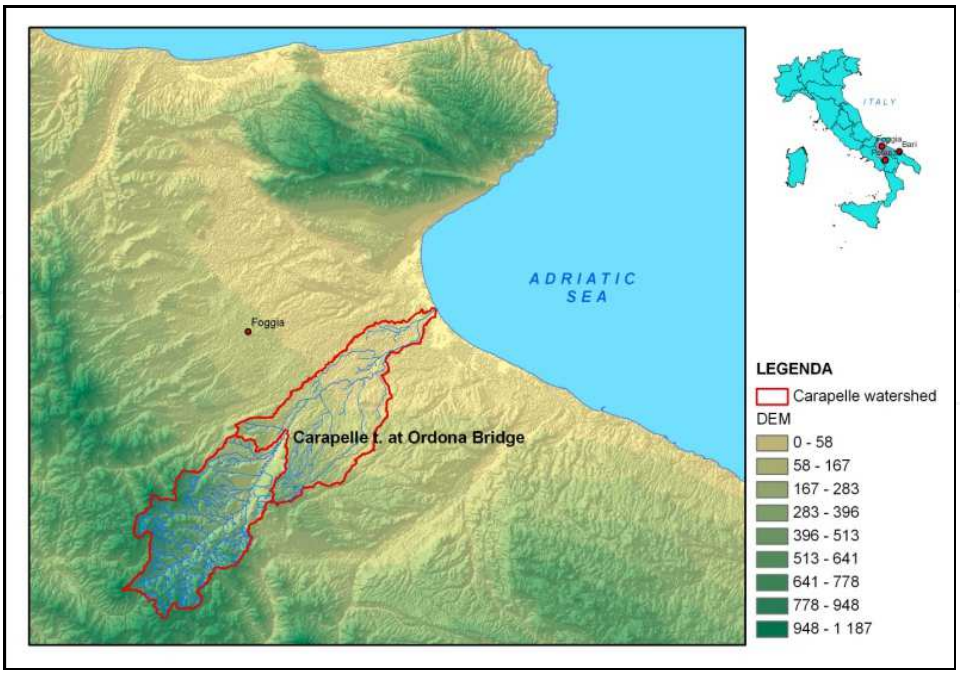

Fig. 1. The Carapelle watershed in Southern Italy

Watershed area	km^2	506.2
Maximum altitude	m a.s.l	1075.0
Average altitude	m a.s.l.	466.0
Minimum altitude	m a.s.l	120.0
Main channel length	km	52.2
Main channel slope	%	1.8
Mean watershed slope	%	8.2

Table 2. Main characteristics of the Carapelle watershed at Ordona bridge.

Fig. 2. The suspended sediment measuring station and the optical device (instrument).

The instrument was laboratory tested using mixtures of different grain size distributions and sediment concentrations. The aim was to determine the existing relationship between the optical data and that obtained with standard methods and to assess the instrument response to different granulometric contents of the mixture. Afterwards, the instrument was field-tested to verify the housing device and the calibration curve of the optical probe (Gentile et al., 2010). This phase was executed collecting 90 samples during the flood seasons in the period 2007-2009 (fig. 3). The field testing confirmed the results achieved in the laboratory, evidencing a linear relationship between the optical and the gravimetric data (fig. 4). The comparison between samples collected inside and outside the tube allowed to verify that the instrument housing does not interfere with the measuring process.
The concentration and the discharge of 27 flood events, monitored at half-hourly scale, were then considered to analyze the sediment transport dynamic (tab. 3).

