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The effect of floods on the transport of suspended sediments and contaminants: A case study from the estuary of the Dese River (Venice Lagoon, Italy)

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Abstract

A flood event was investigated in a measurement section of the estuary of the Dese River, the major tributary of the Venice Lagoon (mean annual discharge = 7.5 m^3/s), to observe the variations induced by the flow on the physico-chemistry of the water column and the transport of particles and pollutants. The flood was generated by a typical summer storm, which had a return period of 2 years. The study was based on the continuous recording of the discharge and the measurement of both current speed and physico-chemical variables along the vertical profile. Water samples were also collected for the analysis of total and dissolved heavy metals (As, Cd, Cr, Cu, Fe, Hg, Mn, Ni, Pb, Zn), and nutrients (TKN, $N-NO_3^-$, $N-NO_2^-$, $N-NH_3$, total phosphorous, $P-PO_4^{3-}$). The suspended particle matter (SPM) concentration increased in the water column during the flood, and the discharge versus SPM relationship showed a counterclockwise hysteresis. The occurrence of hysteresis was related to the delayed response of the load, deriving from the runoff on the basin soils with respect to materials mobilized from the streambed in the initial phases of the flood. The transport of most of the analysed heavy metals was driven by the SPM. The increase in concentration of this parameter significantly affected the amount of Fe, Cu, Pb, Cr, Ni, and partially Zn transported by the stream. Among nutrients, $N-NO_3^-$ concentration also increased significantly during the flood, due to the runoff on agricultural surfaces.

The study allowed describing the mechanisms of load generation with high flow magnitudes, highlighting the importance of floods in the transport of materials and pollutants from the drainage basin to the Venice Lagoon.

Keywords: Floods; SPM; Dese River; Hysteresis; Venice Lagoon

1. Introduction

Floods are fundamental events in the transfer of freshwater, sediments and contaminants from the mainland to the coastal zone. The increase of discharge is quite generally accompanied by marked changes in the concentration of suspended sediments, resulting in a noticeable increase of the loads of particulate-associated pollutants. This relevant variation may in turn affect the annual budget of large and minor rivers.

For example, considering the transport of organic contaminants in the tidal Anacostia River (Chesapeake Bay, USA), Foster et al. (2000) found that higher amounts of PCBs, PAH, and organochlorine pesticides occurred primarily in the particulate phase during high flow events. In a study of the nutrient transport in the Humber rivers (UK), House et al. (1997) demonstrated that the majority of the load was transported in autumn–winter storms. Moreover, these loads are generally delivered in a short-time period, at the point that harmful consequences could be induced in the receiving coastal zone ecosystems (Witt and Siegel, 2000; Schulz, 2001).

Floods must be then considered in monitoring plans (Webb et al., 1997) to avoid the underestimation of sediment and pollutant loads (Foster et al., 1992; Littlewood, 1992).

For their importance in the overall budgets, the study of the formation and evolution of peak discharges in rivers is necessary, also because the high-energy flows

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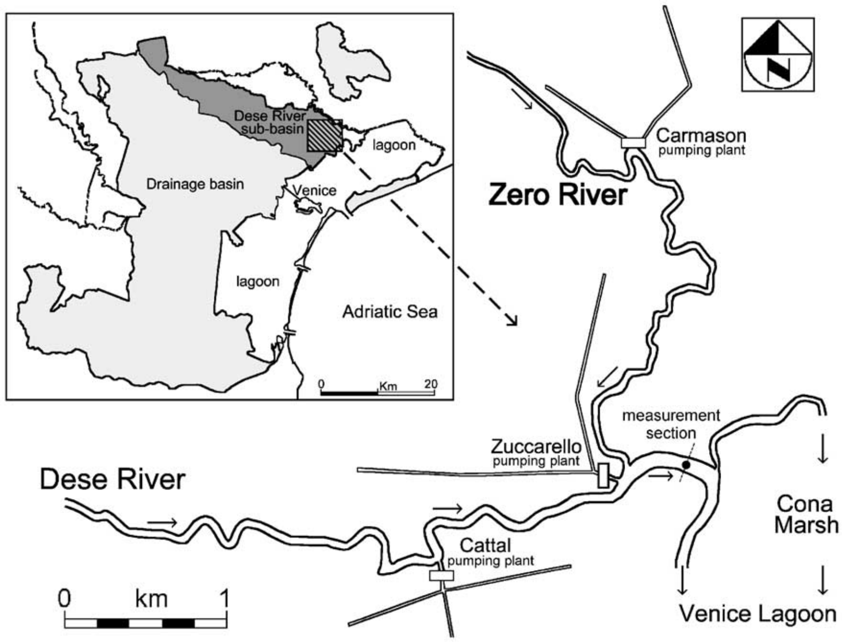

Fig. 1. Map of the lower reach of the Dese River, with the location of the measurement section. In the inset, showing the Venice Lagoon and its drainage basin, the Dese sub-basin is outlined.

induce strong changes in the characteristics of the water column. These are related not only to the sediment yield from the basin but also to the mobilisation of particles settled during the base-flow period. However, owing to problems in sampling during periods of peak flow (Walling and Webb, 1981) and obtaining precise measurements in such a difficult experimental conditions, pollution studies based on field investigations during floods are scarce in the literature.

To evaluate the annual loads of contaminants from the drainage basin to the Venice Lagoon, the discharge and pollutants concentration were measured in the 12 major tributaries, from May 1998 to August 2000 within the DRAIN project[1] (Zonta et al., 2005). Despite their small size (the overall discharge amounts to about 35 m^3/s on a yearly basis, Zuliani et al., 2005), these tributaries represent the major source of contaminants for the lagoon. Therefore, the control and reduction of the related loads are essential tasks for the safeguard of the water quality in the whole lagoon.

The periodical sampling of the project was integrated by a specific sampling in flood conditions. The results showed the important role of floods in the delivery of contaminants to the lagoon, particularly for metals associated to the particulate matter (Collavini et al., 2005).

