



Sediment and phosphorus transport during flood events in a Mediterranean temporary river

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Received: 16 June 2023 / Accepted: 24 February 2024 / Published online: 25 March 2024
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Abstract

Flood events, whose number and intensity are predicted to increase in the Mediterranean region, are difficult to monitor. This causes the number of observations of suspended sediment and total phosphorus concentration (ISSI and ITPI, respectively) during their occurrence to be still scarce. Non-perennial or temporary water bodies, which react more promptly to rainfall events, represent ideal natural observatories. In this study, observations of streamflow, ISSI and ITPI, carried out during some flood events, in the Celone river basin, a temporary river located in south-eastern Italy, are presented. The research examined the correlations between flows, concentrations and loads of sediment and phosphorus and investigated factors that influence sediment and phosphorous dynamics in the river basin. The results show no relationship between the time of the year and the precipitation quantity of each event. The high coefficient of determination of the ISSI–ITPI correlations ($R^2 = 0.67$ on average) proves the importance of soil erosive processes in the delivery of phosphorus to the river. More than 73% of the total suspended sediment load and 83% of total phosphorus load in the period 2010–2011 were transported during the 11 monitored events. In addition to the discharge, ISSI and ITPI also depend on numerous other factors related to land management, such as soil cover and fertilizations. The study, thanks to the improved understanding of the mechanisms governing sediment and phosphorus losses, represents a useful contribution for river basin authorities who have to draw up management plans aimed at preventing eutrophication phenomena and soil fertility reduction.

Keywords Flood event · Suspended sediment · Total phosphorus · Soil erosion · Temporary river · Runoff

Introduction

Globally, temporary, or non-perennial water bodies are the dominant river type and are not confined only to arid and semiarid areas (Levick et al. 2008; Schneider et al. 2017; Gallart et al. 2012) such as the Mediterranean region (Bonda and Resh 2013; Skoulikidis et al. 2017). In arid and semiarid regions, scarce precipitations together with high levels of transpiration are considered among the main causes

of river intermittency (Datry et al. 2017a and Robinson et al. 2016). However, formerly perennial streams and rivers have also transformed into temporary water bodies due to increasing water abstraction for agriculture, industry and tourism (Datry et al. 2014; Skoulikidis et al. 2011), groundwater overexploitation (Skoulikidis et al. 2017; Stefanidis et al. 2016; McDonough et al. 2011; Loukas et al. 2007; Dodds et al. 2004) and dam construction (Skoulikidis et al. 2017; Tockner et al. 2009).

Intermittency is therefore currently expanding and is expected to continue to grow in response to global warming and increased water consumption (Datry et al. 2017b, 2014; Acuna et al. 2014; Larned et al. 2010; McDonough et al. 2011; Querner et al. 2016; Tramblay et al. 2021; De Girolamo et al. 2022), with further shifts from perennial to intermittent flows expected by 2050 in many parts of the world (Döll and Schmied 2012), including Europe (Skoulikidis et al. 2017).

Specifically global warming will contribute to an increase of intermittency, because of the very likely intensification of

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the hydrogeological cycle (WHO 2017) with, among the others, a decrease in the number of rainy days and an increase in rainfall intensity and flooding (Lake et al. 2000; Palmer et al. 2008; Feng and Wu 2016; Papadimitriou et al. 2016; IPCC 2018; Garnier and Holman 2019).

Among other possible consequences of global warming also capable of contributing to an expansion of intermittency, it is worth mentioning a general increase in average temperature and a possible, but not as much certain and generalized, decrease in annual and in particular in summer precipitation affecting Southern Europe. Considering rainfall in the Mediterranean area in fact, some authors, report a decrease, some a stable and some others even an increase of annual precipitation amount. (Philandras et al. 2011; Stathi et al. 2023; Mersin et al. 2022). These phenomena, apart from favoring the expansion of intermittency, will also be responsible for the increase in overland flow and erosion, and consequently for the further increase in the quantities of suspended sediment and total phosphorus (SS and TP, respectively) that reach water bodies during event driven flows (Lucas et al. 2023).

It is known that large amounts of the annual sediment load originate from few storm events occurring every year (Rodriguez-Blanco et al. 2010a; Soler et al. 2008). In addition, it was reported that few annual intense storm events are also responsible for the majority of the phosphorous (P) that reaches water bodies (Sharpley and Rekolainen 1997; Haygarth et al. 1998; Jordan et al. 2007). For example, Sharpley et al. (2000) report that few major storm events can generate up to 90% of annual P losses.

Considering Europe (where for the reference year 2010, Panagos et al. 2015, estimate an average rate of soil loss of $2.22 \text{ t ha}^{-1} \text{ year}^{-1}$), Mediterranean areas are especially subject to soil erosion due to the simultaneous presence of several characteristics: high rainfall intensity, deforestation (García-Ruiz 2010 that quotes Poesen and Hooke 1997; Wainwright and Thornes 2014) and soils characterized by particularly high erodibility factors (Wischmeier and Smith 1978). Moreover, in the area, crops are often grown on steep slopes, few herbaceous species survive after the dry summer season and the intense autumn rains, typically as extreme first flush events (Obermann et al. 2007), fall on bare soils causing intense runoff and significant erosion, also due to the considerable sediment availability after the dry summer period (Cerdà 1998; Torrent et al. 2007; Estrany et al. 2009; Khan et al. 2022; Ezzati et al. 2023). At country level, the highest mean annual soil loss rate (8.46 t ha^{-1}) has been surveyed in Italy (Panagos et al. 2015).

In addition, because the subsurface horizons of many Mediterranean soils are relatively rich in effective P sorbents (Delgado et al. 2006; Torrent et al. 2007), considerable amounts of P are retained in the top 1–5 cm of the soil profile (Zaimes and Schultz 2002). Consequently, P is

primarily lost as particulate P associated with eroded soil (Shields et al. 2009; David and Gentry 2000; Vaithiyathan and Correll 1992). However, in temporary water bodies, further processes can complicate the already complex P dynamics. For example, it is known that drying reduces P adsorption and stimulated P mineralization measured in lake sediments, increasing the percentages of labile and soluble P compounds (Dieter et al. 2015; Kinsman-Costello et al. 2016). A similar mechanism has been hypothesized also for the dry riverbed of temporary streams (Zoppini et al. 2014; Zoppini and Marxen 2011). Therefore, upon rewetting, a considerable release of soluble P could take place (Keitel et al. 2016).

Until relatively recently, non-perennial streams were considered to possess scarce economic or ecologic value (Skoulidakis et al. 2017; Datry et al. 2014). Their study has long been overlooked (Munné et al. 2021) with few monitoring stations generally installed along their course (Tramblay et al. 2021). The consequent incomplete knowledge of their hydrological processes and function (De Girolamo et al. 2022) has contributed to the lack of adequate protection policies, legislation and management practices that, in turn produced a growing deterioration of an already impaired resource. In some countries for example, legislation considers “rivers” to be only water courses characterized by a perennial flow (Datry et al. 2017b). This is the case of the European Water Framework Directive (Directive 2000/60/EC) that mostly ignores temporary streams (Logan and Furse 2002), excluding them from the program of measures to be implemented to achieve good status for all water bodies (Garnier and Holman 2019).

Nowadays it is recognized that non-perennial streams are functional parts of the river networks and groundwater systems they belong to (Datry et al. 2017b; Dodds and Oakes 2006). They are recognized as biogeochemical hot spots, able to retain, transform and transport nutrients and sediments along river networks (McDonough et al. 2011). They are moreover considered responsive monitors of the effects of global changes (Bull 1997), as they react more promptly than perennial rivers to the occurrence of extreme events such as droughts, heavy rains and floods, whose number and intensity is predicted to increase during this century (Lake et al. 2000; Palmer et al. 2008; Feng and Wu 2016; Papadimitriou et al. 2016; IPCC 2018; Garnier and Holman 2019). Nevertheless, despite the acknowledgement of the importance of non-perennial water bodies, there remain significant gaps in the understanding of contaminant transport along their course.