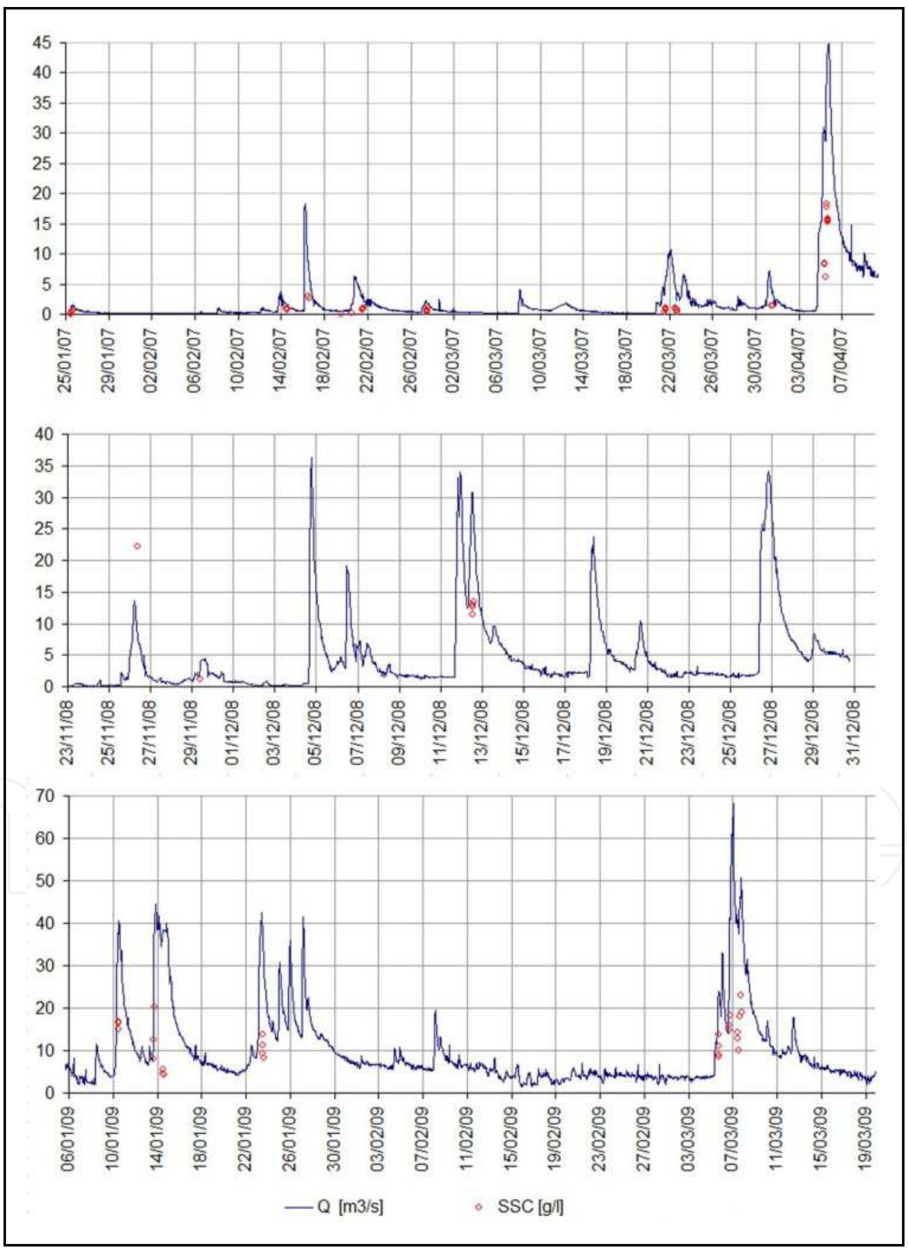

Fig. 3. Sampling of suspended materials during the flood seasons 2007-2009.

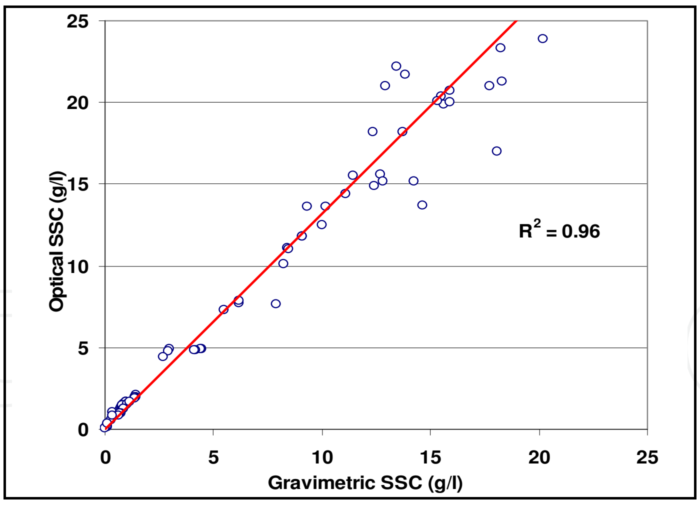

Fig. 4. Field calibration of the optical probe.

Event	Q_p (m^3/s)	Flood volume (m^3)	SSC_{max} (g/l)	Sediment load (t)
27-Feb-07	2.3	167481	2.1	202.7
7-Mar-07	4.1	188457	2.3	232.4
21-Mar-07	10.7	974542	2.5	2184.1
24-Mar-07	6.7	484555	1.4	462.2
28-Mar-07	14.4	600895	3.7	1097.0
31-Mar-07	7.3	470471	2.1	593.0
5-Apr-07	44.9	5551463	20.7	36124.0
9-Apr-07	10.2	54442	9.5	1279.5
23-Jan-08	1.6	187033	2.9	358.0
6-Mar-08	26.7	4076370	18.5	18231.6
6-Dec-08	19.1	987512	32.8	11336.1
18-Dec-08	23.8	1335547	26.6	13064.8
20-Dec-08	6.2	672826	4.9	1997.0
26-Dec-08	34.2	2679841	17.4	25503.3
8-Jan-09	11.6	917056	19.2	5155.6
10-Jan-09	40.6	4133587	22.4	23694.0
14-Jan-09	44.6	6561790	41.2	59652.7
23-Jan-09	42.6	3870310	14.8	21959.2
8-Feb-09	19.4	1418963	28.8	10137.1
5-Mar-09	33.0	1489752	43.0	28208.6
7-Mar-09	68.4	3947932	34.7	87947.0
10-Mar-09	17.1	730348	7.8	2131.3
12-Mar-09	17.7	756934	5.78	2726.8
20-Mar-09	69.2	4014736	20.45	43746.0
22-Mar-09	33.0	2779452	7.77	9879.0
24-Mar-09	21.7	3298477	7.77	10867.6
2-Apr-09	22.9	1630998	27.75	14973.4

Table 3. Hydrologic characteristics of the flood events monitored in the Carapelle torrent.