[1] The DRAIN project (DeteRmination of pollutAnt INputs from the drainage basin into the Venice Lagoon) was carried out on behalf of Consorzio Venezia Nuova, concessionaire of the Italian Ministry of Public Works—Venice Water Authority, as part of the operations designed to safeguard the Venice Lagoon (law 798/84).

During the project activities a flood event in the Dese River (the major tributary of the lagoon) was investigated in detail to obtain information on the river response to storms, in terms of hydraulics, physico-chemical behaviour of the water column and the transport of particulate matter and pollutants.

2. Study area

The Dese River originates from the spring alignment of the Venetian piedmont area and, differently from most of the other tributaries of the Venice Lagoon whose flow is partially or completely regulated, it is characterised by an almost natural drainage. Its sub-basin (surface area 240 km^2) is located in the northern part of the drainage basin (Fig. 1), and the average annual discharge (7.5 m^3/s) corresponds to about the 20% of the overall freshwater inputs. The length of the main stream is about 49 km; a few kilometres from the lagoon mouth, the Dese receives the contribution of the Zero River, a 41-km-long watercourse draining 97 km^2 of the sub-basin surface. Close to the confluence, the stream also receives the inputs from three pumping plants.

The measurement section, located downstream of the confluence (Fig. 1), has a width of 83 m and a mean depth of about 1.5 m. It is affected by the tide excursion (about 80 and 30 cm in spring and neap tide conditions, respectively) with salt wedge intrusion propagating some kilometres upstream. Downstream of the measurement section, the watercourse branches out in

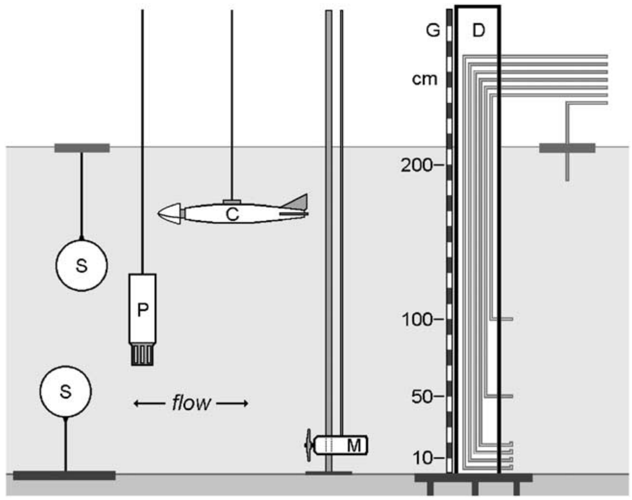

Fig. 2. Scheme of the experimental set-up: self recording current meters (S); propeller-type current meter (C); micro-current meter (M); multiprobe (P); staff gage (G); sampling device (D).

two tidal canals, which direct toward the lagoon crossing salt marsh areas.

3. Methods

A scheme of the experimental set-up is shown in Fig. 2. Current speed was measured using two types of instruments: self-recording and hand-operated propeller-type current meters. The two self-recording instruments (InterOcean mod. S4, USA) were positioned in the central part of the section at 60 cm from the surface and at 50 cm from the streambed, respectively. They acquired current speed and direction, water level, temperature and conductivity, with a sampling interval of 15 min. The procedure adopted to calculate discharge values from the current speed series acquired in the gauge section is described elsewhere in this issue (Zuliani et al., 2005).

Two propeller-type current meters were employed for the direct reading of velocity profiles. A lightweight instrument (Valeport mod. 105, UK) was employed for profiling in the range between the surface and the depth of 20 cm from the bottom. A micro-current meter (OTT mod. C2 Small no. 10150005.B.E, Germany), equipped with a 30 mm diameter propeller, was instead used for detailed flow measurements in the 30 cm depth interval close to the streambed. The readings obtained by these two propeller-type instruments at the depth of 30 cm above the bottom were systematically compared. The same value was generally obtained, with maximum differences of 7% in the acquired velocities.

The physico-chemistry of the water column along the vertical profile was investigated by means of a multiprobe (Hydrolab mod. H20, USA), which measured the values of temperature, conductivity, turbidity, dissolved oxygen, pH and redox potential. Hydrodynamics, physico-chemical measurements, and water samplings were performed at least on an hourly basis.

A specific device, shown in Fig. 2, was designed to allow for simultaneous water samplings at six different depths (5, 10, 15, 20, 50 and 100 cm from the bottom); a constant depth of 20 cm below the surface was also sampled by means of a floating intake.

Suspended particle matter (SPM) concentration was determined in all the collected samples. Chemical analysis was systematically performed on samples collected at 20 cm below the surface and 20 cm above the bottom, while samples from the depths of 100 and 5 cm above the bottom were also frequently analysed.

Determinants included 10 heavy metals (As, Cd, Cr, Cu, Fe, Hg, Mn, Ni, Pb, Zn, for both the total and dissolved concentrations) as well as nitrogen and phosphorus species (TKN, $N-NO_3^-$, $N-NO_2^-$, $N-NH_3$, total phosphorous (P_{TOT}), and $P-PO_4^{3-}$). The total nitrogen concentration (N_{TOT}) was obtained as the sum of TKN, $N-NO_3^-$ and $N-NO_2^-$, while the organic nitrogen (N_{ORG}) was obtained as the difference of TKN and $N-NH_3$. Analytical methodologies are reported elsewhere in this issue (Collavini et al., 2005).