The aim of this paper is to investigate the complex suspended sediment and P transport mechanisms in intermittent rivers, using selected monitored severe flood events on the Celone, a temporary river located in Puglia (SE-Italy), as a case study. In addition to the Celone river, this study is also

relevant to other temporary rivers across the Mediterranean region and to those currently perennial rivers, which will most likely become temporary in the next few years. Moreover, the insights have an albeit small value, for the integrated water and soil management also of perennial water bodies, as recommended by the most recent legislation on the protection of the environment from pollution (e.g., CEC 2006; EC 2012; Directive 2000/60/EC).

Finally, it should be noted that although it is long, compared to works dealing with similar topics, the monitoring period considered covers only one year of observations (apart from the four events of the 2014–2015 monitoring campaign). It goes without saying that a longer period would have allowed even more weight to be given to the hypotheses made to explain the observed phenomena.

Materials and methods

Catchment description

The study area is the 72 km² portion of the Celone River basin, located upstream of "Masseria Pirro", which is in

turn located 8 km upstream of the Capaccio reservoir, in Apulia, a region in Southern Italy (Fig. 1). The basin elevation ranges from 150 to 1150 m above sea level (a.s.l.). The Celone river starts on Monte San Vito (1015 m) within the Apennines mountain chain. Its main course flows for approximately 28 km before reaching the Capaccio reservoir, while the entire drainage network of this portion is 81 km long and has a dendritic pattern. The river manifests a temporary character. This, according to the Italian Legislative Decree 131/2008, means that it is subject to dry periods along some or all of its course, annually or at least in two years out of five (DM Ambiente n. 131 2008).

The mountainous area of the basin is characterized by steep slopes and accentuated erosion (Fig. 2a). The river channel is incised and is responsible for the transport of large amounts of sediments, derived from the surrounding soils, the resuspension of river bed material and bank erosion. Several check dams have been built along this stretch of the river. Once in the relatively flat alluvial plain, the river deposits much of the transported coarse material and its main channel assumes the shape of twisted channels. Successively it continues its course with a meandering pattern (Fig. 2b).

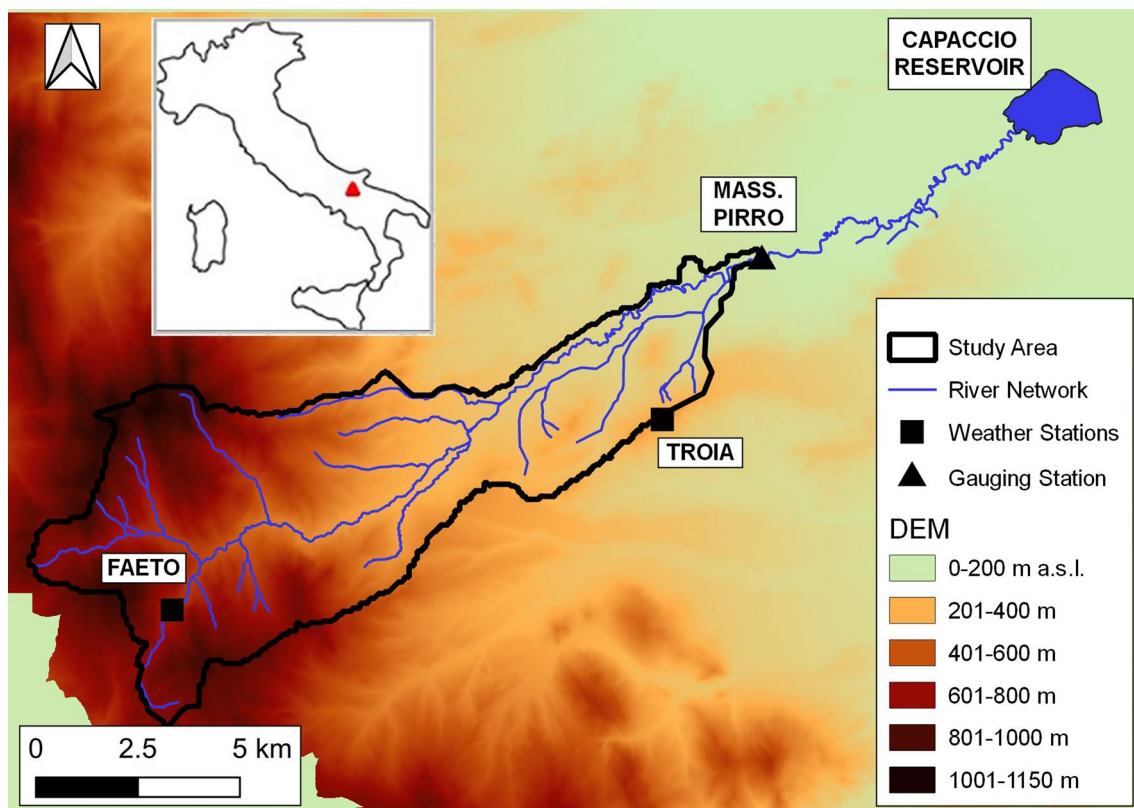


Fig. 1 Location of the study area, with the Digital Elevation Model (DEM) in the background. M. Pirro (Masseria Pirro) in the main figure, is the gauging station location. The smaller figure on the top left

shows the location of the study area (red triangle) within the Italian territory. DEM from: "SIT-Puglia" the Geographic Information System Web Site of Puglia Region

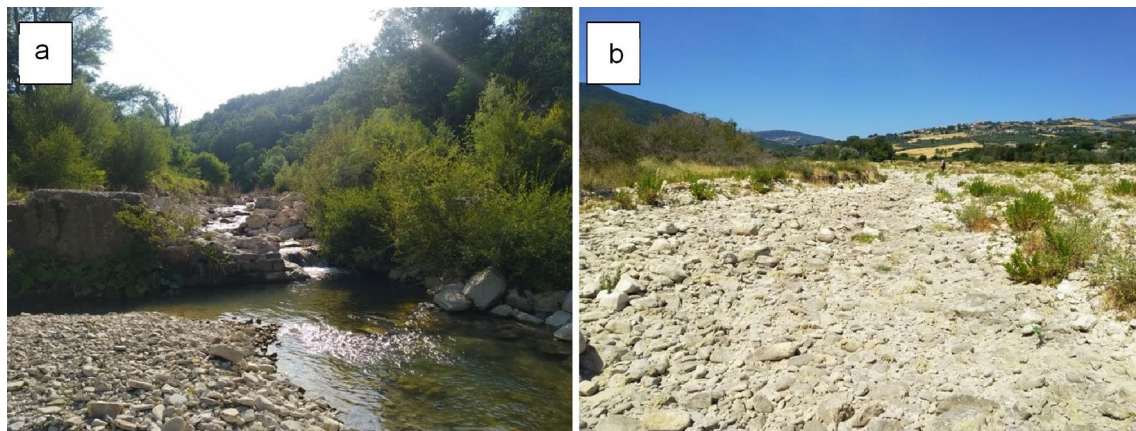


Fig. 2 Celone River basin. **a** The river course in the mountainous area. **b** The dry riverbed in the plain area, during summer

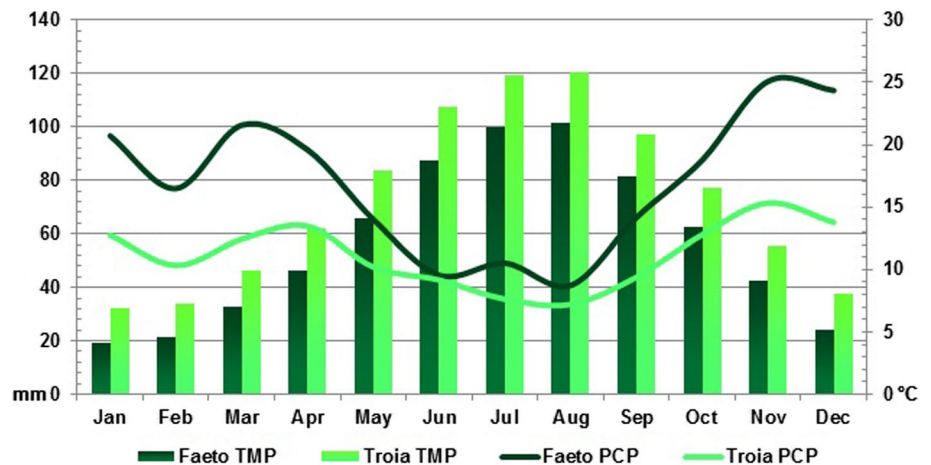
The lithology of the area includes flyshoid formations and grey-blue clays in the upper part and alluvial deposits in the lower portion. Soil composition reflects that of the underlying bedrock, with clayey, clayey-loamy and sandy-clayey-loamy textures. Soil physical and hydrological characteristics are very variable; soil thickness in particular is lower (< 1 m) in the upper part of the basin and greater in the valley area.

