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# GROUNDWATER AND FLOOD EVENTS IN DIFFERENT HYDROGEOLOGICAL PERIODS: A CASE STUDY IN THE ASPIO RIVER (MARCHE REGION)

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## EXTENDED ABSTRACT

Ad oggi, la modellazione idrologica rappresenta un aspetto essenziale nella caratterizzazione e determinazione del comportamento di un corso d'acqua. A partire dagli anni '60, la comprensione e l'analisi dei fenomeni naturali è stata accompagnata da un crescente interesse verso i software di modellazione e di calcolo, che ha portato ad un crescente sviluppo e divulgazione di procedimenti di calcolo automatizzati mirati inizialmente a semplificare le procedure di valutazione dei singoli componenti. Nella maggior parte dei casi essi determinano in maniera reale il comportamento dei fenomeni a partire da singoli dati puntuali raccolti in maniera discontinua, talvolta essi sottostimano o si discostano dal comportamento reale, soprattutto per quanto riguarda singoli eventi estremi che interessano bacini fluviali di ridotte dimensioni. Il lavoro ha come obiettivo principale quello di valutare i fattori che contribuiscono alla formazione della portata fluviale in un piccolo bacino avente un'estensione di 29 km², situato in Italia centrale in prossimità del Monte Conero; in che modo tali fattori incidono sull'aumento del rischio idraulico e come sono relazionati alla durata e all'intensità degli eventi meteorici. L'attenzione è focalizzata sul contributo delle acque sotterranee ed in particolare su come la modellazione idrologica risponde agli input del livello piezometrico in eventi di piena improvvisa che si verificano in periodi idrologici differenti, suggerendone delle strategie per migliorarne la capacità previsionale. Il bacino di studio è caratterizzato da un elevato tasso di popolazione, attività commerciali e importanti vie di comunicazione. Dal punto di vista geologico esso coinvolge i termini argillosi, argilloso-marnosi e sabbioso-ghiaiosi Plio-pleistocenici del dominio Umbro-marchigiano. Il reticolo fluviale è caratterizzato da due rami secondari che confluiscono in un ramo principale, al termine del quale è posizionata una stazione idrometrica con un sensore di registrazione in continuo per il quale è stata messa a punto la scala di deflusso. Il bacino è altresì attrezzato con un sensore di misurazione in continuo del livello piezometrico e con alcune stazioni pluviometriche. Delle campagne di analisi infiltrometriche con doppio anello sono state effettuate in diversi periodi idrologici per determinare i valori di conducibilità idraulica dei depositi superficiali, intesi come coltri di alterazione delle diverse litologie sottostanti. A partire dall'intersezione tra categorie di uso del suolo e le classi di permeabilità dei depositi superficiali è stato applicato il metodo del *Soil Conservation Service* basato sulla determinazione del *Curve Number*. Tale parametro definisce la capacità che tale intersezione favorisca o meno il ruscellamento superficiale a discapito dell'infiltrazione sub-superficiale e profonda. Operando in ambiente GIS sono stati ricavati i principali caratteri morfometrici utili a determinare i tempi di corrivazione per i sottobacini in esame. Attraverso il software di modellazione idrologica HEC-HMS sono stati analizzati tre eventi meteorologici intesi che hanno coinvolto il bacino di studio nei mesi di maggio 2015, febbraio e marzo 2018; essi sono caratterizzati da diversi input di precipitazione (durata ed intensità) e da un diverso andamento del livello piezometrico. L'inserimento dei dati di pioggia registrati da tre stazioni pluviometriche per ciascun evento, dei tempi di corrivazione e del valore di *Curve Number* medio per ciascun sottobacino, ha permesso di determinare, mediante modello, la portata transitata alla sezione di chiusura considerata. Tale portata è stata confrontata con quella misurata in continuo mediante il sensore in alveo. Gli eventi manifestano un trend molto diversificato e non sempre di immediata interpretazione. Il comportamento della portata determinata tramite il modello si adatta bene all' andamento delle portate misurate, soprattutto in prossimità del picco; alcune discrepanze si osservano nelle fasi post picco dove le portate determinate tramite il modello sottostimano quelle misurate durante gli eventi. Tale comportamento è attribuibile principalmente all'influenza delle acque sotterranee che tendono a mantenere alta la portata che transita nel corso d'acqua. L'influenza delle acque sotterranee, e nello specifico del livello piezometrico, si ripercuote anche nella risposta che il corso d'acqua ha ai diversi *input* di precipitazione. Si osserva inoltre che i due rami secondari del corso d'acqua rispondono in maniera differente alla formazione della portata in funzione delle diverse litologie sui quali si impostano. Con il presente studio si sottolinea l'importanza di accoppiare i software di modellazione idrologica alla misurazione in continuo del livello piezometrico, non solo finalizzata al dimensionamento delle opere in funzione del valore della portata al colmo, ma anche alla valutazione dell'esposizione delle stesse a condizioni critiche prolungate nel tempo. Tale metodologia andrebbe implementata in bacini idrografici caratterizzati da differenti coperture litologiche, in modo da verificare in modo più esteso l'influenza delle acque sotterranee sul rischio idrogeologico a scala di bacino.

## ABSTRACT

When applying hydrological models at basin scale, it is essential to take into account the contribution of groundwater and its behaviour, together with the hydrological state before and after storm events. The main objectives of the present study were the evaluation and discussion of factors contributing to the formation of river discharge, how and to what extent these factors affect the risk of flood and, finally, how they are related to the type, duration and intensity of rainfall events, especially associated with flash floods.

This was achieved by applying HEC-HMS models to a small watershed in central Italy, characterised by high hydrogeological risk. The watershed is equipped for total rainfall, river discharge and groundwater level measurement. In addition, double ring infiltrometric tests were performed during different hydrological periods. The results highlighted a direct correlation between flood risk and the hydrological period; the insertion of groundwater data in the model allowed for a sensitivity analysis of the relationship between the level of risk and the hydrogeological settings and properties of the area. Moreover, the analysis of some "extreme" events occurring in the summer period highlighted river behaviour in very different hydrological states.