Grain-size analysis was performed on 5-l samples simultaneously collected at four depths, at the beginning of the flood

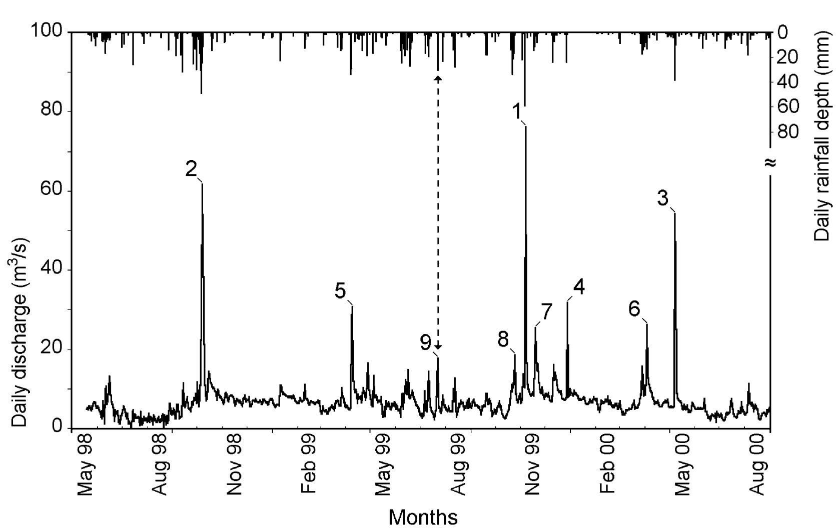

Fig. 3. Plot of the daily discharge and rainfall depth of the Dese sub-basin in the period from May 1998 to August 2000. The main floods are numbered in order of magnitude; the investigated event, which occurred in the night between 22 and 23 July 1999, is marked.

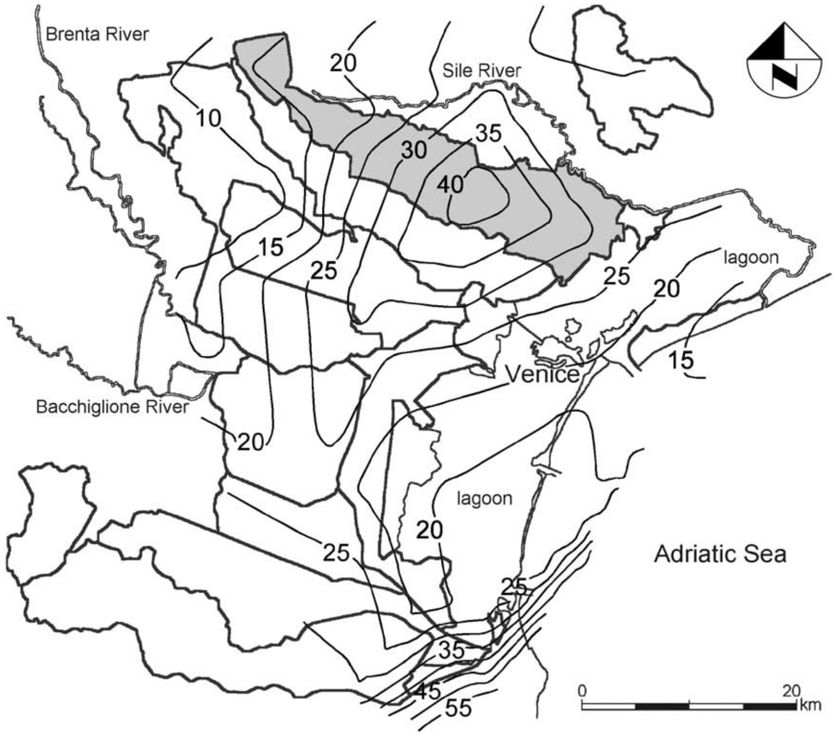

Fig. 4. Isohyet map of the investigated storm event (units in mm) for the drainage basin.

recession. Prior to analysis, the suspended fraction was concentrated by centrifuging the samples. Particle size distribution in the diameter range $d < 125$ μm was measured by means of a laserbeam analyser (Leeds and Northrup, Microtrac mod. X-100, USA).

4. Results and discussion

The discharge hydrograph of the Dese River for the whole 27-month period of monitoring of the DRAIN project is shown in Fig. 3; the main flood events are numbered in order of magnitude. The daily rainfall depth on the sub-basin, obtained by the Thiessen polygon methods (Chow, 1964) on data from nine gauge stations, is superimposed.

The most important storms occurred in October 1998, November 1999, and May 2000; they had magnitudes typical of exceptional events and induced a strong increase in the daily river discharge, up to 10 times the mean annual value (76.2 m^3/s, November 7th, 1999). By analyzing the flood-frequency according to the Gumbel EV1 method (Gumbel, 1958), the return periods (τ_r) of these events resulted even greater than 10 years.

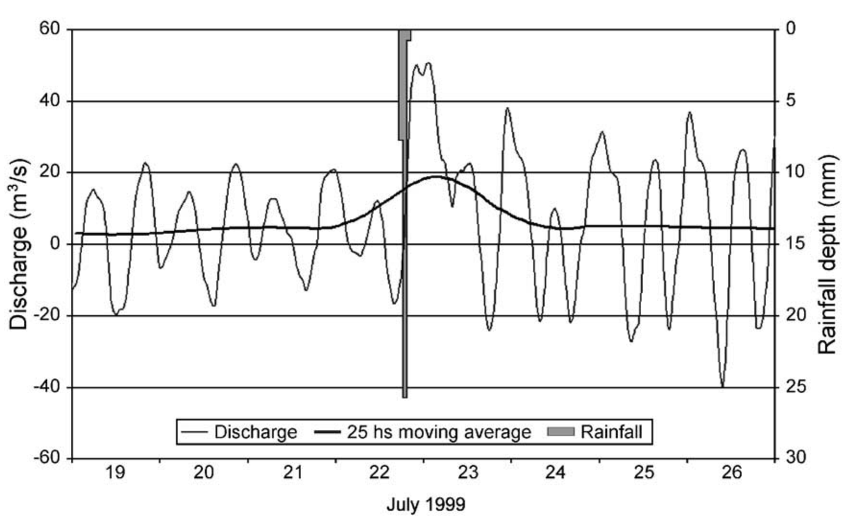

Fig. 5. Trend of the Dese River discharge in the period 19–26 July 1999. The discharge curve obtained by filtering data with a 25-h forward and reverse moving average and the hourly rainfall depth are superimposed.