The climate is typically Mediterranean with mean monthly temperatures ranging between 4.1 and 6.9 °C in January and between 21.7 and 25.6 °C in August in the mountainous and valley areas, respectively. Average annual precipitation (1991–2020) ranges between 950.0 mm in the mountain area (Faeto gauging station, 860 m a.s.l.) and 627.8 mm in the plains (Troia gauging station, 350 m a.s.l.), respectively. Precipitation, often localized, is mainly concentrated in autumn and spring, but short and particularly intense events are frequent during summer (Fig. 3). This rainfall regime greatly conditions the flow regime, causing intermittency and flash

floods that are responsible for marked erosion and nutrient transport, with both diffuse (sheet) and concentrated (rill and gully) erosion observed.

Agriculture represents the main land use, with durum wheat (45%), sunflower (9%), olive groves (8%) and pasture (6%) being the main crops. Deciduous forests are also present in the upper part of the basin and cover nearly 29% of the study area (Fig. 4). Apart from deciduous forests and pastures, that are not fertilized, all the other main crops in the area, regularly receive P fertilizations. The approximate phosphorus amount, employed annually in kg per hectare is 40–50 for durum wheat, 40–80 for sunflower, 80–160 for olive groves (data provided by the farmers local Consortium). Livestock manure and poultry litter from farms in the catchment are also used as fertilizers in the area, but since they are livestock manure and poultry litter from farms in the catchment, which farmers dispose (almost without control) over the land of their farms or those nearby, it is almost impossible to indicate even the approximate quantities.

Fig. 3 Mean monthly temperatures and mean monthly precipitations from Faeto and Troia (period 1991–2020). Data taken from the Annals of the Civil Protection Service of the Puglia Region



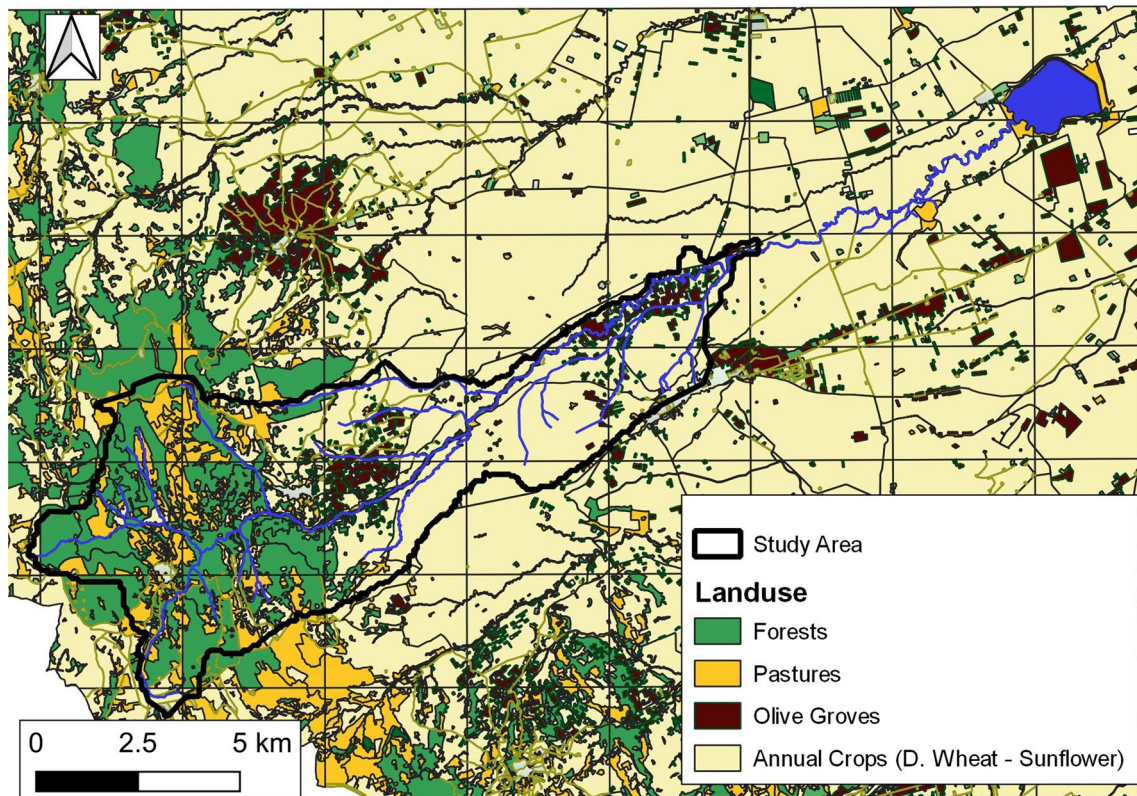


Fig. 4 Land use map of the study area with the main crops. Data from: "SIT—Puglia" the Geographic Information System Web Site of Puglia Region

Data collection

Water level, velocity, suspended sediments (SS) and total phosphorus (TP) were measured in the river Celone during two monitoring campaigns in 2010–11, while the MIRAGE project was underway (see the acknowledgments at the end of the paper) and 2014–15, when years after the end of the project and after a long interruption, data collection resumed, but after several instrumentation breakdowns, two extraordinary rainfall episodes, definitively swept away the instrumentation used for water sampling. The above-mentioned parameters were measured to investigate the relationships between the SS, TP and the corresponding hydrologic context. During the monitoring period July 2010–May 2011, 21 flood events occurred, of which 11 events regarded as most significant, based on the sampler (see next paragraph) collecting a minimum of five samples, are presented.

With reference to the March 2014 to March 2015 monitoring campaign, only 4 flood episodes were recorded due to instrumentation breakdowns. These 4 events represent only a subset of the floods that occurred during this period, so it is not possible to determine the significance of their contribution to the annual SS TP loads in the river. However, they have been considered all the same, as recommended in De

Girolamo et al. 2018, to better capture the extreme variability that characterizes floods in different periods of the year, together with the corresponding sediment and phosphorus transport.

Water sampling

The monitoring station located at “Masseria Pirro”, 8 km upstream of the Capaccio reservoir, was set-up with an automatic sampler (ISCO6712FS) equipped with an internal data logger and connected to a flow module (ISCO 750 Area Velocity Flow Module) that collected velocity and stream water stage measurements every fifteen minutes (Fig. 5a). Stage was converted to cross-sectional area of the stream based on the regular and permanent shape of the river section. Total event runoff (mm) was derived from total discharge considering the basin area of 72 km².

The sampler, which contained 24 1-L bottles (Fig. 5b), was programmed to collect water samples for subsequent suspended sediment and total phosphorus analysis. Sampling was activated by water level increases greater than 0.02 m in one hour during the rising limb of the hydrograph and by velocity decreases greater than 0.3 m s⁻¹ in one hour during the falling limb. Using this sampling strategy, the



Fig. 5 **a** The gauging station at Masseria Pirro. **b** The inside of the automatic sampler

time interval between the collection of two consecutive samples varied between 15 min and 2 h along the rising limb and between 2 h and 1 day during the falling limb of the hydrograph. Consequently, the number of samples differed between one flood event and another. Further details concerning sampling are provided in De Girolamo et al. 2015.