***Keywords**: equipped basin, flood, groundwater, hydrological models, natural hazard*

## INTRODUCTION

In the last decades, European political pressure has increasingly focused on environmental problems, especially those produced by floods, with a specific emphasis on forecasting and managing flood risk scenarios (Pappenberger *et alii*, 2005).

Although in the past extreme flood events mainly involved big watersheds characterised by large dimensions and very long water courses, nowadays flood risk is higher and more common especially in small basins with a short runoff time (Pappenberger *et alii*, 2005). These rainfall events are characterised by flash floods linked to the change in meteorological events and this is particularly true in basins where human activities have had a strong impact (Tazioli *et alii*, 2015). In addition, natural hazard assessment is needed for correct management of the basin, regardless of its dimensions, taking into consideration all the parameters and the phenomena occurring in the environment. The importance and the benefits of studying both the risk of flood in small basins and the factors that contribute to creating the hazard, are based on the fact that the parameters and the variables affecting the formation of flood can be evaluated more easily and show almost the same processes and properties that occur in larger basins. This paper focuses on factors affecting flood events in different hydrogeological periods, paying particular attention to the correlation between flood behaviour and groundwater level trends, in order to identify some critical aspects of hydraulic modelling software and suggest some strategies to improve its forecasting efficiency.

The novelty of this paper is its focus on the importance of taking into account, in hydraulic modelling, the continuous variation in piezometric level during a single storm event.

For this purpose, a watershed located in central Italy and characterised by limited dimensions, very high population density, factories and commercial activities, together with a high level of natural hazard (Tazioli *et alii*, 2015; 2010) was selected for applying the hydrological model. The factors and properties involved in the modelling processes were also investigated.

These features are comparable with other watersheds of limited dimensions, present in the Mediterranean area (Tazioli *et alii*, 2010).

The most dangerous meteorological hazard in the Mediterranean area, after droughts, is represented by floods, which are often related to human activities and their impact on the environment are nowadays considered as a component of the local climate. This is particularly true in European countries like eastern Spain, southern France, Italy and Greece (Llasat *et alii*, 2010).

The study methodology involved the use of a specific software for hydrological modelling. Watershed modelling, before 1960, was limited by the inadequate capability of computers and by the availability of a restricted set of data. After 1960 hydrological modelling started to become easier and more comprehensive, thanks to the exponential growth of computer science. A short time later this modelling software was integrated into watershed planning and management (Singh & Frevert, 2003).

Despite a great improvement in the models over the years, they still have some limitations, especially because they are based on a parametric implementation of known natural aspects, which require necessary approximations of processes (Beven, 2001). According to Beven these limitations are associated to problems of nonlinearity, scale, uniqueness, equifinality and the uncertainty of the models (Beven, 2001).

In general, hydrological models, despite their prominent value and worldwide utilisation, are not able to describe a changing system without the continuous use of field data. This is particularly true when many models are developed from limited data sources, and calibration testing on one or two catchments is an insufficient test of a model's universal applicability (Dunne, 1983).

One of the key features of this study is its focus on these limitations including the modelling of the groundwater level that also heavily influences the trend in hydrometric level and discharge flow in relation to the hydrological observation period. According to the latest hydrological models, the flow in saturated zones is usually assumed to be two-dimensional horizontal. However, most comprehensive physically-based models solve a three-dimensional ground water flow equation in order to calculate the spatial and temporal variation in hydraulic heads

(Islam, 2011). According to Islam, modelling methods include: the gravity drainage scheme following a linear reservoir, the two parallel linear reservoirs method, the storage discharge ratio; and the quasi three-dimensional cascade model.

However, although all these models generally allow for a good mathematical reproduction of groundwater behaviour, they are based on only one or a few measured data at piezometric level. The behaviour of groundwater is simulated by the model in space and time and even if it gives a good response to the general trend of the flood event, it shows some discrepancy in certain parts of the hydrograph. This discrepancy is not negligible for river risk prediction especially when associated with the resilience of hydraulic works. In fact, it is not enough to model the peak instant when, on the contrary, most of the risk in some parts of the basin is linked to the persistence of a certain hydrometric level or discharge flow over a long period of time.

Another key feature of this study consists in the fact that the observations and remarks derived from the results can be exported to other basins with similar geological and hydrological settings. The selected basin is the Aspio watershed, in the Marche region (central Italy), located in the province of Ancona near the Adriatic coast and adjacent to Mt. Conero (Fig. 1). It is characterised by the