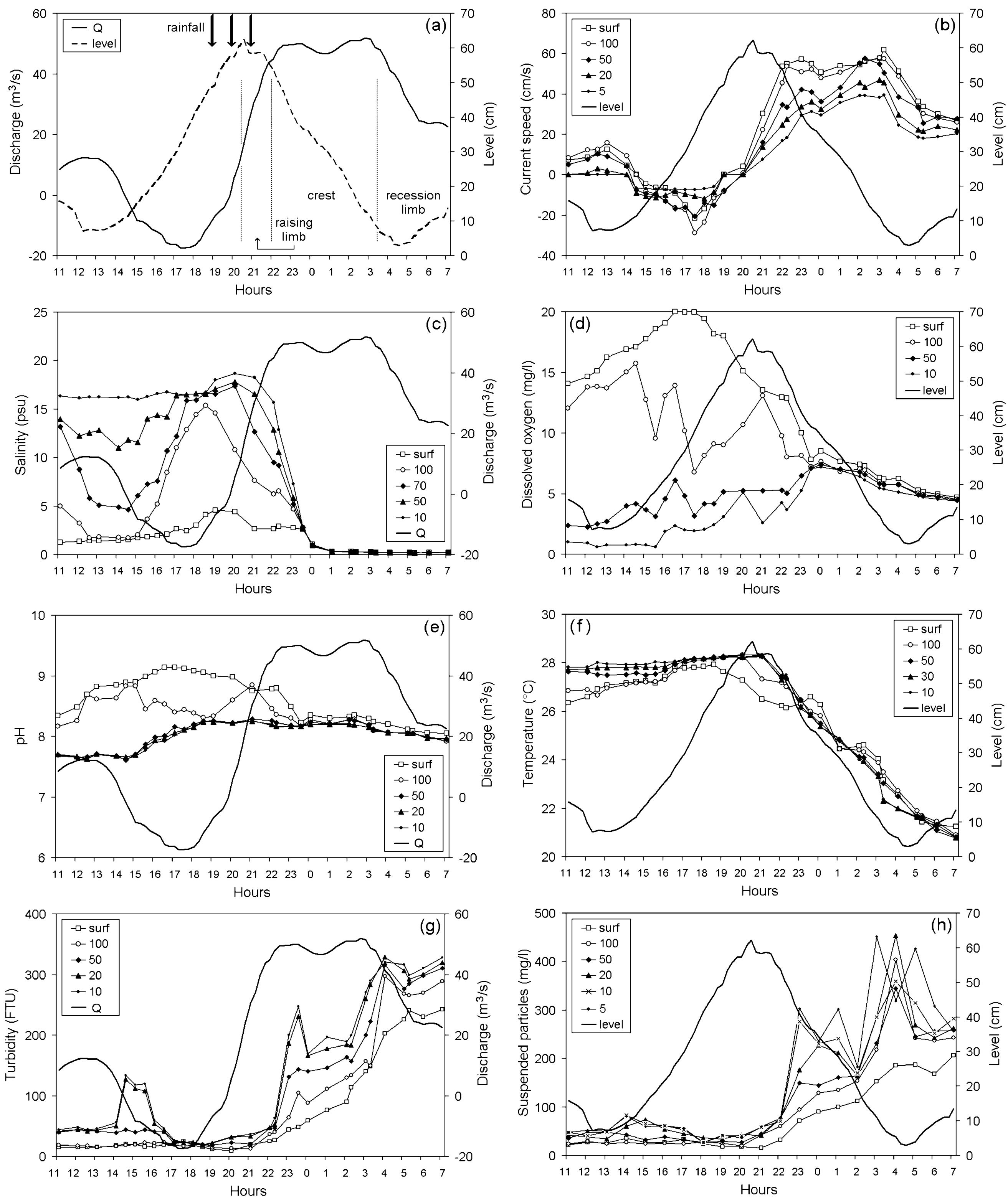

Fig. 6. Plot of discharge and tide level (a). In the graphs (b–h) the trend of water level and discharge are alternatively superimposed to the evolution of current speed (b), salinity (c), dissolved oxygen (d), pH (e), temperature (f), turbidity (g), and SPM concentration (h) at the different depths. The numbers in the legends refer to the height above the bottom; "surf" indicates the measurement depth at 20 cm below the surface. The time interval refers to the period from 22 July 11.00 to 23 July 07.00.

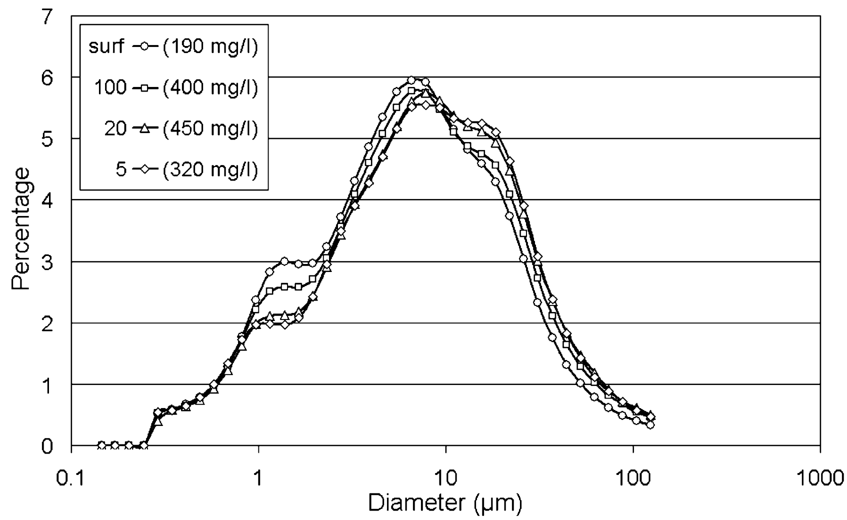

Fig. 7. Grain-size distribution in the samples collected at four depths in the initial phase of the flood recession (04.00). The numbers in the legend refer to the sampling depth above the bottom, whereas "surf" indicates the sampling depth at 20 cm below the water surface. The related suspended particle concentration is also reported.