Laboratory analyses

Suspended sediment concentration (ISSI) in the samples was measured using the gravimetric method reported in the APAT-IRSA Standard Analytical Methods (APAT IRSA-CNR 2003) that provides for the vacuum filtration of predetermined volumes of water samples through 0.45 μm pore diameter nitrocellulose filters and the oven drying of the sediment residue for 24 h at 105 $^{\circ}\text{C}$. ISSI (mg l^{-1}) of each sample was calculated from the weight of the dried sediment and the volume of the filtered sample.

Total phosphorus concentration (ITPI) was measured using the photometric method with an AQUALYTIC-AL400 photometer, according to standard methods (APHA-AWWA-WEF 2017). The method consists in the transformation of all the phosphorus compounds contained in the water sample into orthophosphate, by acid mineralization with potassium persulphate. The orthophosphate ions are then reacted in an acid environment with ammonium molybdate. In this way a compound is formed, which is reduced with ascorbic acid to molybdenum blue, an intensely colored phosphorus compound, whose absorbance is measured at 660 nm. The determination of ITPI in each water sample was replicated twice to consider possible instrument errors (0.01%).

Data analysis

In this paper, a flood event (from this point onward also referred to as an “event”) was considered to begin when,

after the start of a precipitation episode, the automatic sampler collected the first water sample and to end when it collected the last (see lower plots of each couple of plots in Fig. 6), whether or not the occurrence of the river overflow. In this way it has been possible to easily derive runoff, loads and average concentrations of SS and TP for each event. As can be seen from the upper of each pair of plots in Fig. 6, this definition of event duration provides an adequate agreement with the duration of the peak/peaks in the corresponding hydrographs.

The coefficients of determination R^2 between TP and SS and between SS and TP with discharge were calculated for each of the events (Table 1). Wanting to examine as a whole (not just event by event) the relation between TP and SS, as well as between TP and SS on the one hand and Q on the other hand and given that the number of samples collected was not the same for all the 15 events, a weighted average of R^2 was calculated for each of the three correlations. In this way, in the calculation of the three average values of R^2 , the importance of each of the starting R^2 values, specified by its weight, has been considered. These R^2 -weighted average values are shown in the last row of Table 1.

To calculate the SS and TP loads transported during the events, flow measurements recorded every 15 min and measured, or estimated, concentration values of SS and TP were used. To estimate ISSI and ITPI in cases when the interval between two consecutive measurements was longer than 15 min, linear interpolation was used.

Total load was then calculated using the equation:

$$L_{\text{evn}} = 0.9 \sum_{t=1}^m Q_t C_t,$$

where L_{evn} is the total load of SS or of TP in kg transported by the water body during the n th event; m is the number of 15-min intervals in the n th event; 0.9 is a numerical element that includes 900 (seconds in each of the 15-min intervals

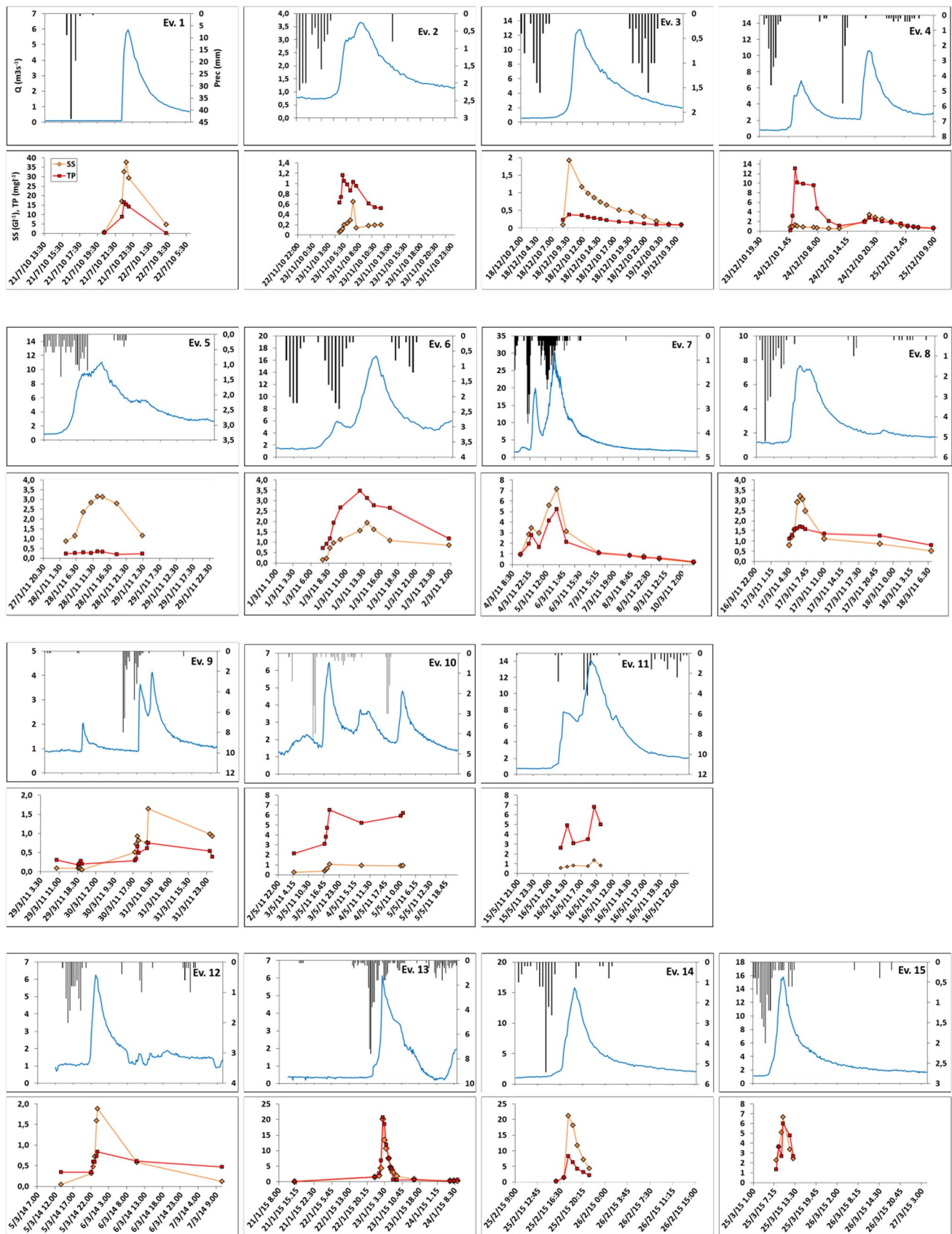


Fig. 6 Rainfall from Faeto and streamflow trend (top graphs), suspended sediment and total phosphorus concentration (bottom graphs), referred to each of the flood events considered

Table 1 Regression equations between total phosphorus (TP) versus suspended sediment (SS) and between SS and TP versus discharge (Q)