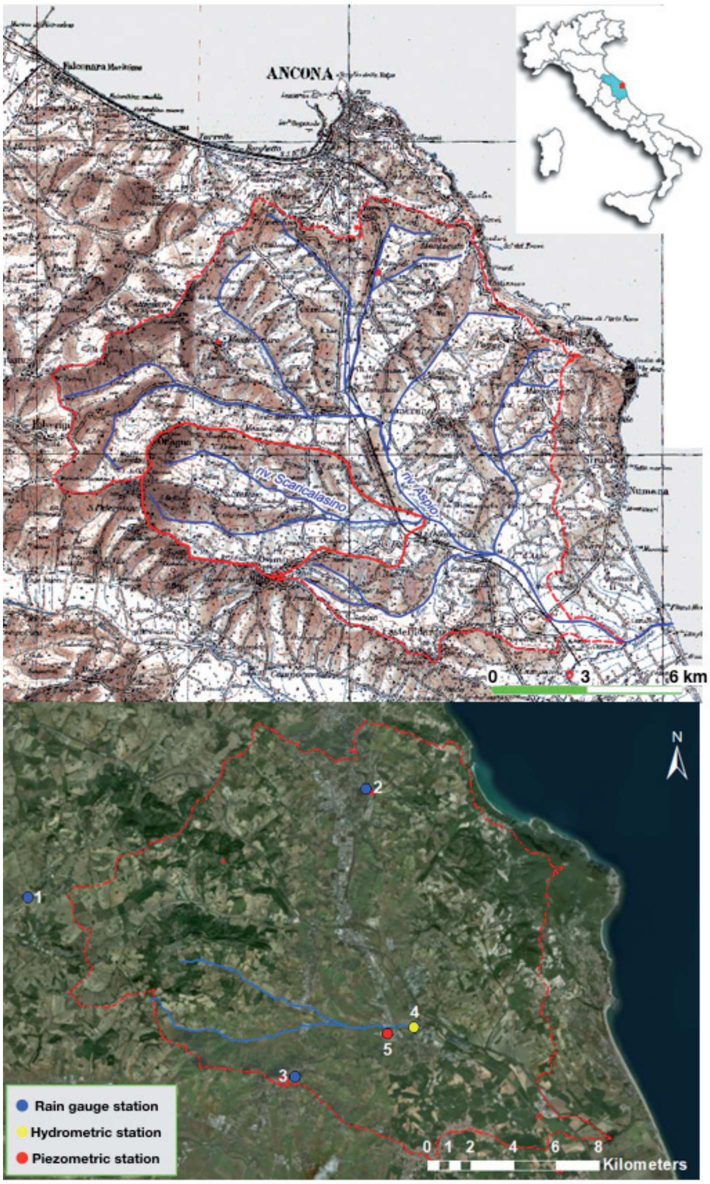

*Fig. 1 - a) Location of the area studied b) Position of piezometric, pluviometric and hydrometric stations in the Scaricalasino sub-basin*

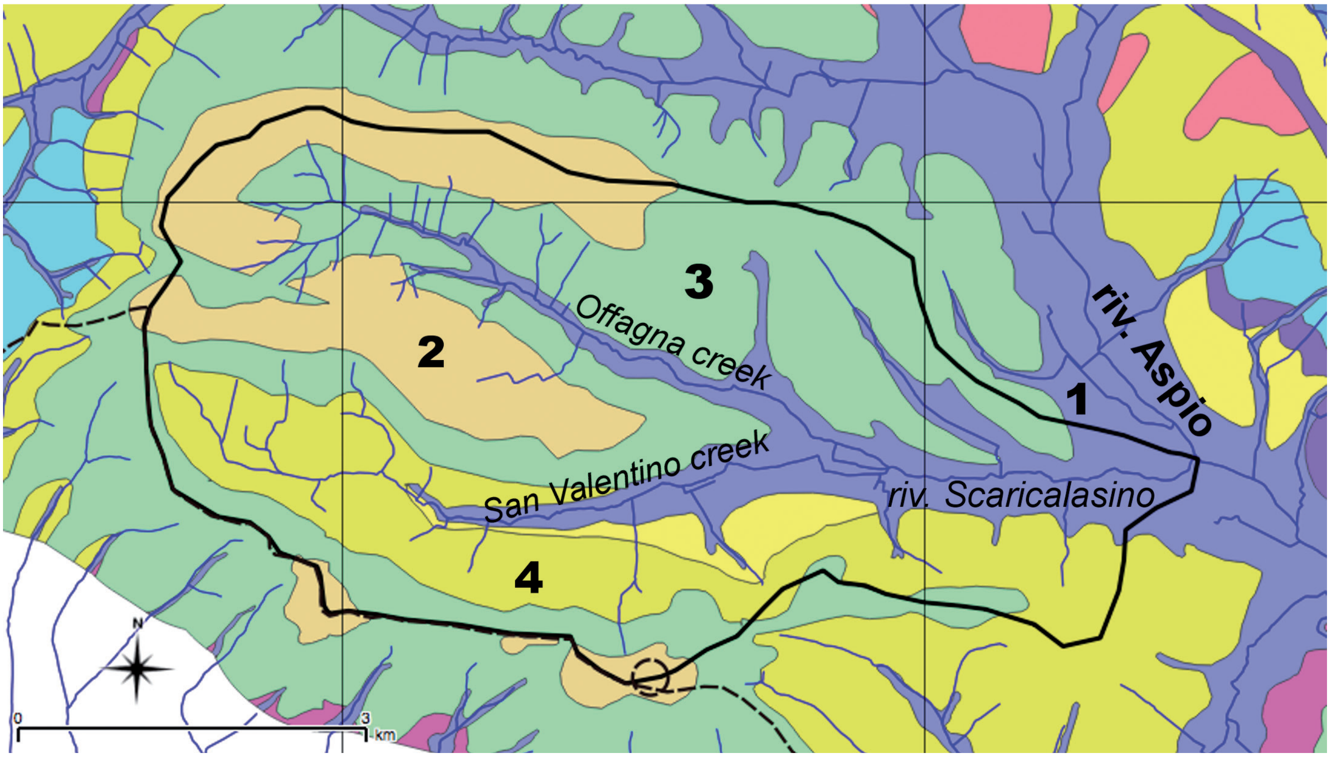

*Fig. 2 - Geological map of the Scaricalasino sub-basin. The black line represents the watershed boundary. 1: alluvial deposits (Pleistocene); 2: alternation of sandstone, gravels and marly clay (upper Pleistocene); 3: alternation of sands (lenses) and blue marly clays (middle Pleistocene); 4: marly clays (middle Pleistocene)*

presence of low hill slopes with an undulating shape, and the main water course is a tributary which merges with the River Musone just 0.5 km from the coast line. In particular, the model was applied to a 29 km² wide Aspio sub-basin called Scaricalasino (Fig. 1).

In this paper the correlation between soil use, hydraulic conductivity of soil, alluvial plain groundwater level and river discharge flow during flood events was investigated in different hydrological periods.