Some minor floods, characterised by rather short return periods of the precipitation, also occurred. Because of their frequency, these events are of primary importance in the hydrologic balance of the system and the transport of suspended matter and pollutants. In fact, even if there is no agreement in the literature on the magnitude of the effective discharge in channel-forming processes, it is generally recognized that relatively frequent discharges dominate the overall transport in natural streams (Richards, 1982). This is also expected for the investigated tributary, even if its hydrology and morphology are partially affected by water management practices.

The investigated flood occurred in the night between 22 and 23 July 1999; it was generated by a typical summer storm, which started in the late afternoon and lasted for only 2 h.

As shown by the isohyet map of Fig. 4, which was drawn using daily data from 39 rain-gauge stations (Zaggia et al., 2001), the rainfall on the drainage basin was characterised by an uneven distribution, as typically occurs in the late-spring and summer period. The storm mainly affected the central and southern part of the Dese sub-basin, where a maximum rainfall depth of 44 mm was measured with respect to the 22 mm mean value for the entire drainage basin. According to the Gumbel EV1 method, the return period for this event was about 2 years.

To analyse the evolution of the flood, the effects of tide fluctuations were removed from the hydrograph obtained from instruments records. Following a procedure inspired to the method used by Simpson and Bland (2000), field data were then low-pass filtered with a 25-h forward and reverse moving average. This allowed obtaining a curve, shown in Fig. 5, which can be considered as the best approximation of the actual trend of freshwater discharge. The peak discharge of the filtered hydrograph was as high as 19 m^3/s, while the instantaneous value

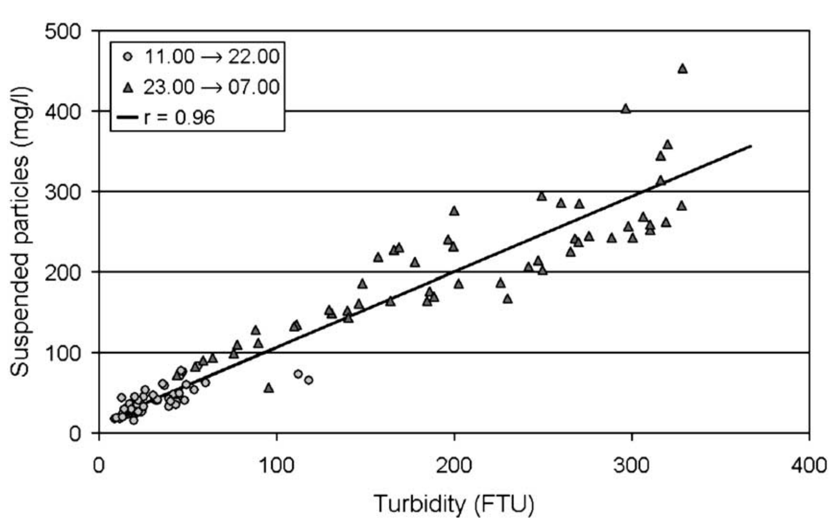

Fig. 8. Scatter plot with regression line of turbidity and SPM concentration values. Circles and triangles respectively refer to data collected before and after the rapid increase of the two parameters.

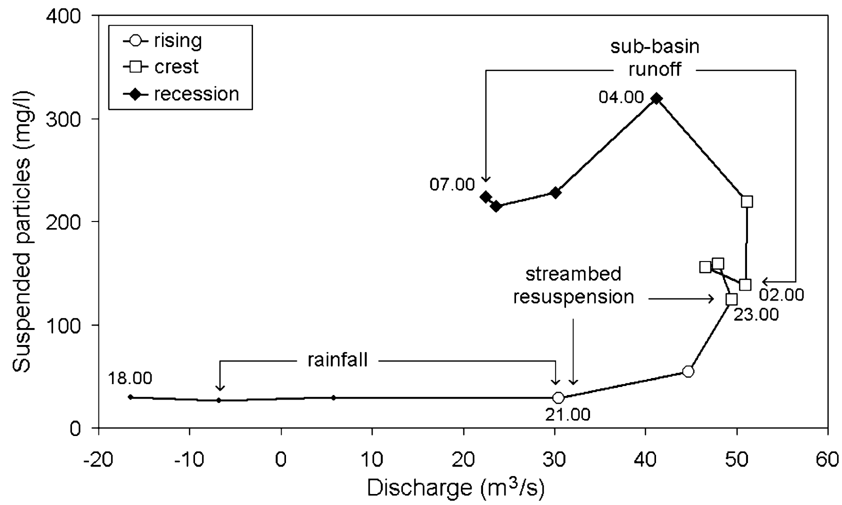

Fig. 9. Discharge versus SPM relationship in the time interval 18.00–07.00; the SPM concentration is calculated as the average of surface and bottom values. The phases of the flood (rising, crest and recession) and the sequence of sample collection are indicated.

exceeded 50 m^3/s. Fig. 5 also shows the hourly rainfall from a nearby station, located about 10 km southeast from the measurement section.

As a consequence of this intense meteorological input, the river basin responded with a sudden pulse of the instantaneous discharge. The resulting high-energy flood-wave was characterized by a particularly short lag-time, of about 2 h. This lag-time is markedly shorter than those estimated for the larger floods occurred during the project monitoring period (about 24 h), that were related to storms on a regional scale, characterized by longer rainfall duration (Zaggia et al., 2001).

Considering the hydrological and climatic characteristics of the period, the response of the sub-basin to this event was particularly strong. This was due to the high rainfall intensity combined with the effects of previous precipitations (from 7 to 15 July, see Fig. 3), the latter inducing the partial saturation of the soils and the reduction of water demand for agricultural purposes.

The trends of the current speed and physico-chemical variables at different depths are shown in Fig. 6. By referring to the tide, the rainfall started in the late flood phase, at approximately 19.00 (Fig. 6a). The augmented stream energy enhanced the effects of flow reversal, which occurred at approximately 20.00, determining a rapid increase of current speed in the whole water column (Fig. 6b). In the time interval 20.00–21.00 the discharge (Q) increased from 5.7 to 30.5 m^3/s. Consequently, the flood was characterised by a steep hydrograph, with a rising limb lasting for only 1.5 h; the current speed reached values as high as 55 cm/s at the surface.