	Number of samples	Regression eq. TP–SS	R^2	Regression eq. SS–Q	R^2	Regression eq. TP–Q	R^2
Event 1	6	TP=0.48 SS – 0.49	0.96	SS=4.88 Q + 6.19	0.78	TP=2.24 Q + 2.70	0.69
Event 2	11	TP=0.43 SS + 0.73	0.09	SS=0.11 Q – 0.06	0.28	TP=0.04 Q + 0.73	0.02
Event 3	13	TP=0.17 SS + 0.11	0.78	SS=0.08 Q + 0.22	0.25	TP=0.02 Q + 0.12	0.41
Event 4	19	TP=0.42 SS + 4.19	0.01	SS=0.31 Q + 0.09	0.76	TP=0.38 Q + 1.97	0.06
Event 5	8	TP=0.03 SS + 0.21	0.29	SS=0.28 Q + 0.06	0.78	TP=0.01 Q + 0.18	0.52
Event 6	10	TP=0.61 SS + 0.44	0.93	SS=0.30 Q + 0.53	0.70	TP=0.17 Q + 0.86	0.55
Event 7	12	TP=0.70 SS + 0.15	0.98	SS=0.26 Q + 0.38	0.89	TP=0.19 Q + 0.37	0.93
Event 8	10	TP=0.25 SS + 0.97	0.78	SS=0.40 Q – 0.28	0.78	TP=0.12 Q + 0.81	0.86
Event 9	13	TP=0.35 SS + 0.21	0.83	SS=0.27 Q – 0.03	0.46	TP=0.11 Q + 0.18	0.47
Event 10	8	TP=4.97 SS + 1.26	0.94	SS=0.12 Q + 0.20	0.34	TP=0.69 Q + 1.87	0.43
Event 11	6	TP=4.76 SS + 0.35	0.70	SS=0.06 Q + 0.31	0.58	TP=0.32 Q + 1.33	0.57
Event 12	7	TP=0.25 SS + 0.38	0.82	SS=0.23 Q – 0.10	0.57	TP=0.06 Q + 0.35	0.50
Event 13	16	TP=1.13 SS + 0.21	0.95	SS=2.71 Q – 3.45	0.73	TP=2.96 Q – 3.78	0.64
Event 14	7	TP=0.34 SS + 0.53	0.98	SS=1.41 Q – 3.72	0.60	TP=0.47 Q – 0.61	0.56
Event 15	6	TP=0.70 SS + 0.80	0.50	SS=0.44 Q – 1.05	0.90	TP=0.28 Q + 0.39	0.37
Total	152	R^2 -weighted average	0.67		0.62		0.48

considered) and that also considers the different units of measures of the factors present in the equation; Q_t is the average discharge in l s^{-1} within the 15-min time interval t ; C_t is the concentration, in mg l^{-1} of SS or of TP at the t th 15-min interval of the n th event, derived from linear interpolation between SS and TP samples.

The average hourly load of SS and of TP of each event was calculated from the total load transported by the river and the event duration. Finally, the discharge-weighted concentration, which represents the average concentration of SS (g l^{-1}) or of TP (mg l^{-1}) of the whole event, was calculated from the total load and the total event discharge (m^3).

Results

Discharge variability during the events

Figure 6 shows 15 pairs of graphs, each referring to one of the flood events examined. Peak discharges differed considerably between one event and another, ranging from $3.7 \text{ m}^3 \text{ s}^{-1}$ in event 2, to $30.2 \text{ m}^3 \text{ s}^{-1}$ recorded during event 7. In each pair, the upper graph reports the flood hydrograph, together with the hyetograph from the Faeto measurement station. This station recorded higher rainfall than the Troia station in 12 out of 15 events.

The hydrographs show single, double and, in two cases, triple discharge peaks. Double and triple peaks occur in the rainiest periods (winter and spring), during which it is however possible to also observe several single peaks. In the double and triple peaks each single peak still shows the

typical shape characterized by a very rapid rising limb and a much slower recession limb, as described, for example, in De Girolamo et al. 2015.

With reference to double and triple peaks it can be observed that for all events, apart from event 10, the flow in the first peak is lower than the second. The anomalous behavior of event 10 (May 3rd–4th) is explained by the high antecedent soil moisture condition prior to this event. Exceptional rainfall in the week preceding May 3rd at both Faeto and Troia (98 and 58 mm, respectively) (Regione Puglia 2014) saturated the ground, reducing rain infiltration capacity causing therefore, the high discharge value measured at the first peak of event.

Figure 6 also shows considerable variability in event duration that ranges from 5 h (event 15) to almost 6 days (event 7). With the exception of event 10, which occurred in May 2011, all of the sampled events lasting more than 24 h were recorded between December and March.

This time, the peculiar behavior of event 10 can be explained by considering that only 1 full year of events was considered. Examining, in fact, the daily rainfall of the period 1990–2011, it is possible to observe rainfall lasting more than 24 h, also outside the period December–March. Nonetheless, it must be underlined that the period considered was deemed significant of the historical hydrologic conditions in the area (De Girolamo et al. 2015, 2018).

SS and TP variability during the events

The temporal patterns of measured SS and TP concentrations approximately follow that of discharge, with concentrations

rapidly increasing during the rising limb of the hydrographs and then decreasing more slowly during the descending limb (Fig. 6).

During the events, $ISSI$ ranges from 37.6 g l^{-1} (with a corresponding value of $\max |TPI|$ of 16.4 mg l^{-1}) of event 1, to 0.65 g l^{-1} (with a corresponding value of $\max |TPI|$ of 1.16 mg l^{-1}) during event 2. The maximum $|TPI|$ concentration measured of 20.7 mg l^{-1} was measured during event 13.

Considering single peaks, instead of entire events, the graphs in Fig. 6 show that in 15 cases out of 19, $ISSI$ and $|TPI|$ peaks precede (by less than 1–3 h) the discharge peak, while in the remaining 4 cases follow it.

Correlations of $|TPI|$, $ISSI$ with one another and with Q during the events

In the previous paragraphs a certain relationship between $|TPI|$ and $ISSI$, as well as between $|TPI|$ and $ISSI$ on the one hand and discharge on the other hand, has been observed. To examine these relations more quantitatively, the corresponding regression equations were calculated for each of the events under consideration, together with the related coefficients of determination R^2 (Table 1). This shows that the highest correlation coefficients are generally between TP and SS (highest for 10 events, and ranging from 0.01 to 0.98) and between SS and Q (highest for 4 events, ranging from 0.25 to 0.90) and lowest between TP and Q (0.02–0.93).

Table 1 at the bottom of each of the three R^2 columns, also shows the weighted averages of the R^2 referred to that column. These weighted averages of the R^2 , although not presenting a strict statistical significance, still allow to make some interesting qualitative observations. For example, comparing these three R^2 values, it can be noted that the R^2 referred to the correlation $|TPI|$ – $ISSI$ is slightly greater than that between $ISSI$ and Q , which is in turn greater than that between $|TPI|$ and Q (R^2 -weighted averages = 0.67, 0.62 and 0.48, respectively). As explained in De Girolamo et al. 2015, $R^2 = 0.67$ means that 67% of $|TPI|$ variance is explained by $ISSI$ values (therefore indicating that most of the P reaches the river bound to soil particles), while 33% depends on other factors such as time elapsed between fertilization and the immediately following rainfall event, soil management and vegetation cover.

Similarly to the explanation provided for the correlation $|TPI|$ – $ISSI$, the value 0.48 of the weighted average for the $|TPI|$ – Q correlation can be explained considering that, while Q depends essentially on precipitation (intensity and duration), $|TPI|$ variance depends on Q for only 48%, while for the remaining 52% depends on other factors, such as the time elapsed from a fertilization or tillage and the first subsequent runoff generating precipitation or the quantity of fertilizer applied on the soil.

SS and TP losses during the events

Table 2 reports numerous parameters that allow further considerations to be made to explain the differences, in many cases considerable, between one event and another, in terms of SS and TP losses. The explanation of these differences is made particularly complicated by the fact that in addition to hydrological factors (rainfall quantity, intensity and duration, streamflow), several other elements (e.g., vegetation cover, tillage, soil erodibility, slope) are also involved.

In the table, with reference to each event, in addition to values regarding rainfall, flow rates and maximum concentrations of SS and TP measured, also total loads (L), average hourly loads (AHL), and discharge-weighted concentrations (DWC) are reported.

Apart from the diversity already highlighted in the previous paragraphs with reference to Q , $ISSI$ and $|TPI|$ peaks, also the other features reported in Table 2 vary considerably from one event to another; to better highlight these variations, the cells containing the highest and lowest values of each variable (line) have been marked in bold and italic, respectively.

Considerable differences are observed, with reference to AHL (which varies from 2.4 to 390.4 t for sediments and from 2.5 to 190.0 kg for total phosphorus) and to DWC (which varies from 0.2 to 23.1 g l^{-1} for SS and from 0.2 to 10.3 mg l^{-1} for TP). Then considering L , it can be observed that it goes from 57.3 to 7843.9 kg for TP and from 15.9 to 21,419.5 t for SS , with a variation of even three orders of magnitude.