## GEOLOGICAL SETTING

The area studied is characterised by peculiar lithological and geo-structural settings, deriving from geological events which occurred from the Cretaceous to the Mio-Plio-Pleistocene period, and affected the final arrangement of sediments and morphological and tectonic forms (Nanni, 1980; Calamita & Deiana, 1986; Scisciani, 2009). Meso-Cenozoic sequence outcrops (characterised by limestone and marly limestone lithotypes and lifted by the Miocene tectonics) are present in the higher zones of the watershed, by the sea, and are represented by the Mt Conero ridge (Mussi *et alii*, 2017; Coltorti *et alii*, 1987). Most of the slopes are represented by the Mio-Plio-Pleistocene sequence (consisting of marly clays, marly clays with sandstone layers, clays and marly clays, sandy silty clays with sandstone layers, sands with gravel lenses and sandstone with clay layers) that covers the former sediments giving rise to a particular morphology of ridges and depressions. The Plio-Pleistocene basin developed along the tectonic lines and underwent a compressive phase, which was responsible for the final surfacing of the basin area (Bally *et alii*, 1986; Barchi *et alii*, 1998; Mirabella *et alii*, 2008). Quaternary continental covers (mainly consisting of silty clay and clayey sand, eluvial-colluvial deposits and a debris slope) are widespread in the watershed both in the alluvial plains and on the slopes (AA.VV., 1991) (Fig. 2).

Folds with gentle slopes and faults in the Apennine and anti-Apennine direction are present in the area. The NW-SE faults show horizontal components and release the NE-SW structures (Nanni & Vivalda, 2009)

## MATERIALS AND METHODS

The Aspio watershed is equipped with eight rain gauge stations, six hydrometric stations, three piezometric level stations, managed by the Università Politecnica delle Marche (UNIVPM) and the Regione Marche. One hydrometric station and one piezometric station are located in the Scaricalasino sub-basin (Fig. 1).

Infiltration tests, to determine the hydraulic conductivity of soils (Tab. 1), were made at different points of each shallow

| Shallow Deposit | Hydraulic conductivity (cm/s) |
|---|---|
| Alluvial deposits | $1.37\ 10^{-5}$ |
| Sandy with gravels deposits | $2.92\ 10^{-5}$ |
| Silty-sand and silty-clay deposits | $6.39\ 10^{-6}$ |
| Clay deposits | $3.39\ 10^{-8}$ |

*Tab. 1 - Hydraulic conductivity of soil (expressed in cm/s), determined for each type of shallow deposit (determined by the granulometric test)*

deposit by means of a stainless steel double-ring infiltrometer (Fig. 3). Each shallow deposit is directly connected to the geological substratum below it: the sand with gravel covers the alternation of sandstone, gravels and marly clays, the silty sand and silty clay deposits cover the alternation of sands and blue marly clays, while the clay deposits are relative to the marly clay rocks (Fig. 2).

The values in Table 1 were used, according to the Curve Number- Soil Conservation Service (CN-SCS) method (National Engineering Handbook of Soil Conservation Service, 1956), to divide the shallow deposits into two classes. Alluvial deposits and sand with gravel deposits are represented by soil class C of the CN-SCS method. Silty-sand and silty-clay deposits and clay deposits are represented by soil class D of the CN-SCS method (Tab. 2).

Using QGIS ver. 2.18.4® (QGis Development Team, 2009), the Scaricalasino sub-basin was divided into three other sub-basins which present uniform morphological characteristics. In order to determine the run-off time, a morphometric analysis was carried out for each sub-basin.

According to the dimensions and the morphometric characteristics of the sub-basins, the run-off time was determined using Puglisi's formula (1) (Puglisi & Zanframundo, 1978):

$$T = 6\,L^{2/3}\,(h_{max} - h_0)^{-1/3} \qquad (1)$$

where $T$ is the run-off time expressed in hours, $L$ (expressed in km) is the length of the main water course, $h_{max}$ (expressed in meters) the maximum altitude of the basin and $h_0$ (meters) the minimum elevation of the basin.

Three meteorological events, characterised by different groundwater behaviour and different hydrological conditions prior to the analysed event, were investigated using the Hydrologic Engineering Center- Hydrologic Modelling System (HEC-HMS) ® (Hydrologic-Engineering Center, 2000).

*Fig. 3 - Stainless steel double-ring infiltrometer used in the field tests*

| Soil use | Soil category | |
|---|---|---|
| | C | D |
| | *Alluvial deposits & sandy with gravels deposits* | *Silty-sand and silty-clay deposits & clay deposits* |
| Cultivated soils | 78-88 | 81-91 |
| Forests with modest coverage | 77 | 83 |
| Commercial area, 85% impervious | 94 | 95 |
| Residential areas, 65% impervious | 90 | 92 |

*Tab. 2 - Intersection table between soil use and soil category in the study area. The values represent the Curve Number*

In order to apply the model, QGIS was used to determine an average Curve Number for each sub-basin, starting from the intersection of the soil use shapefile (obtained from the Marche Region 2012 Corine Land Cover) with the shapefile of hydraulic soil conductivity classes previously determined for each shallow deposit. For each polygon obtained by this intersection, a representative Curve Number was assigned, as shown in Table 2.

Each CN value in table 2 is related to an average soil moisture condition, with an Antecedent soil Moisture Content (AMC), taking into account the five days of precipitation prior to the analysed event. This CN is named *CN (II)* and it is different from *CN (I)*, which is related to dry conditions and *CN (III)* related to wet conditions before the analysed event as shown in Table 3.

The average curve number for each sub-basin was calculated

| | | Total five-days antecedent rainfall (cm) | |
|---|---|---|---|
| Antecedent moisture content condition – Curve Number | Description | wet season | dry season |
| AMC I - CN I | Dry soils. Lowest runoff potential. Although soils are dry they are not wilted. | Less than 1.25 | Less than 3.5 |
| AMC II - CN II | Average soil moisture for the case of annual flood. No water drainage by gravity is presented in the soil. | 1.25-2.75 | 3.5-5.25 |
| AMC III - CN III | Nearly saturated soil due to heavy rainfall previous five days. Highest runoff potential. | Over 2.75 | Over 5.25 |

*Tab. 3 - Relationship between Antecedent soil Moisture Content and Curve Number*