The trend of the physico-chemical variables shows that during the end of the rising limb and the beginning of the crest (21.00–23.30), the gauge section was interested by water previously transported upstream. During this period, the flow started breaking the vertical gradients in the water column, progressively leading to uniform physico-chemical conditions, which took place after midnight. This phenomenon is partic-

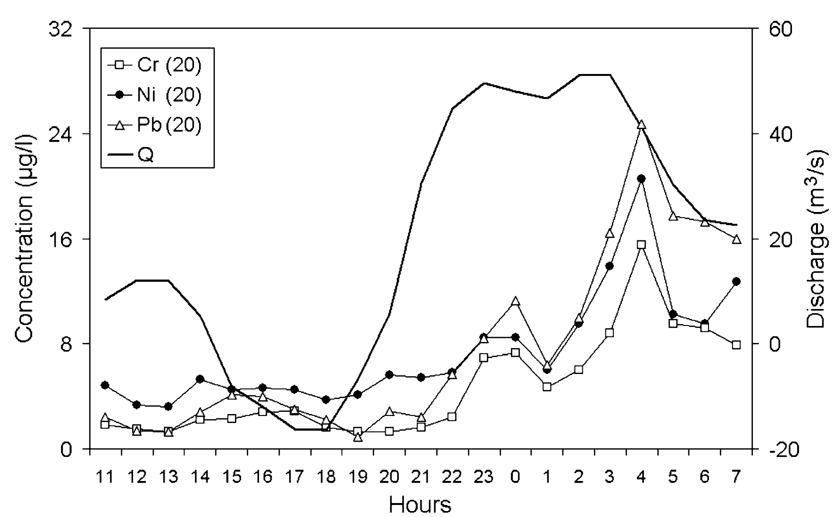

Fig. 10. Trend of discharge and total concentrations of Cr, Ni and Pb at 20 cm above the streambed.

Table 1
Correlation matrices ($p < 0.001$) obtained for SPM, Cr, Cu, Fe, Ni, Pb, Zn and nitrate concentrations measured at 20 cm below the surface (a) and 20 cm above the streambed (b)

	SPM	Cr	Cu	Fe	Ni	Pb	Zn
(a)							
Cr	0.84						
Cu	0.95	0.82					
Fe	0.98	0.84	0.98				
Ni	0.93	0.82	0.97	0.95			
Pb	0.95	0.79	0.88	0.92	0.85		
Zn	0.79	0.63	0.83	0.83	0.80	0.75	
$N-NO_3^-$	0.93	0.69	0.89	0.94	0.88	0.88	0.86
(b)							
Cr	0.98						
Cu	0.69	0.70					
Fe	0.98	0.98	0.75				
Ni	0.94	0.95	0.83	0.96			
Pb	0.97	0.98	0.76	0.99	0.94		
Zn	0.91	0.89	0.76	0.94	0.94	0.92	
$N-NO_3^-$	0.91	0.90	0.64	0.93	0.81	0.93	0.80

ularly evident for salinity (Fig. 6c), dissolved oxygen concentration (Fig. 6d) and pH (Fig. 6e), as well as redox potential (not shown).

For all the duration of the crest (00.00–03.00), discharge and physico-chemical variables maintained almost constant values ($Q \approx 50$ m^3/s; salinity = 0.2 psu; dissolved oxygen $\approx$ 6.5 mg/l; pH = 8.2; redox potential = 355 mV). The water temperature (Fig. 6f) decreased gradually in the whole profile, with an approximately constant rate of about 0.8 °C per hour.

As shown by the trend of turbidity (Fig. 6g) and SPM concentration (Fig. 6h), the transport of sediments increased starting from about 1 h after the sudden increase of velocity along the vertical profile. Relatively high values of both the variables are observable in the lower layers of the water column at the beginning of the crest–corresponding to the breaking of the physico-chemical gradients–by effect of resuspension of materials from the streambed. An input of matter derived from the immediate surface runoff may also be taken into account, especially in the upper water layer.

Considering the evolution of the described parameters, it can be seen that the investigated section experienced the full effect of the flood starting from the midnight. In the second part of the crest, turbidity and SPM concentration were subjected to a further increase: their maximum values (329 FTU and 454 mg/l, respectively) were recorded at 04.00, i.e. in the initial phase of the flood recession. The grain-size distributions of the corresponding samples, reported in Fig. 7, show a general uniformity, even if a slight shift toward coarser grain sizes with depth is observable. The transported materials are particularly fine: all the four distribution spectra are in fact centred on a diameter of about 7 μm, and about 80% of particles are smaller than 20 μm.

During the recession limb (05.00–07.00), even the SPM concentration showed uniform values in the water column. The high concentration of fine particles mobilised by the flood leads to the linear relationship between turbidity and suspended particles displayed in Fig. 8. The existence of a strong correlation between the two variables over a wide range of discharge is an important feature for estimating the transport of sediments and the associated pollutants. In fact, it could allow for the continuous monitoring of the suspended transport by using turbidity sensors (Grayson et al., 1996; Wass et al., 1997).

The SPM concentration–discharge relationship for the time interval 18.00–07.00 (Fig. 9) shows a pronounced counter-clockwise (CCW) hysteresis loop. Hysteresis is a complex phenomenon that depends on a variety of hydrological and chemical factors (Webb and Walling, 1992; Sokolov and Black, 1996; Evans and Davies, 1998; House and Warwick, 1998; Steegen et al., 2000) such as land-use, soil mineralogy and moisture conditions, the characteristics of the storm event and transported sediment as well as different flow paths (direct surface runoff, interflow, groundwater flow), the occurrence of sediment flushing, the presence of sediment and/or pollutant point sources within-channel, etc.

The variation of concentration with flow can therefore highlight significant hydrological and chemical controls, also indicating likely sediment and pollutant sources (Neal et al., 1997).