Looking at the individual events in Table 2, it is evident that the events with the highest number of maximum values (bold cells) are event 1, governed by the very high rainfall intensity at Faeto, and event 7, governed by a particularly long duration (5 and 6 bold cells, respectively). The event with the greatest number of minimum values (7 italic cells) is event 2, that was associated with low values of both duration and rainfall intensity. Precisely because of their characteristics, these three events will be described individually afterwards, in the discussion.

Discussion

Event importance in terms of SS and TP loss

With reference to the river Celone basin, according to De Girolamo et al. (2018), annual sediment load varies considerably not only depending on hydro-climatic variables, but also on the estimation method; values from 2.6 to 5.2 $\text{t ha}^{-1} \text{ year}^{-1}$ have been calculated, an interval similar to that found by other authors (e.g., Estrany et al. 2011; Lique et al 2009) with reference to other Mediterranean basins.

Table 2 Hydrological, sedimentological and total phosphorus data for each of the events considered

Event	2010			2011			2014			2015		
	1	2	3	4	5	6	7	8	9	10	11	12
Date	Jul. 21–22	Nov. 23	Dec. 18–19	Dec. 24–25	Jan. 28–29	Mar. 01–02	Mar. 04–10	Mar. 17–18	Mar. 29–Apr 01	May 03–05	May 16	Mar. 05–07
Duration	7 h	6 h 45'	19 h	30 h 45'	23 h	18 h	5d 20 h 30'	1d 2 h 30'	2d 15 h 15'	1d 20 h 30'	6 h 15'	1d 21 h
Rainfall mm												
Faeto	73.4	12.4	14.4	28.0	17.2	22.6	52.8	22.4	3.0	25.8	12.8	16.0
Troia	0.1	1.8	6.0	3.4	16.4	12.2	53.0	4.8	4.3	15.8	10.8	11.8
Rainfall intensity mm h ⁻¹												
Faeto	10.49	1.84	0.76	0.91	0.75	1.26	0.38	0.85	0.05	0.58	2.05	0.36
Troia	0.01	0.27	0.32	0.11	0.71	0.68	0.38	0.18	0.07	0.36	1.73	0.26
Average flow m ³ s ⁻¹	2.1	2.9	5.2	4.0	7.3	7.3	6.0	3.1	1.4	2.8	9.2	1.8
Maximum flow m ³ s ⁻¹	6.0	3.7	12.8	10.6	11.1	16.7	30.2	7.5	4.1	6.5	14.2	6.2
Maximum SS conc g l ⁻¹	37.6	0.65	1.92	1.28	3.15	1.94	7.13	3.21	1.64	1.06	1.36	1.88
Maximum TP conc mg l ⁻¹	16.4	1.16	0.38	13.08	0.34	3.48	5.24	1.71	0.75	6.5	6.8	0.84
Runoff mm	0.8	1.0	5.0	6.2	8.5	6.7	42.4	4.2	4.5	6.2	3.0	4.1
Load												
SS tons	1260.5	15.9	284.4	880.8	1491.8	603.8	21,419.5	442.5	272.8	359.5	194.4	225.2
TP kg	564.8	57.3	87.3	1567.3	152.4	1194.7	7843.9	409.8	157.0	2246.8	961.3	178.5
Average hourly load												
SS tons	180.1	2.4	15.0	28.6	64.9	33.5	152.5	16.7	4.3	8.1	31.1	5.0
TP kg	80.7	8.5	4.6	51.0	6.6	66.4	55.8	15.5	2.5	50.5	153.8	4.0
Discharge-weighted concentrations												
SS g l ⁻¹	23.1	0.2	0.8	2.0	2.4	1.3	7.0	1.5	0.8	0.8	0.9	0.8
TP mg l ⁻¹	10.3	0.8	0.2	3.5	0.3	2.5	2.6	1.4	0.5	5.0	4.5	0.6

The cells containing the highest and lowest values of each line have been marked in bold and italic, respectively

Considering the 2010–2011 monitoring campaign, during the 11 flood events examined (approximately 4.4% of the whole period), a sediment load of 27,226 t has been measured. This value corresponds to 73.1% of the higher limit of the above-mentioned estimated range and even to 146.2% of the lower limit.

During the same 11 flood events, also 15,242.6 kg of TP passed through the section of the river where the gauging station is located. This amount corresponds to 82.9% of the TP load calculated with reference to the whole period 2010–2011.

It has moreover to be considered that the above-mentioned percentages of SS and TP load, in itself already rather high, refer only to 11 out of the 21 events occurred in the same period. These 11 events are those regarded most significant and are for this reason, the only ones discussed with reference to the first of the two monitoring campaigns considered by the present paper.

Discharge, SS and TP variability during the events

The evidence that in case of multiple peak events, the first peak is usually lower than the second, can be explained considering that most likely, the soil was drier before the rainfall responsible for the first peak. This caused greater infiltration and consequently lower runoff coefficient, in the first peak compared to the second and in case, to the third peak.

Examining sub-hourly rain values, it was observed that, among the events with multiple peaks hydrographs, only event 7 is not compatible with this hypothesis because it rained a lot both in Faeto and in Troia on March 1st, and albeit much less, also on March 2nd and 3rd. In this event, by far the longest one, more than 15 h passed between the first and the second flow rate peak. It is likely that during so a long-time interval, during which on the basin adverse weather conditions persisted, it rained in areas other than Faeto and Troia, where gauging stations do not exist and where for this reason, it has not been possible to consider rainfall data. These “unverifiable” rains could have contributed to the second Q peak, higher than the first.

In “Results” it was reported that considering single peaks, the graphs in Fig. 6 show that in 15 cases out of 19, ISSI and |TP| peaks precede the discharge peak or coincide with it, while in the remaining 4 cases follow it. ISSI and |TP| peaks preceding the corresponding Q peak are a sign of source-limited events and reveal an exhaustion of SS and TP which can take place for example, when one of the sources of the eroded material is the channel itself (riverbed and/or bank erosion) as reported by Soler et al. (2008). This behavior is favored in hydrologic conditions like that of the study area where, considerable amounts of sediment and phosphorus can settle on the riverbed during the long-lasting periods of normal and low flow. Another case of early exhaustion

of SS and TP occurs when easily erodible soil and erodible sediment-bound P are scarce and therefore run out, before Q reaches its maximum (Zabaleta et al. 2007). The occurrence of source-limited events is corroborated by De Girolamo et al. (2015) that, in a study performed with reference to the same area, when plotting ISSI versus Q, find clockwise hysteresis loops either with reference to the first peak of multiple peak events, or with reference to events generated by very intense rainfall.

Such a high number of source-limited events might seem strange, given the high amount of eroded sediment mentioned earlier with reference to the Mediterranean area and Italy. However, this behavior can be explained by considering first of all that the above remark concerns the Mediterranean basin as a whole and does not consider the extreme variability of the soils in the area and consequently of their erodibility. Secondly, it should also be kept in mind that in addition to the erodibility factor, soil erosion also depends on other factors, such as rainfall erosivity, slope, crop management and support practices (Panagos et al. 2012). Furthermore, another factor that plays an important role in reducing erosion, is the protection effect of surface stone cover. According to Panagos et al. (2014), stoniness, which is high in the Mediterranean basin and in particular in the study area, can protect soil by reducing its erodibility by up to 40%, with an effect of soil loss limitation that can be even greater than that of vegetation.

Always considering the high number of source-limited events, it is important to note first of all, that as reported in the introduction, given that large amount of the annual sediment and P loads originate from few storm events, the 27,226 t SS found, while being only the amount of sediment transported during the 11 most significant events considered, it is very likely to represent a good percent of the amount of the soil eroded in the basin during a whole year, which is therefore not very high.

Secondly, even if not particularly high, this quantity of eroded soil can, however, damage the water quality of a stream, due to the high concentration of P bound to eroded soil particles (Arias et al. 2016) and has, for this reason, to be taken in due account. In this regard, the OECD considers $0.03\text{--}0.10\text{ mg l}^{-1}$ to be the critical range of |TP| for eutrophication to develop (OECD 1982), and this range was exceeded not only during the 15 flood events examined (line: “discharge-weighted concentration TP mg l^{-1} ” in Table 2), but also by the average value (0.27 mg l^{-1}) of a series of manual samplings, carried out under normal flow conditions, between 2009 and 2010 (De Girolamo et al. 2014).