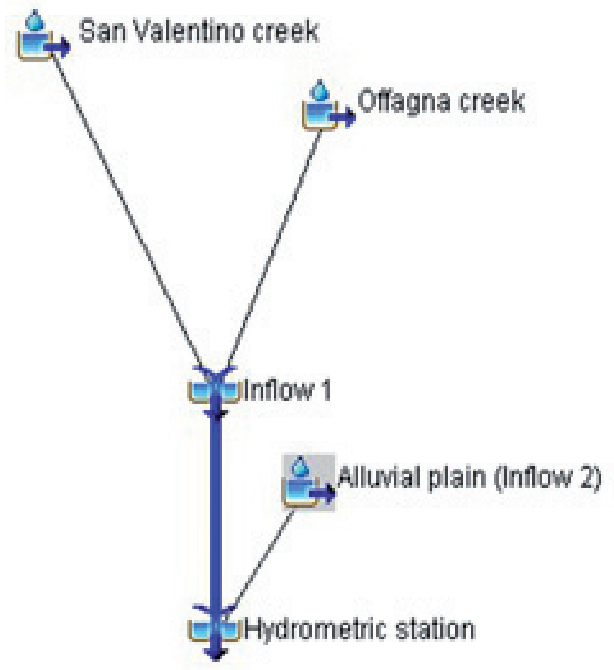

*Fig. 4 - HEC-HMS model of the Scaricalasino basin*

| Month | 2015 | 2017-2018* |
|---|---|---|
| January | 0.068 | 0.033* |
| February | 0.063 | 0.032* |
| March | 0.066 | 0.043 |
| April | 0.047 | 0.041 |
| May | 0.076 | 0.022 |
| June | 0.041 | 0.023 |
| July | 0.021 | 0.021 |
| August | 0.020 | 0.021 |
| September | 0.018 | 0.023 |
| October | 0.027 | 0.031 |
| November | 0.035 | 0.033 |
| December | 0.048 | 0.034 |

*Tab. 4 - Constant monthly base flow expressed in m³/s for the years 2015 and 2017-2018**

using the formula below (2):

$$CN\,(II)_m = [CN\,(II)_i \cdot A_i]/A_{tot} \qquad (2)$$

where $CN\,(II)_i$ is the value of the Curve Number assigned by each intersection polygon using Table 2, $A_i$ is the area of each polygon and $A_{tot}$ is the total area of each sub-basin.

The run of the HEC-HMS model is preceded by the creation of a basin model.

The basin model consists of three sub-basins (San Valentino creek, Offagna creek and Alluvial plain). The San Valentino and Offagna flow contribution reached downstream is named Inflow 1. This contribution flows through the confluence between inflow 1 and the hydrometric station. The contribution of the alluvial plain sub-basin (inflow 2) arrives at the hydrometric station (Fig. 4).

HEC-HMS also requires a meteorological model and control specification. The control specification involves the insertion of a start time and an end time, in addition to a computation time step in order to calculate hydrographs relating precipitations to discharge flow. The meteorological model is based on observed precipitation and water discharge data (Oloche & Li, 2010).

The precipitation events of 21-23 May 2015, 21-22 February 2018 and 20-21 March 2018 represent the input of the HEC-HMS model together with the run-off time for each sub-basin. Starting from the precipitation data, recorded from three gauging stations located in the Aspio basin, the Thiessen method was used to spatialise rain data (Thiessen, 1911). Most of the precipitation in the basin is captured by the Osimo rain gauge with a value of 90% coverage.

For each sub-basin a CN-SCS loss method was applied and the run-off contribution for each precipitation input was determined by the HEC-HMS model applying the formula below (3).

$$P_n = (P - I_a)^2/(P - I_a + S) \qquad (3)$$

where $P_n$ is run-off (expressed in mm), $P$ is the rainfall (expressed in mm), $S$ is the potential maximum soil moisture retention after run-off begins (expressed in mm) and $I_a$ is the initial abstraction (expressed in mm) or the amount of water before run-off, such as infiltration, or rainfall interception by vegetation. The relation between the initial abstraction and the potential maximum soil moisture retention after run-off begins is (4):

$$I_a = 0.2\,S \qquad (4)$$

For the alluvial plain sub-basin, a constant monthly base flow for the years 2015 and 2017-2018 was calculated from the continuous registration of the discharge flow measured by the hydrometric station located in the river (Tab. 4).

The base flow values were inserted in the HEC-HMS model to take into account the contribution of the alluvial plain groundwater to the water course. The computation of HEC-HMS calculates the hydrograph for the selected events, relating it to the real hydrograph recorded by the hydrometric station. The discharge flow (expressed in m³/s) was compared to the groundwater level measured by the piezometric level station located in the alluvial plain in the same period.

## RESULTS

The morphometric characteristics, useful for determining the run-off time using Puglisi's formula and the total area for each sub-basin, were obtained by QGIS analysis; the run-off time and the Curve Number ($CN(II)_m$) determined for each sub-basin are reported in Table 5.