The initial sediment resuspension from the streambed, which is evidenced in Fig. 9 (21.00–23.00), is followed by a period of relatively constant values of both SPM and Q (23.00–02.00). In this interval, the river was mainly transporting particles mobilised in the upstream reach, as well as materials deriving from the runoff of soils close to the stream channel. The arrival in the measurement section of the runoff from the sub-basin territories is evidenced by the sharp increase in SPM concentration with constant Q that occurred at 02.00.

As expected, the increased concentration of fine particles in suspension enhanced the total concentration of heavy metals in the water column. In the example of Fig. 10 the trend of total Cr, Ni and Pb are shown. The first concentration raise corresponding to the period of resuspension was followed by a second greater increase, which led to a peak at 04.00; concentrations subsequently decreased during the recession limb.

A correlation analysis was performed on the chemical data and SPM concentration for the upper and lower layers of the water

Table 2
Comparison between concentration levels of the analysed species before (column A) and during (column B) the flood

	A (μg/l)	B (μg/l)	B/A
Fe	517	6723	13.0
SPM	28,000	207,000	7.4
Cu	2.6	18.8	7.3
Pb	2.3	12.7	5.4
Cr	1.4	7.0	5.0
Ni	2.1	9.5	4.6
Zn	20	49	2.5
$N-NO_3^-$	663	1502	2.3
Mn	103	179	1.7
$N-NH_3$	221	368	1.7
N_{TOT}	2132	2792	1.3
P_{TOT}	205	258	1.3
Cd	0.2	0.2	1.0
As	9.2	8.1	0.9
$N-NO_2^-$	63	54	0.9
N_{ORG}	1185	878	0.7
$P-PO_4^{3-}$	125	92	0.7
Hg	–	–	–

Column B/A reports the ratio between B and A.

column. Table 1a,b reports the correlation matrices obtained for SPM, Cr, Cu, Fe, Ni, Pb, Zn and nitrate at the two depths ($p<0.001$). Because of the high degree of correlation, these species show a quite similar CCW hysteresis loop, which follows the trend of the SPM loop shown in Fig. 9. Nitrite and ammonium also show a CCW hysteresis, while organic nitrogen and orthophosphate did not show a clear relationship with the discharge.

For all the analysed species, Table 2 compares the concentration levels measured before (column A) and during (column B) the flood peak. Data in column A were calculated as the average concentration in the upper layer (from the surface to 100 cm above the streambed) in the time interval 12.00–14.00. By referring to the trend of salinity in this interval (Fig. 6c), the considered depth was relatively unaffected by the mixing with saltwater and the measured concentrations can be expected to be representative of the true water quality of the river before the flood. Data in column B were instead obtained by averaging concentrations in the surface layer and in samples collected 20 cm above the streambed, during the crest and the recession phase (i.e. in the time interval 00.00–07.00).

The ratio of the two averaged concentrations (column B/A) shows that $N-NO_3^-$, Zn, Ni, Cr, Pb, Cu, and Fe increased considerably in flood conditions, by a factor ranging from 2.3 up to 13. Concentrations of P_{TOT}, N_{TOT}, $N-NH_3$, and Mn also increased in flood, but to a lesser extent (B/A varies from 1.3 to 1.7 times). Finally, Cd, As, NO_2-N, N_{ORG}, and PO_4-P concentrations were substantially unchanged or even lower during the flood. The comparison is not possible for Hg, due to the large number of samples with concentration lower than the detection limit (0.05 μg/l).

Therefore, besides causing an increase of total Fe and SPM loads, the flood determined a considerable increase in the transport of total Cu, Pb, Cr, and Ni, which are metals of toxicological interest and may have a negative impact on the nearby shallow-water lagoon ecosystem. The observed increase of nitrate, related to the mobilisation from diffuse agricultural sources, is also of environmental significance. Even floods of moderate intensity, whether they occur immediately after soil fertilisation, can in fact deliver to the lagoon a noticeable load of nitrate in a very short period.

On the other hand, the loading of species such as Cd, As and $P-PO_4^{3-}$, which were not subjected to a concentration increase, are only influenced by the increase of the discharge.

The dissolved concentration of the majority of the analysed metals is lower during the flood, particularly at the bottom layer. As shown in Fig. 11a,b, where the concentrations of some metals in the samples collected at 20 cm above the streambed are plotted