The cases in which ISSI and |TP| peaks follow discharge peaks (anticlockwise hysteresis loops) can instead be explained by bank collapse during the descending limb of the hydrographs (De Girolamo et al. 2015) or by abundant precipitations (responsible for the peak flow)

occurred earlier on less erodible areas and later, by less abundant precipitations occurring on areas richer in sediment and phosphorus, due for example, to recent tillage and/or fertilizations.

In addition to the variability of the moment in which they occur with respect to the corresponding peak flow (clockwise and anticlockwise hysteresis loops just considered), not always higher values of maximum discharge correspond to higher |SS| and |TPI| peaks values. Event 7 for example, presents a maximum flow rate of $30.2 \text{ m}^3 \text{ s}^{-1}$, with corresponding |SS| and |TPI| peaks of 7.1 g l^{-1} e 5.2 mg l^{-1} , respectively. Instead during event 13, maximum |SS| and |TPI| values of 20.2 g l^{-1} and 20.7 mg l^{-1} were measured in correspondence of a streamflow peak of only $6.1 \text{ m}^3 \text{ s}^{-1}$.

An explanation for this evidence could be that while event 7 occurred in March, when soil is protected from erosion by the emergence of wheat plants, event 13 took place in January when, on large parts of the basin, the soil is still completely bare. The fact that event 7 is characterized by SS and TP loads that are much higher than those of all the other events, on the other hand, depends on its extremely long duration (almost 6 days).

Plotting |SS| against Q, also mixed shaped loops have been observed. Such a variable trend of the sediment-flow curves confirms the multiplicity and complexity of the factors that govern the erosion phenomena in the study area.

De Girolamo et al. (2015) observed that in the study area, during the occurrence of multiple peak events, there is no exhaustion of |SS| availability and explained this behavior hypothesizing that multiple sediment source areas in the basin can contribute sediment to the water body during floods.

Even with reference to |TPI|, no exhaustion has been monitored during multiple peak episodes. This represents further evidence that phosphorus mainly moves bound to the eroded soil and that for this reason, different sediment sources (e.g., soil erosion, riverbed erosion, riverbank collapse) potentially represent as many phosphorus sources.

The only exception to this SS and TP behavior, during multiple peak events, is represented by the two discharge peaks of event 4, during the second of which, a considerable exhaustion of |TPI| is observed, without a corresponding |SS| exhaustion. A likely explanation could be, in this case, the spreading on the ground of manure coming from one of the numerous animal farms present in the basin, just before the rain responsible for the first peak of flow. In correspondence with the second discharge peak (higher than the first), a slightly higher |SS| value and a decidedly lower |TPI| value are observed, compared to those of the first peak; this probably due to the removal of much of the manure present on the ground, already with the rain responsible for the first peak of flow.

Correlations of |TP|, |SS| with one another and with Q during the events

Considering the R^2 -weighted averages in the last line of Table 1, the fact that $0.67 > 0.62 > 0.48$ indicates that while TP and SS are more directly related to each other, PP represents in fact, in most of cases the dominant form of P lost (Shields et al. 2009; David and Gentry 2000; Vaithyanathan and Correll 1992), SS and Q are only indirectly related. SS in fact depends not only on erosion, which in turn depends on precipitation which influences Q, but also on other factors such as transport. For this reason, TP depends on Q even less directly (mainly because most of the P reaches the river bound to soil particles). This less direct link between |TPI| and Q seems to be confirmed also by the lower value of the sum of R^2 -weighted average referred to the |TPI|–Q correlations, shown in the last column of Table 1.

Apart from the R^2 values, also the slope coefficients of the correlation straight lines in Table 1 provide information on flood events. Within each of the three correlations |TPI|–|SS|, |SS|–Q and |TPI|–Q, a considerable slope variability of the corresponding straight lines is observed. For example, for the |TPI|–|SS| correlation, the angular coefficient values range from just over 0 to 4.97.

Rodriguez-Blanco et al. (2010b) to explain this variability hypothesize a difference between the sediment sources. TP–SS lines with a higher slope would be those referring to events that mobilize more sediment from areas with a higher P content.

Significant slope differences can also be observed considering the |SS|–Q correlations. In this case, the differences could be attributed (all other conditions being equal) to a diversity in the erodibility of soils (due to for example, to differences in the spatial location of rainfall). |SS|–Q straight lines with a higher angular coefficient would be those relating to events that affected areas of the basin characterized by greater soil erodibility (e.g., event 13 compared to event 3). On the other hand, in case of events such as 2 and 11, which occurred in November and May, respectively, the greater quantity of sediment transported into the river with the same Q by event 2, is most likely because in November fields are almost bare and therefore, they offer less protection against erosion.

Considerable slope differences can also be observed considering the |TPI|–Q correlations (maximum and minimum slopes 2.96 and 0.01 referred to event 13 and 5, respectively). In this case, a possible explanation could be that event 13 mobilized more P from an area better connected to the stream than event 5 did, so that the probability of P redeposition after the detachment from the source, would be much lower for event 13 than for event 5. This hypothesis would also seem to be supported by the fact that even

considering the correlation $ISSI-Q$, the angular coefficient of event 13 is greater than that of event 5.

SS and TP losses during the events

Considering only the hydrological factors on which they depend and the equations with which L , AHL and DWC have been calculated, it appears evident that, L is directly proportional to flow rate, but also to erosivity and therefore to rainfall intensity. AHL is directly proportional to L and inversely proportional to the duration of the event, while DWC is directly proportional to L and inversely proportional to the volume of water that passes, during each event, in the section of the river where the flow gauging station is established.

This is especially true for events 1, 2, and 7, described below in some detail, in which particularly high or low values of runoff and of rainfall quantity and duration from Faeto and Troia, are mainly responsible for the values of L , AHL and DWC reported in Table 2.

Event 1 took place in July and lasted only seven hours, during which the highest precipitation value (73.4 mm from Faeto) compared to that of all the other events was recorded. Because of so a great rain quantity fallen in so a short time interval, also rainfall intensity from Faeto outweighs by far that of all the other events. This, in turn entails rather high values of SS and TP load although, due to the short duration of the event, the measured runoff is the lowest compared to that of all the other events. An effect of so a low runoff and high loads is that the DWC s of SS and TP are the highest of all the events considered.

Event 1 represents a typical flash flood. These sudden episodes are frequent in the Mediterranean area from late summer to early autumn and although typically not entailing particularly high runoff, they are often responsible for the contribution of considerable sediment quantities in water bodies. This happens not only because of the particularly high intensity that allows to mobilize sediment deposited in the riverbed during the previous dry season, but also because of the scarce summer vegetation which favors erosion (De Girolamo et al. 2012, 2015).

Event 7 occurred in March, one of the wettest months and lasted almost 6 days, during which not only the rain from Troia, but also the total precipitation (average of Troia and Faeto) is higher than that of all other events. Consequently, this episode is characterized by the maximum runoff values of the entire study period. Nevertheless, mainly because of its long duration, average rainfall intensity is not particularly high (0.38 mm h^{-1} , from both Faeto and Troia).

All together these features are responsible for the quite high values presented by DWC and AHL , especially as regards SS and this is because evidently, the effect of the

exceptionally high load of SS exceeds the dilution effect due to the high runoff.

Again, considering event 7, the AHL and DWC values referred to phosphorus are not as high as those referred to SS . This is most likely due to the occurrence of concentrated erosion caused by the intense rain fallen both in Faeto and Troia. The formation of rills and gullies, which may represent in some cases the major sediment source to the water of a river (Rodriguez-Blanco et al. 2010a) is actually, a frequent phenomenon in the study area. As reported in the introduction in fact, because considerable P amounts are retained in the first 1–5 cm of the soil profile, sediment that reaches the river coming from rills and gullies, whose depth goes well beyond 5 cm (Queensland Government 2013), is characterized by much lower amounts of sediment-bound P .