5. Results

During the monitoring seasons 2007-2009 twenty-seven events, having continuous data and absence of anomalies in the time series, have been selected. Most of the relationships between sediment concentration and discharge (fig. 5), registered at half-hourly scale, revealed the existence of hysteresis (clockwise, counterclockwise, mixed-shaped). This means that the relationship between suspended sediment concentration and discharge is quite different for the rising limb of the hydrograph than for the falling one. The tendency for sediment concentration to have different values at identical stream discharges is the primary drawback to the application of a rating curve during a storm flow. In some cases there can be the absence of hysteresis as shown in figure 5.

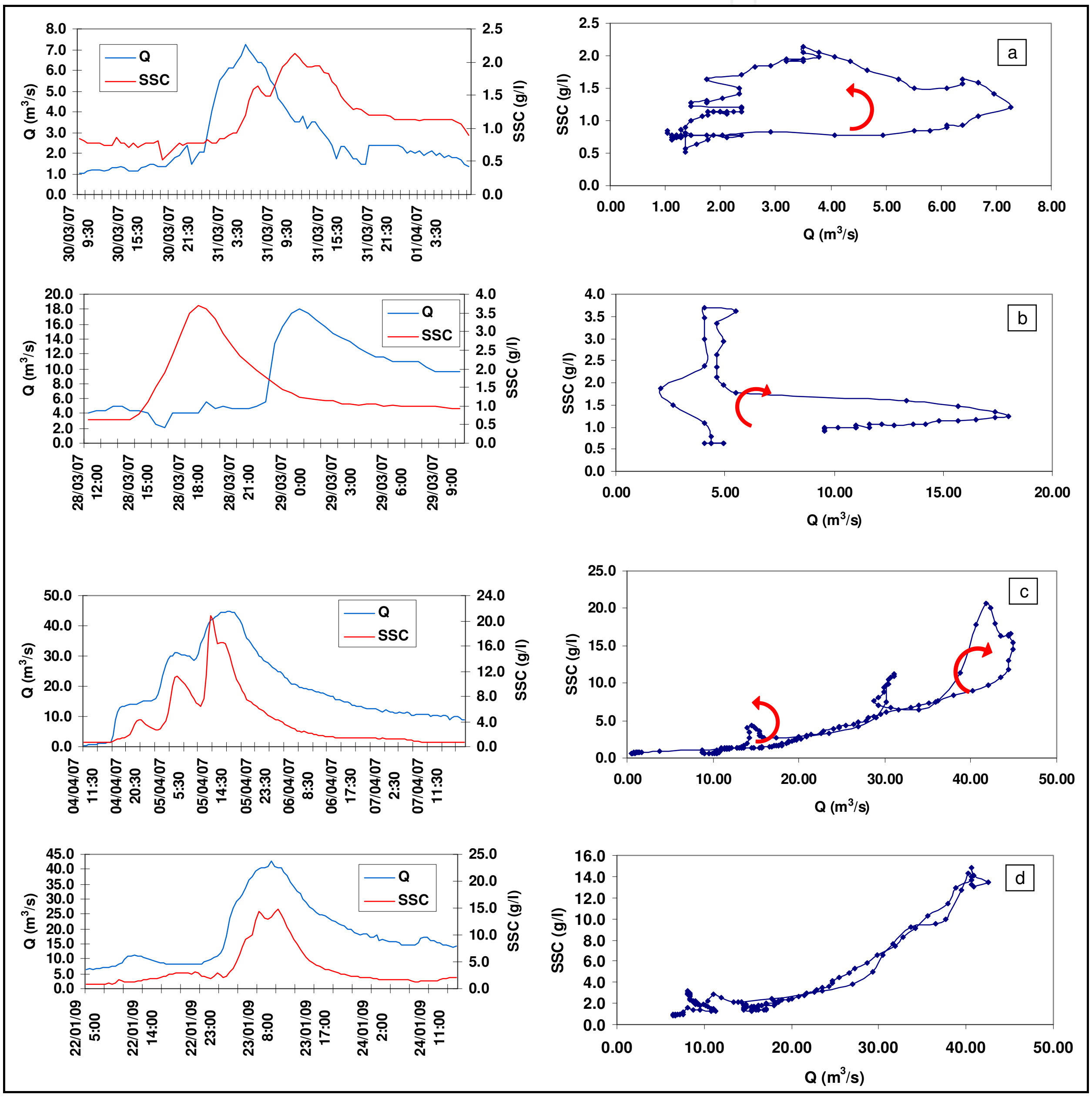

Fig. 5. Types of relationships between sediment concentration and discharge during flood events in the Carapelle torrent.