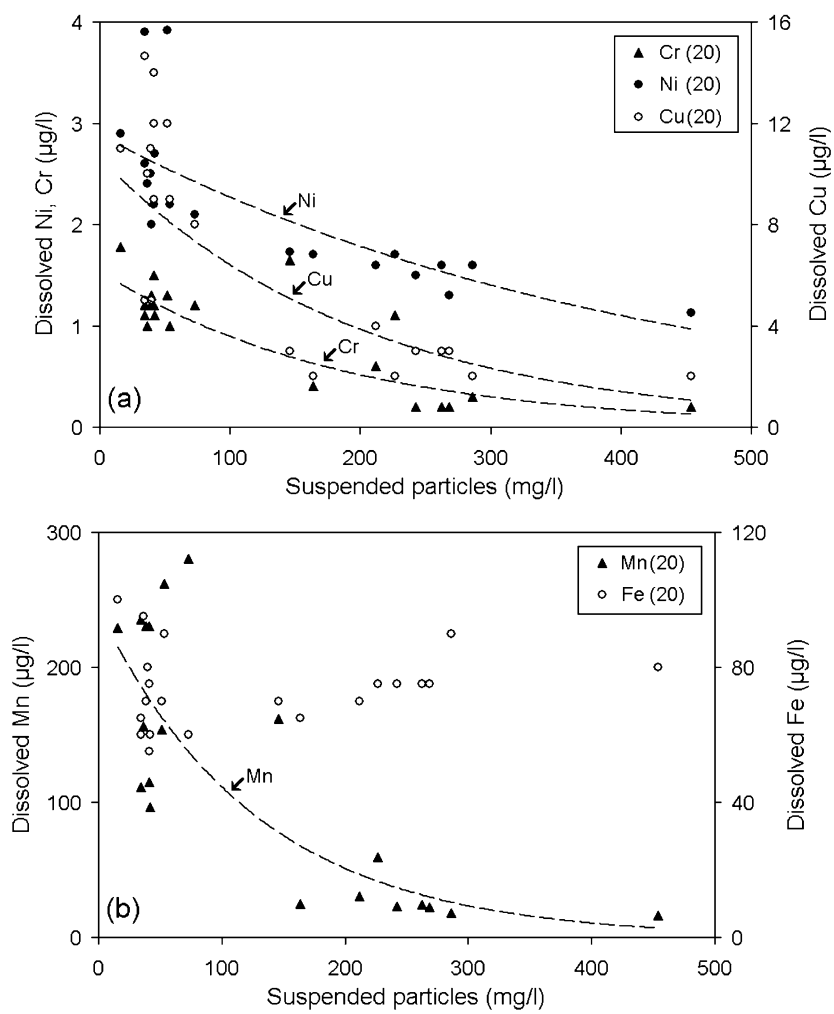

Fig. 11. Scatter plot of SPM and dissolved Cr, Ni, Cu (a) and Mn, Fe (b) concentrations, in the samples collected at 20 cm above the streambed.

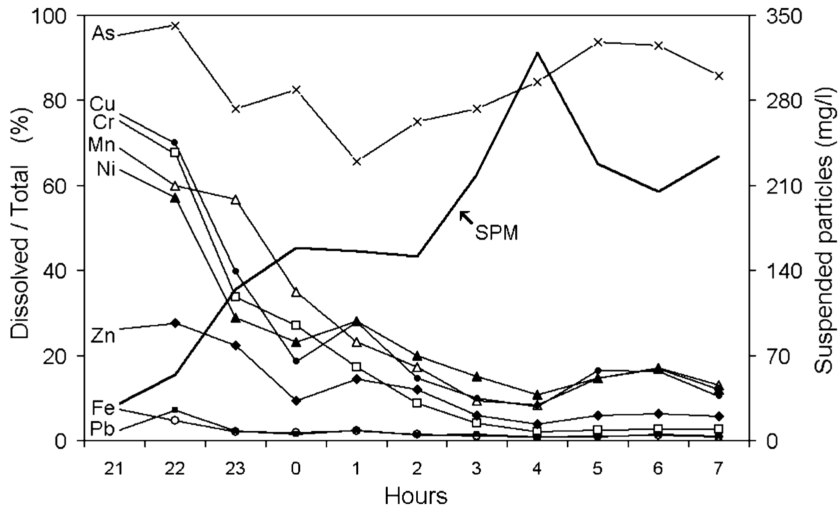

Fig. 12. Percentage ratio between dissolved and total metal concentrations during the flood. Data are obtained as the average of the values measured along the vertical profile. The trend of the average suspended particle concentration is also shown.

as a function of SPM, the increased amount of suspended particles induced by the flood affected the concentration of dissolved Cr, Ni, Cu, Mn. The resulting decrease, which is evidenced in the figure by means of an exponential fitting, may be mainly ascribed to the scavenging effect by the particulate (Burton, 1976). This process is not important for Fe (Fig. 11b), Pb and Zn, while As was predominantly found in the dissolved phase in all the analysed samples. The behaviour of the dissolved Cd is difficult to define, because its concentration was lower than the detection limit (0.01 μg/l) in a relevant number of samples.

Finally, to highlight the effect of the flood on the metal–particle association, the trend of the percentage ratio between dissolved and total metal concentrations is plotted in Fig. 12.

With the exception of As, all metals are mainly transported as associated to the suspended particles, in flood condition. The shift of the partition toward the particulate phase is more evident for Cr, Cu, Mn, and Ni, which exhibit the minimum values of the ratio in correspondence to maximum SPM concentrations.

5. Conclusions

The investigated flood, despite ranking among the minor storm events affecting the Dese River from May 1998 to August 2000, is interesting for its peculiar characteristics. Firstly, it was generated by a flashy-precipitation: an intense summer storm that strongly affected the central and lower part of the river sub-basin. Secondly, the flood coincided with the interval between the tide reversal and the beginning of the ebb phase. These two factors combined, determining an acceleration of the flow and a high-energy flood wave, characterized by a hydrograph with a steep rising limb and relatively short duration.

A two-step mechanism regulated the transport of matter during the flood. In the initial phases, streambed materials were mobilized by shear-stress, resulting in a moderate increase of suspended sediment transport, particularly in the lower layer of the water column.

Successively, the suspended load further increased by effect of materials delivered from the runoff on the sub-basin soils, which are essentially constituted by fine-grained sediments with a large percentage of particles smaller than 20 μm. This load reached the measurement section in the second part of the flood crest, giving rise to a counterclockwise hysteresis on the SPM–discharge relationship.

The total concentration of the majority of the heavy metals—in particular, Cu, Pb, Cr, Ni and, to a lesser extent, Zn—considerably increased during the flood, following the trend of SPM. Nitrate also increased in the corresponding period, in relation to the leaching of agricultural surfaces.

The simultaneous peak of both discharge and concentrations during the flood can therefore considerably enhance the instantaneous values of the load of these species with respect to the base flow conditions. At the same time, the flood induced a shift of the heavy metal partitioning toward the particulate phase. This process, combined to the characteristics of morphology and water circulation in the estuarine system of the Dese (Zonta et al., 1994), may enhance the transport of contaminants in the nearby shallow water areas of the lagoon, where they easily accumulate, favoured by the slack hydrodynamics.

The typical response of a watershed to storm events cannot be inferred on the basis of the analysis of a single flood. Nevertheless, the study allowed for the observation of the evolution of hydraulic and physico-chemistry of the stream water as well as the variability of particulate and contaminants transport, and drawing some hypothesis on the mechanisms of load generation. This kind of field observations can be crucial to establish proper basin-scale models of circulation of material through the hydrologic response. Finally, the results highlight the importance of detailed monitoring of these events in order to obtain representative estimates of the pollutants load to the Venice Lagoon.

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