Event 2 is characterized by particularly low values of numerous variables. The loads of SS and TP (15.9 t and 57.3 kg) are for example lower than those transported in the river during all other events. The measured values of both AHL and DWC referred to SS are also lower than those of all other events. The reason for this characteristic of the event lies in the combined effect of the short duration (less than 7 h) and the low quantity of rain (average of the precipitations from Faeto and Troia higher only than those of event 9).

However, as has already been mentioned, in addition to hydrological factors, numerous other elements affect the supply of sediment and phosphorus to water bodies. These elements take on a leading role in the events other than 1, 2 and 7, just due to the lower weight exerted by factors such as runoff and amount and duration of precipitation from Faeto and Troia.

Among these, for example, rains fallen in areas of the basin more or less rich in P . It is known in fact, that most of the P present in the agricultural land derives from fertilization and that the Italian rural landscape is extremely fragmented. This is also true in the study area where, moving only a few kilometers, it is possible to observe the presence of different crops that require a different P fertilizer supply. The consequence is a notable fragmentation also of the P content of the soil, with the possibility that rains with similar duration and intensity characteristics, fallen within hours of each other, on different areas of the basin, are responsible for the contribution of very different amounts of TP to the river. This is what can be observed by comparing for example, for events 3 and 4, the values of AHL and DWC referred to TP and which is confirmed observing, in Table 1 the slope coefficient of the straight-line $TP-SS$ referred to event 4, greater than that referred to event 3 (0.42 and 0.17, respectively).

A significant contribution of P to the river waters due to rains, even if not very intense, also occurs in case of P fertilizations performed shortly before rainfall occurrence and/or with phosphorus quantities beyond the saturation of

the P sorption capacity of the soil, with consequent lack of time, for both crop P uptake and/or for P adsorption on soil particles. An explanation of this type justifies the differences observed by comparing, for example, L, AHL and DWC referred to TP in event 6, with respect to the same parameters referred to event 3.

Another factor that explains, other conditions being similar, the differences between one event and another, in terms of SS and TP transported in the water body, is vegetation cover density. In this regard, for example, Sauer and Ries (2008) report that a plant cover exceeding 60% can considerably reduce erosion in semiarid environments.

This is very likely, the reason of the differences observed for example, comparing events 11 and 14. Event 14 occurred in February, when vegetation cover is not well developed yet and despite having similar duration, intensity and runoff to those of event 11, it has L, AHL and DWC referring to SS much greater than those of the event. 11, which occurred in May.

The same parameters referring to TP, on the other hand, have very similar values between the two events. This means that for the same amount of sediment that reaches the water body, during event 14 a much lower TP load is transported in the water body than that which reaches the river during event 11. This can be attributed to the occurrence of concentrated erosion because of the intense rain fallen both in Faeto and in Troia in the days immediately preceding event 14.

Finally, it should be underlined that the explanations provided in this paragraph regarding the values of L, AHL and DWC consider the rain that has fallen only in Faeto and Troia, the unique two locations within the basin where there is a rainfall measurement station. Nevertheless, it is very likely that in the days corresponding to the events discussed, it also rained in other non-instrumented areas. These unverifiable rains, despite having contributed to runoff formation and to SS and TP losses, could not be considered among the data reported in Table 2 and in the related discussion.

Conclusions

The present paper investigated the complex sediment and P transport dynamics in an agro forested catchment belonging to the upper Celone basin, a temporary river located in the Mediterranean area, during a series of flood events, with the aim to examine the role of single controlling factors and of their interaction.

Unlike other publications dealing with similar topics, this work examines a fairly large basin and a rather long monitoring period. For this reason, the reported results consider a mosaic of various soils, land uses and management practices. While this, on the one hand, has complicated the determination of simple cause–effect relationship between

rainfall, overland flow and the amount of SS and P reaching the water body, on the other hand it has anyway made it possible to catch the resultant of all the variables involved in the contribution of sediment and phosphorus to the river during floods.

The subject is of particular importance with reference to the study area not only because the removal of considerable soil quantities from the surface horizons is responsible for the rapid loss of soil fertility, but also because the river Celone represents the main inflow of the Capaccio reservoir where, apart from reducing water storage capacity, the sediment transported, conveying considerable phosphorus quantities, can trigger eutrophication phenomena, dangerous for water quality and for the survival of aquatic organisms.

The results indicate that sediment transport is highly dependent on flood events. In fact, during the 11 events considered in the period 2010–2011, which represent just 4% of the period, a quantity of sediment is transported, which corresponds to 73.1% of the higher limit and even to 146.2% of the lower limit of an estimated range of SS loads, obtained using several estimation methods and referred to the whole period 2010–2011. TP load measured with reference to the same 11 flood episodes on the other hand, amounts to 82.9% of that estimated for the whole period 2010–2011.

The study indicate that SS and TP concentrations are not exclusively dependent on discharge, but also depend on several other factors such as tillage, fertilization practices and date of precipitation after the utilization of fertilizers, that all together condition soil erosion and sediment mobilization.

There is instead, a greater correlation between TP and SS. This represents a further confirmation that also in the study area, as in many other parts of the world, most of the P (86.7% according to De Girolamo et al. 2012) reaches the water body in particulate form.

This evidence is particularly useful for river basin management, suggesting that strategies aimed at reducing erosion, also represent valuable tools to reduce phosphorus amount in the water body.

The study also highlights a considerable variability among the events.

This evidence stresses that to carefully catch the complex dynamics that govern sediment and P transfer from land to water, during rainfall events, long term monitoring, accompanied by frequent sampling, able to estimate the rapid variations of sediment and P concentrations, is a prerequisite condition.

Linked to this, it is also necessary to underline the extreme importance of installing, even in not extremely large basins, such as the one considered, a series of measurement stations, in particular of the rains, as numerous as possible. This is to avoid neglecting, in the discussion of the runoff values and of the observed SS and TP losses, the contribution of rains that most likely fell in areas of the basin,

presently not equipped with rainfall gauging stations, in the days corresponding to those of the events considered.

The findings obtained, apart that for the area considered, have also a more general importance due to the extremely likely air warming and intensification of the hydrological cycle, expected for the years to come in all the Mediterranean climate regions, with consequent on the one hand, growing number of water bodies that will take a temporary character and on the other hand, with the worsening of eutrophication phenomena.

In this context, the results of this work, providing further information on the mechanisms governing the transport of sediment and phosphorus in temporary water bodies represent in particular, a useful contribution for decision-makers who have to set up management practices aimed at reducing sediment and P losses, so to prevent eutrophication of receiving waters, a problem that seriously limits surface water use and that can lead to severe environmental and socioeconomic problems, in particular in the Mediterranean areas, where freshwater is already scarce.

Finally, the approach adopted in the present work, taking into consideration many of the elements involved in the mobilization of SS and TP from both cultivated and wooded land, represents an example of integrated climate, water and soil management, as recommended by recent legislation on environment and water protection and also by the current Common Agricultural Policy.

Acknowledgements The work presented in this paper was funded by the European Community's Seventh Framework Programme, FP7/2007–2011, through the MIRAGE Project (Contract n. 211732). The authors gratefully acknowledge the contributions of Claudia Campana, who provided some of the precipitation and flow data and of Anna Maria de Girolamo, who provided valuable suggestions for data processing and figures realization.

Author contributions Original draft and following draft versions preparation and editing: MG; Data collection and lab analysis: GP, Monica Garnier; review of the manuscript drafts and English language correction: IH. All authors read and approved the final paper.

Funding Open access funding provided by Consiglio Nazionale Delle Ricerche (CNR) within the CRUI-CARE Agreement.

Data availability The data analyzed during the current study are available upon request from the corresponding author, for purposes of reproducing the results, subject to confidentiality and ethical considerations.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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2024-03-25

Springer

<https://doi.org/10.1007/s12665-024-11524-2>

Garnier M, Pappagallo G, Holman IP. (2024) Sediment and phosphorus transport during flood events in a Mediterranean temporary river. Environmental Earth Sciences, Volume 83, Issue 7, March 2024, Article Number 212