Counterclockwise loops can be observed during all the flood season and prevail in the moderate events. The sediment concentration increases in the falling limb of the hydrograph due to the distance between the sediment sources (mainly hillslopes) and the measuring station (Brasington and Richards, 2000).
Clockwise loops occur during the most intense events and the sediment concentration start to decrease in the rising limb of the hydrograph. This type of response indicates that sediments delayed in the riverbed contribute to sediment transport (Williams, 1989) but their availability decreases during the event. This type of loop frequently occurs at the end of the rainy season as it is influenced by the depletion of sediments produced by the previous floods (Campbell, 1985).
Mixed-shaped loops occur in multi-peaked floods, for example when an intense flood immediately follows a moderate flood. This kind of loop can be generated also during the steady states of the flow (De Sutter et al., 2001).
When the absence of hysteresis is observed the sediment transport capacity is maximum during the flood.
The unsteadiness of the flow influences sediment transport as the turbulence intensity can change during a flood. The streamwise and vertical components of the turbulence are generally larger in the rising limb of the hydrograph than in the falling one. The increased intensity in the rising limb can be caused by the flood wave overtaking the base flow. The turbulence intensity decreases immediately in the falling limb, having the minimum value in the middle of this limb, and then increases to the value for a steady flow condition. High turbulence intensities maximizes the transport capacity and the sediment concentration is highest when the duration of the rising limb of the hydrograph is short (De Sutter et at., 2001). When the decrease of the turbulence occurs the sediment transport capacity reduces in considerable way. This phenomenon has been observed in some floods of the Carapelle (fig. 6): when the flow becomes stable and the turbulence reduces an abrupt decrease of the values of the concentration occurs.

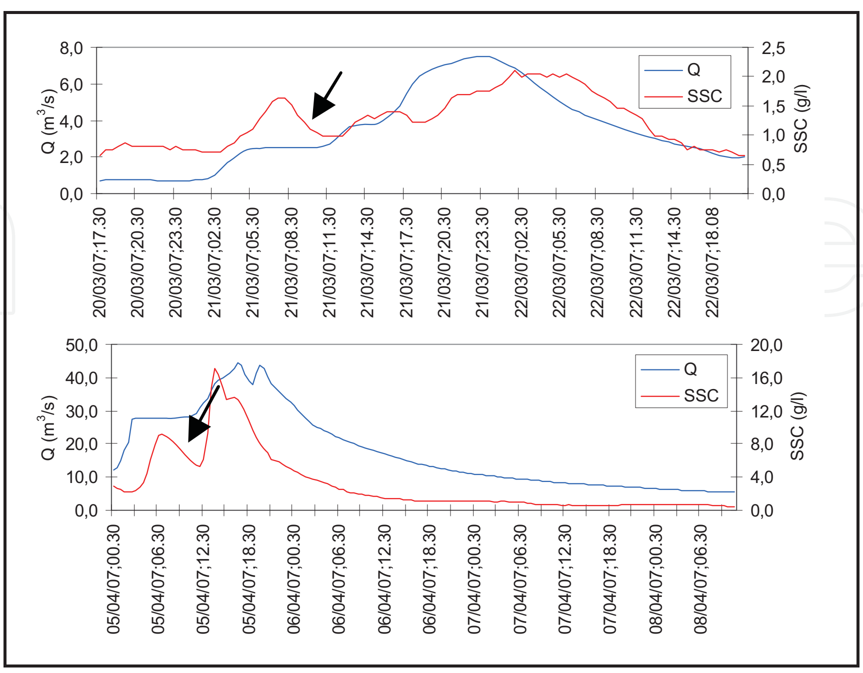

Fig. 6. Decrease of the sediment concentration during the steady states of the flow.