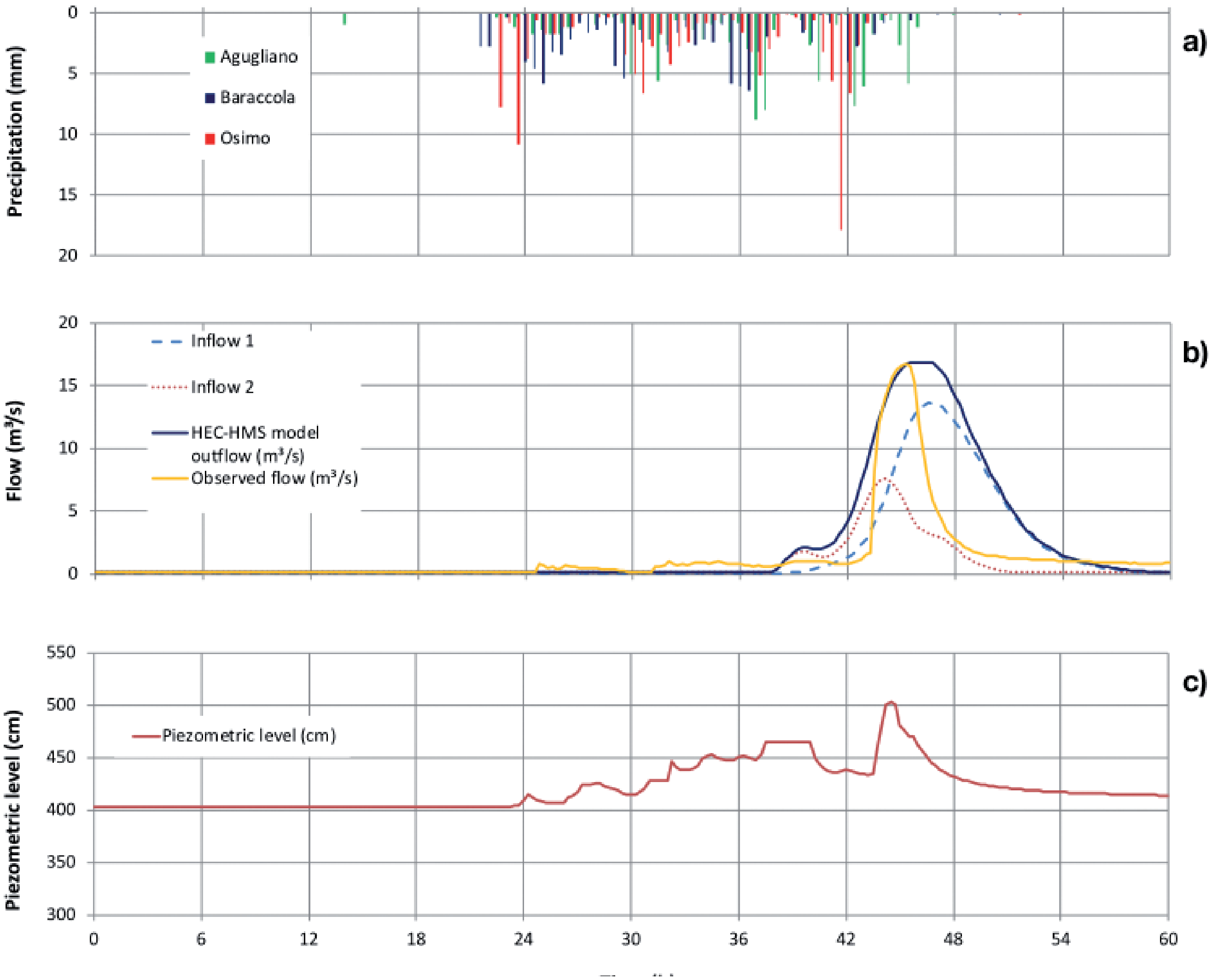

*Fig. 5 - (a) Amount of precipitation for the event in May 2015. (b) Hydrographs obtained by the HEC-HMS model. (c) Piezometric level*

The hydrological results are presented according to the selected meteorological events. For each event two figures are shown.

Figures 5, 6 and 7 report the results with the same graphical setting described as follows. Graph (a) represents the amount of precipitation for each event measured by the rain gauges (Agugliano, Baraccola, Osimo) expressed in mm. Graph (b) represents the hydrograph obtained by the HEC-HMS model, and shows different curves: the yellow curve represents the discharge flow measured by the gauging station, the continuous blue line shows the discharge flow calculated by the model and the dashed and dotted lines represent the discharge flow generated by the contribution of the tributaries (Offagna creek and San Valentino creek) and the alluvial plain respectively. Graph (c) represents the piezometric level measured at the well located in the alluvial plain.

| Scaricalasino sub-basins | Area (A) (km²) | River length (L) (km) | $h_{max}$ (m) | $h_0$ (m) | Run-off time (T) (min) | Curve Number CN(II)$_m$ |
|---|---|---|---|---|---|---|
| Alluvial plain | 5.53 | 2.94 | 139.8 | 16.6 | 167 | 85.94 |
| Offagna creek | 11.13 | 6.44 | 350.7 | 31.2 | 184 | 85.65 |
| San Valentino creek | 11.9 | 7.69 | 356.8 | 29.7 | 219 | 85.95 |

*Tab. 5 - Morphometric characteristics of the watershed. hmax represents the maximum height of each sub-basin, $h_0$ represents the minimum height of each sub-basin*

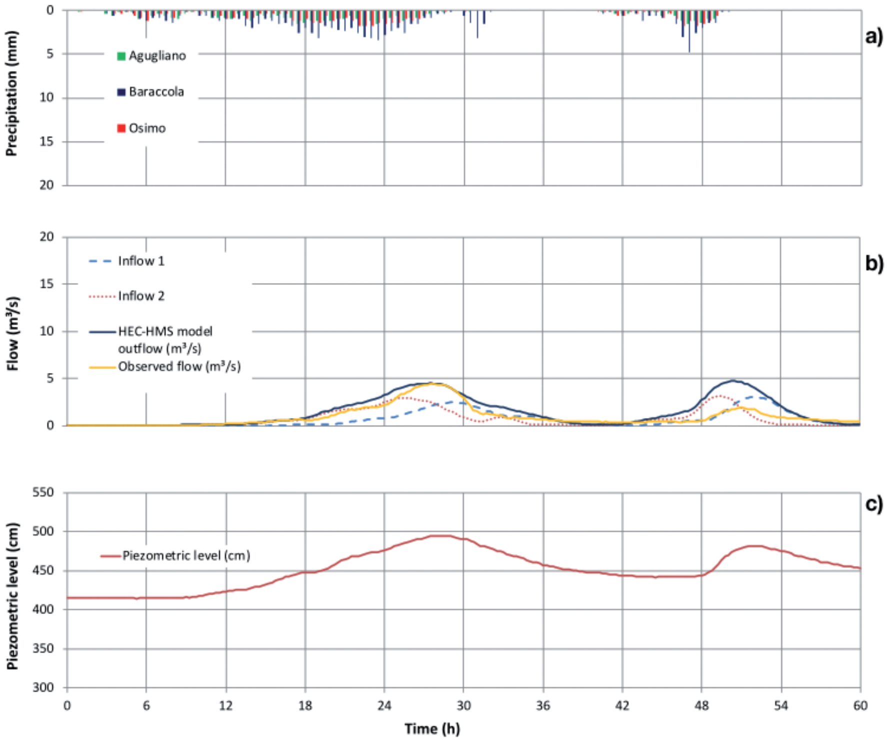

*Fig. 6 - (a) Amount of precipitation for the event in February 2018. (b) Hydrograph obtained by the HEC-HMS model. (c) Piezometric level.*