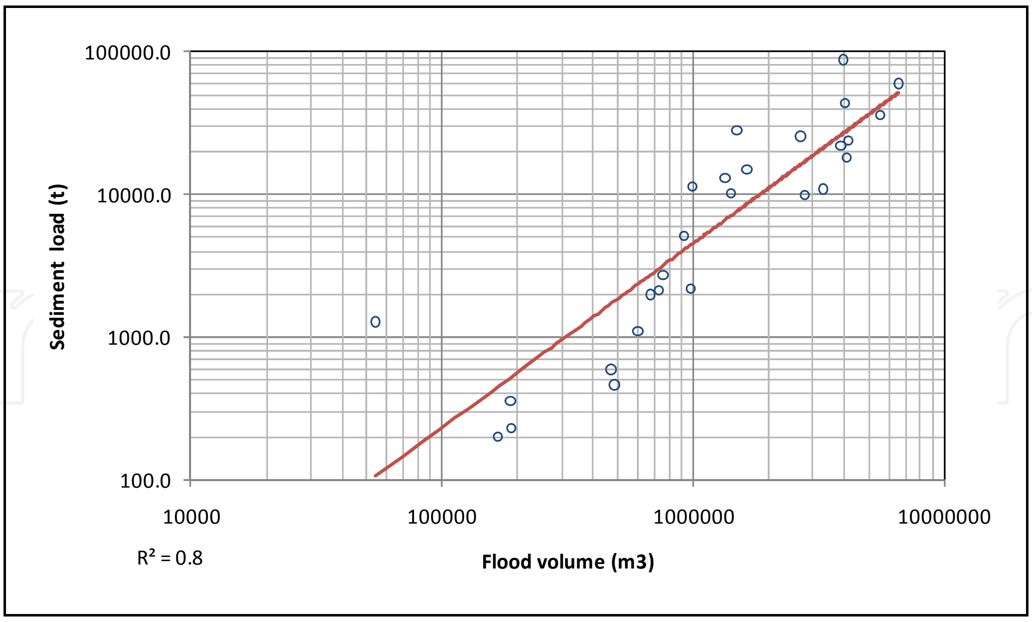

Fig. 7. Sediment load *vs* flood volume

Due to the hysteresis effect the regression scatter of the rating curve SSC = aQ^b between suspended sediment concentration SSC and discharge Q (a and b are empirically derived regression coefficients) is often great for the same river. As a consequence the dependency of the sediment load from the flood volume and of the SSC_{max} from Q_p was assessed. The best-fit regression relationship (fig. 7) between the sediment load [t] and the flood volume [m^3] is the power-law relationship (r^2 = 0.8):

$$y=10^{-4}\,x^{1.3} \tag{1}$$

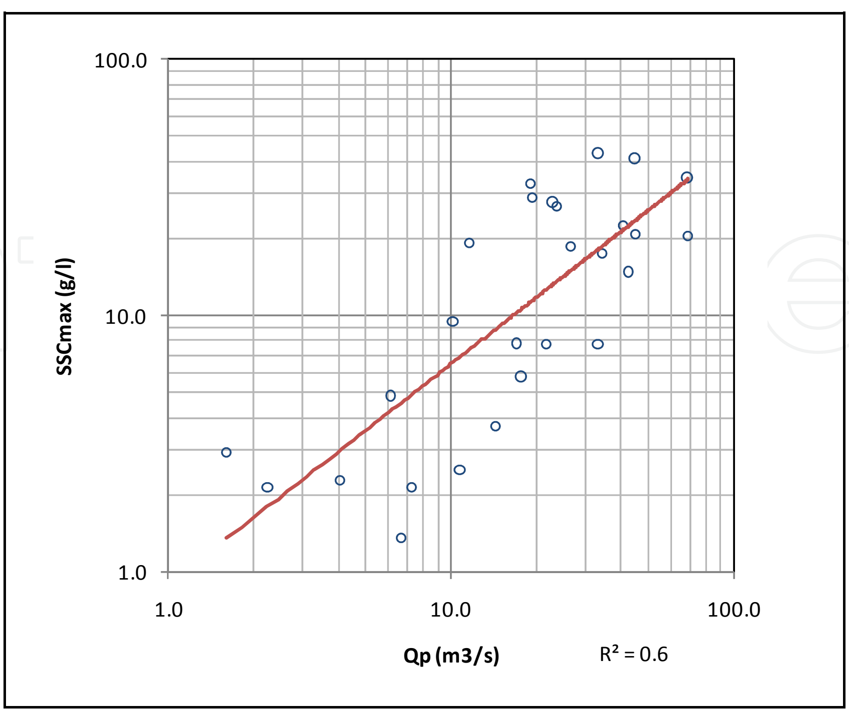

Fig. 8. Maximum suspended sediment concentration *vs* peak discharge.

The SSC_{max} reached during the events has a good correlation with the peak discharge. The r^2 =0.6 means that the variation of SSC_{max} are explained up to 60% by those of Q_p and by 40% by other factors such as the sediment supply, rainfall intensities and land use variations. The best-fit regression relationship (fig. 8) between SSC_{max} and Q_p is the power-law relationship:

$$y=0.89\,x^{0.86} \tag{1}$$

The time delay T between SSC_{max} and Q_p registered during the events varies with the flood intensity (Gentile et al., 2010). Plotting the time delay T versus peak discharge Qp a decreasing trend was observed (fig. 9). Positive values of T indicate that SSC_{max} follows the peak discharge and the hysteresis is counter-clockwise; negative values of T indicate that SSC_{max} occurs before the peak discharge and the hysteresis is clockwise. A time delay equals to zero defines the threshold at which discharge exerts a strong influence on the sediment load and determines the advance of SSC peak value.

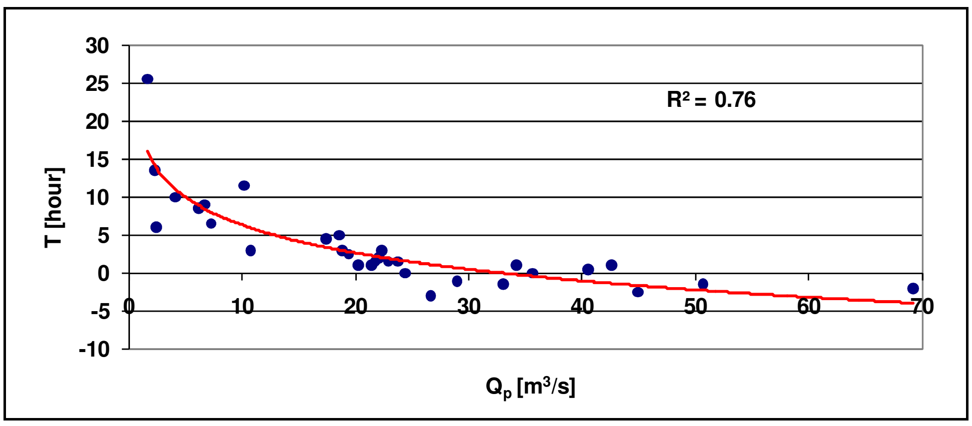

Fig. 9. Time delay T between SSC_{max} and peak discharge *vs* Q_p.

On the basis of the previous results, the variability of the SSC_{max} values among the events was evaluated dividing the floods in moderate events (Q < 30 m^3/s) and intense events (Q > 30 m^3/s). Some considerations on the hydrological response of the watershed are reported.

Three moderate events of the season 2007 (fig. 10), with increasing peak discharges, show similar maximum SSC values. At the same time the moderate flood of 5 Mar 2009 (fig. 11) has higher concentrations than the following having comparable intensities.

On the other hand the intense event of the season 2009 (fig. 12) has markedly higher sediment concentrations than the following floods that show increasing peak discharges.

The reasons of such behaviour can be attributed to the presence in the first flood also of material coming from the river bed. The sediment concentrations mobilized during the following floods mainly derive from hillslopes and a best correlation between SSC_{max} and Q_p can be found.

This can be referred to the sediment depletion from hillslopes that influenced the last events.

The relationship between the maximum SSC and Q_p at event scale was evaluated considering the experimental values of the Carapelle torrent and those reported by Alexandrov et al. (2003), Benkhaled & Remini (2003), Megnounif et al. (2007) and López-Tarazón et al. (2010) in order to determine a possible trend of the suspended sediment transport in semi-arid zones. A general trend exists between the SSC_{max} and Q_p (fig. 13) but,

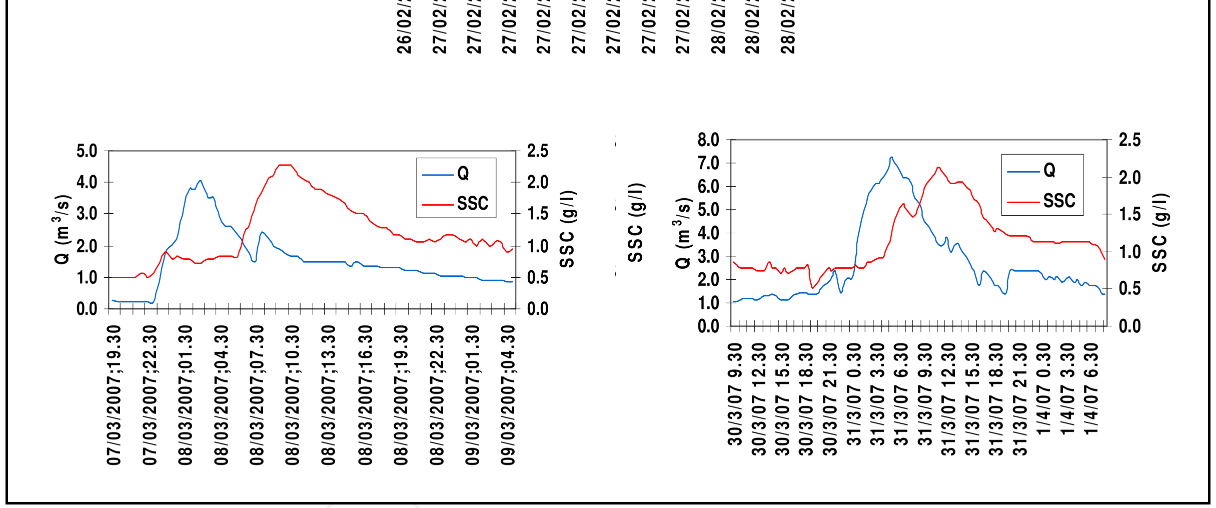

Fig. 10. Consecutive events of moderate intensity of the flood season 2007.