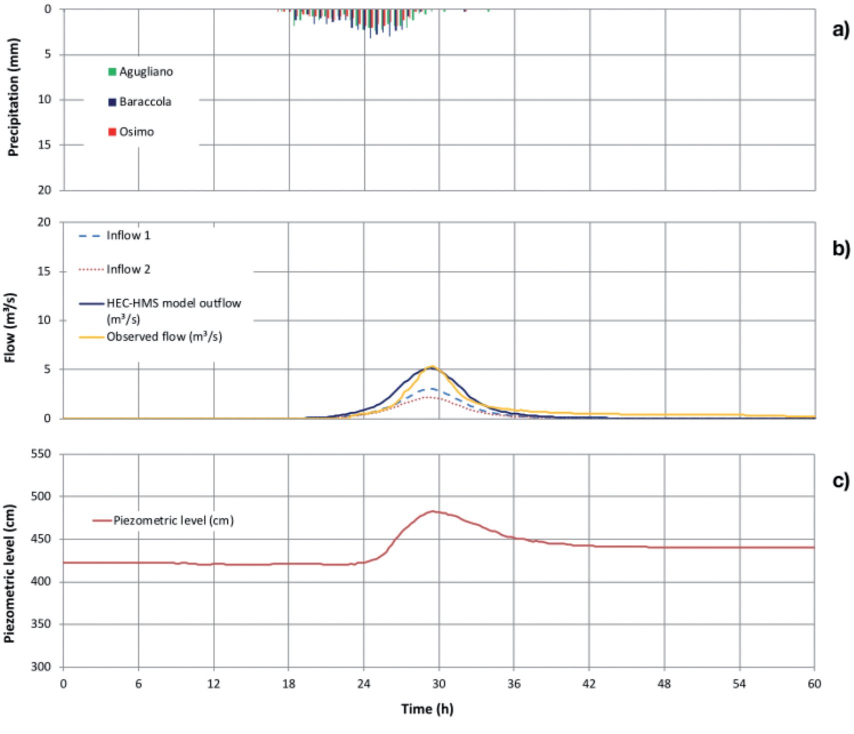

*Fig. 7 - (a) Amount of precipitation for the event in March 2018. (b) Hydrograph obtained by the HEC-HMS model. (c) Piezometric level*

Figures 8, 9 and 10 represent the results as follows. Graphs (a) (b) and (c) represent the values of precipitation, initial abstraction (loss) and run-off (excess) for each sub-basin. Graph (a) is referred to the Offagna sub-basin, graph (b) is referred to the San Valentino sub-basin and graph (c) is referred to the precipitation which involved the alluvial plain sub-basin. Graph (d) represents the hydrographs obtained by the HEC-HMS model without the line which represents the observed flow measured by the gauging station.

### *Rainfall 21-23 May 2015*

The precipitation event on 21-23 May 2015 lasted for 50 hours and was articulated in different sub-events with a maximum intensity of 18 mm/h recorded by the Osimo station and a total rainfall of 117.6 mm for the same rain gauge.

The maximum discharge measured by the gauging station was almost 17 m³/s, so it can be considered an extreme event for this watershed. The discharge flow increased quickly but it was preceded by some sub-increasing parts. The same behaviour was shown by the piezometric level: starting from a value of 400 cm from the bottom of the well, a regular increase occurred until about 500 cm, after which the piezometric level decreased to 410 cm in about ten hours after the peak.

### *Rainfall 21-22 February 2018*

The meteorological event which occurred on 21-22 February 2018 was much less intense than the former. The maximum intensity of precipitation was about 4.8 mm/h. The total duration of the event was about 60 hours with different precipitation inputs for a total rainfall of 56 mm (recorded by the Osimo rain gauge). The discharge flow recorded by the gauging station shows two different peaks. The first was recorded 27 hours after the start of the precipitation, grew slowly and reached 4.4 m³/s; the second peak was observed 51 hours after the start of the precipitation and reached almost 2 m³/s. The groundwater level followed the same behaviour with a slow increase from 415 cm to 495 cm in 18 hours, after which the level decreased slowly to 440 cm and increased again to about 480 cm during the second precipitation. After 60 hours the piezometric level decreased to 450 cm from the bottom of the well.

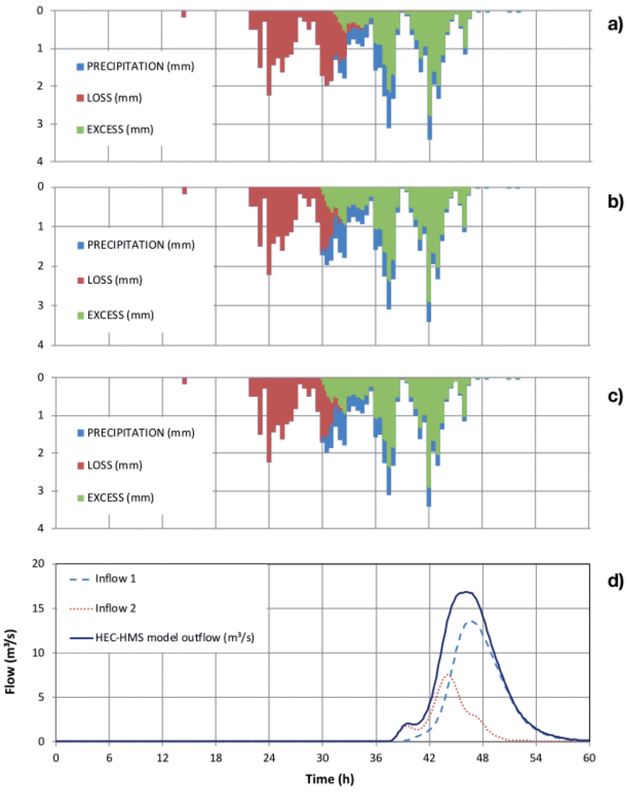

*Fig. 8 - (a) Precipitation, initial abstraction (loss) and run-off (excess) for the Offagna sub-basin. (b) Precipitation, initial abstraction (loss) and run-off (excess) for the San Valentino sub-basin. (c) Precipitation, initial abstraction (loss) and run-off (excess) for the Alluvial plain sub-basin. (d) Hydrographs obtained by the HEC-HMS model*