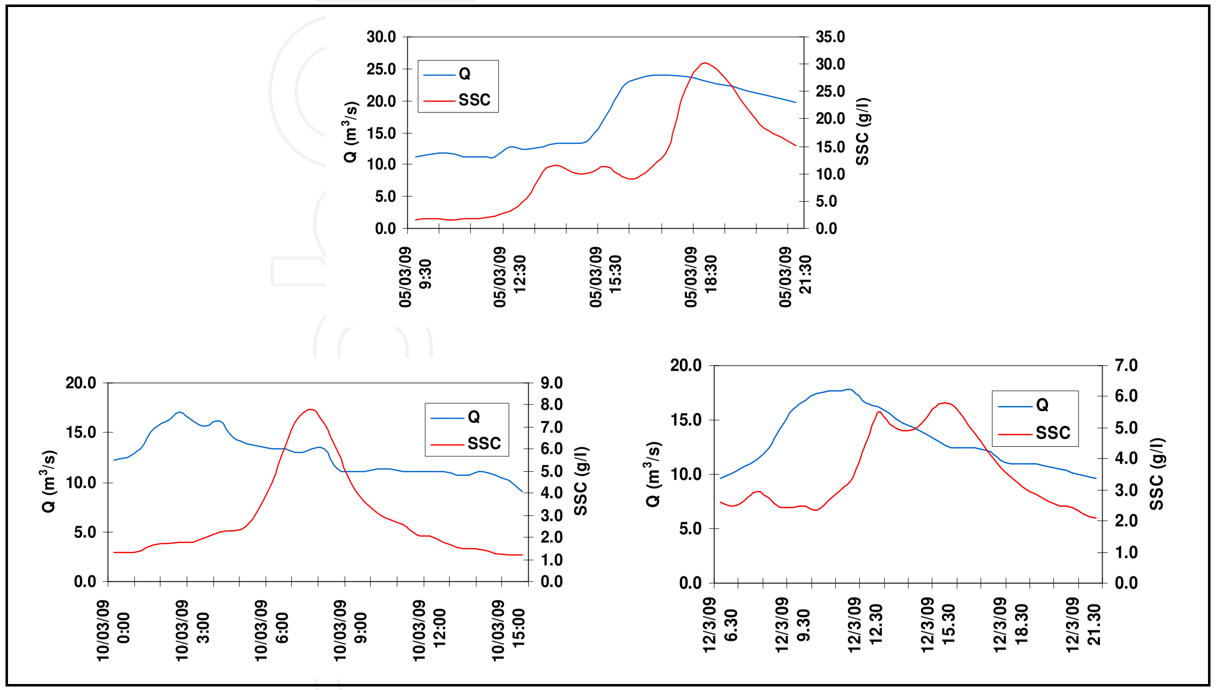

Fig. 11. Consecutive events of moderate intensity of the flood season 2009.

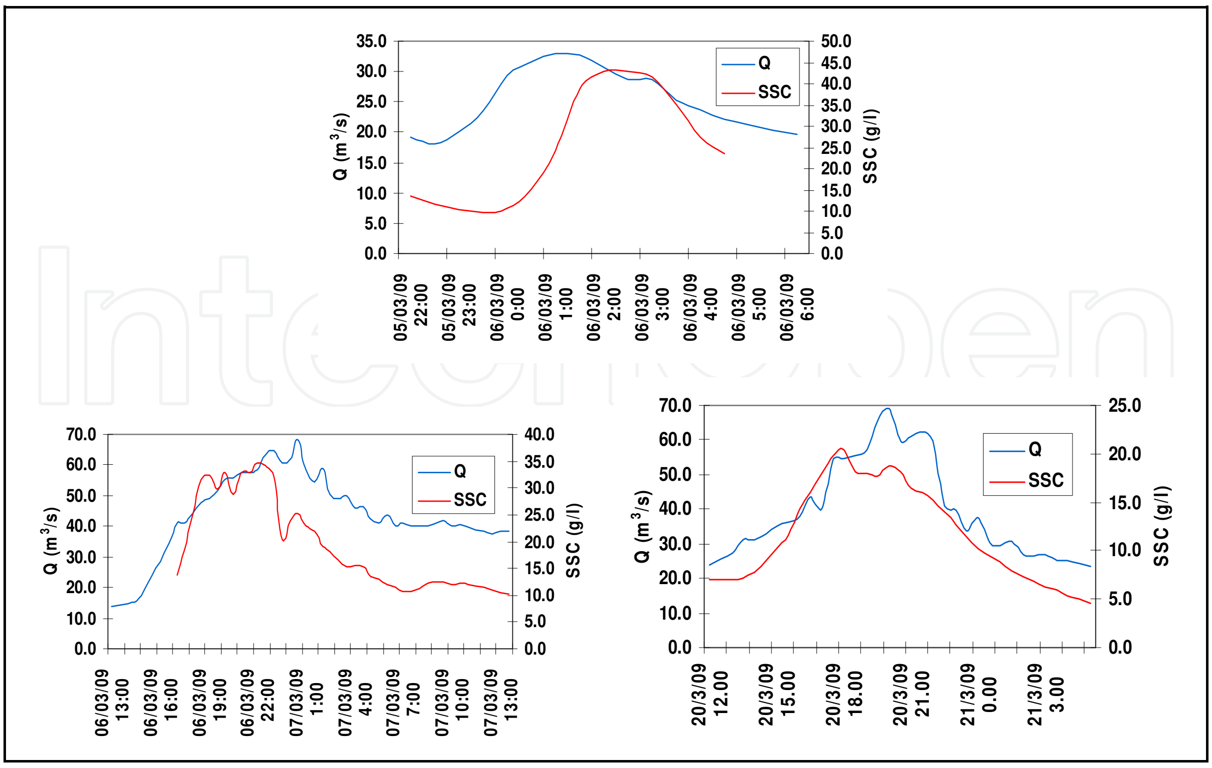

Fig. 12. Consecutive events of high intensity of the flood season 2009.

Rating parameters *a* and *b* of a river strongly depend on flow regime and do not vary in the same proportions (Achite & Ouillon, 2007). Generally the coefficient *b* varies in range 0.3–2.5, while *a* can vary by several orders of magnitude). In arid zone the coefficient *b* is smaller (usually $b < 1$) as compared to typical perennial rivers of the temperate regions where $b > 1$. Intermittent rivers in semi-arid environments seem to have *b* coefficients lower than 1, similar to ephemeral rivers in arid zones. In this work the coefficients of the relationship SSC_{max} - Q_p obtained for five experimental basins are quite consistent with those reported in literature and can be considered typical of the semi-arid environments.

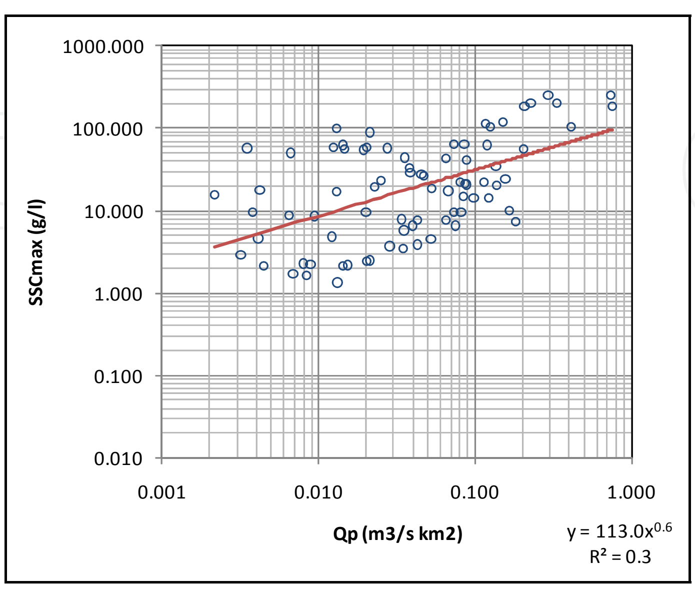

Fig. 13. Trend of the suspended sediment concentration in five semi-arid basins.

6. Conclusions

In recent years many different instruments have been used to determine sediment concentration in rivers. They have different operational modes and range of measurement.

In a semi-arid basin of Southern Italy an optical submerged probe is used for continuous monitoring. The data collected over the period 2007-2009 provided the basis for the analysis of the suspended sediment transport at the event scale.

As in other semi-arid basins, hysteresis between SSC and discharge during flood events has been observed. The main reasons of such non-linear hydrological response can be found in the different flood intensities and in the variations of turbulence that characterize the unsteadiness of the flow.

An excellent correlation exists between sediment load and flood volume and a good agreement has been found also between SSC_{max} and peak discharge. The analysis of the decreasing trend of the time delay between SSC_{max} and Q_p in relation to flood intensity allows to consider separately the behaviour of moderate and intense events.

A general relationship between the maximum SSC and Q_p at the event scale can be determined considering the experimental values collected in five semi-arid basins. The rating parameters *a* and *b* of the relationship estabilish hydrological conditions that characterize the semi-arid environments.

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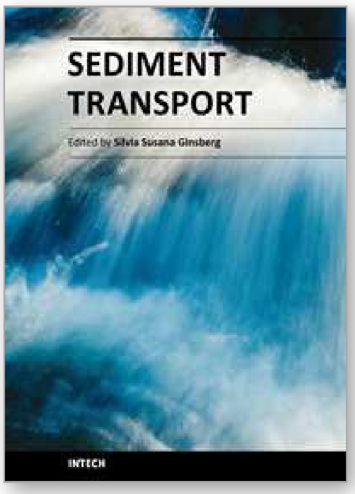

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Sediment transport is a book that covers a wide variety of subject matters. It combines the personal and professional experience of the authors on solid particles transport and related problems, whose expertise is focused in aqueous systems and in laboratory flumes. This includes a series of chapters on hydrodynamics and their relationship with sediment transport and morphological development. The different contributions deal with issues such as the sediment transport modeling; sediment dynamics in stream confluence or river diversion, in meandering channels, at interconnected tidal channels system; changes in sediment transport under fine materials, cohesive materials and ice cover; environmental remediation of contaminated fine sediments. This is an invaluable interdisciplinary textbook and an important contribution to the sediment transport field. I strongly recommend this textbook to those in charge of conducting research on engineering issues or wishing to deal with equally important scientific problems.