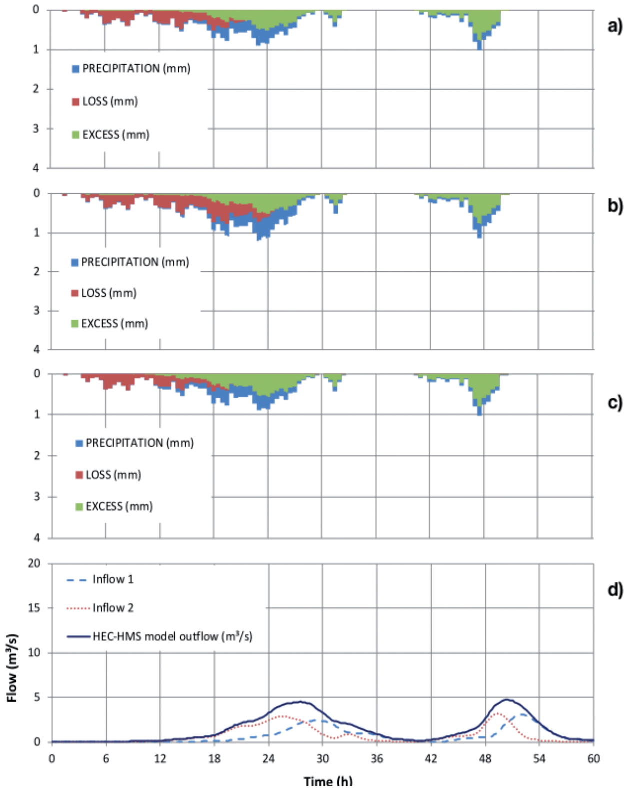

*Fig. 9 - (a) Precipitation, initial abstraction (loss) and run-off (excess) for the Offagna sub-basin. (b) Precipitation, initial abstraction (loss) and run-off (excess) for the San Valentino sub-basin. (c) Precipitation, initial abstraction (loss) and run-off (excess) for the Alluvial plain sub-basin. (d) Hydrographs obtained by the HEC-HMS model*

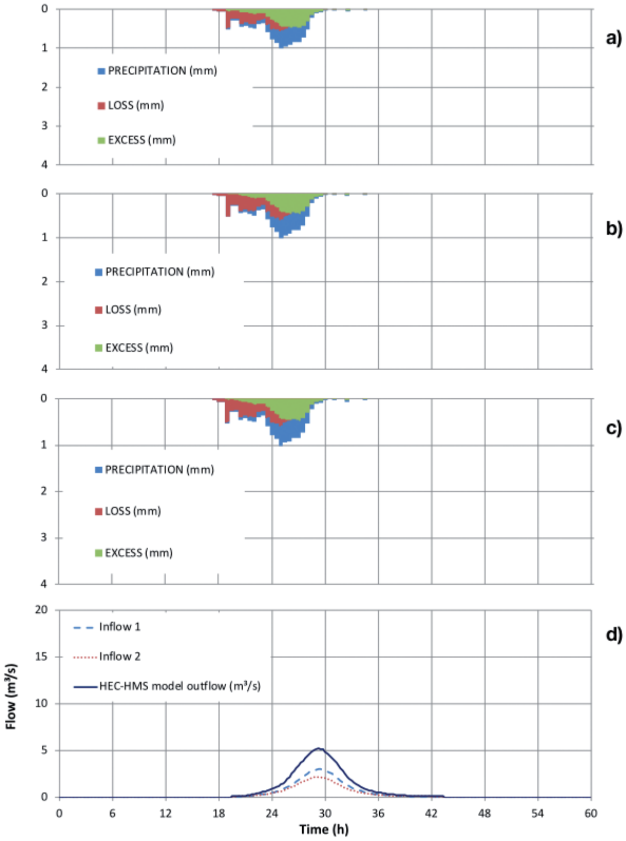

*Fig. 10 - (a) Precipitation, initial abstraction (loss) and run-off (excess) for the Offagna sub-basin. (b) Precipitation, initial abstraction (loss) and run-off (excess) for the San Valentino sub-basin. (c) Precipitation, initial abstraction (loss) and run-off (excess) for the Alluvial plain sub-basin. (d) Hydrographs obtained by the HEC-HMS model.*

### *Rainfall 20-21 March 2018*

The last event analysed, 20-21 March 2018, was characterised by a short duration with a maximum intensity almost equal to the previous precipitation 3.2 mm) and total rainfall of about 24 mm recorded by the Osimo rain gauge. The maximum discharge was about 5.4 m³/s. The piezometric level before the precipitation was about 425 cm which rose by about 60 cm, before decreasing very slowly in the hours following the storm.

## DISCUSSION AND CONCLUSIONS

Hydraulic modelling is an important method for understanding the behaviour of rivers and for preventing risks related to intense meteorological events (Knight & Shamseldin, 2005). This study, in fact, stresses how hydraulic modelling can give a good response to real situations occurring in the field, especially as regards the analysis of the hydrograph area near the peak. Nevertheless, the study also brings to light some critical aspects and suggests that other factors and parameters should be taken into consideration in the analysis.

Firstly, a specific and detailed reconstruction and interpretation of the geological settings, with particular focus on shallow deposits and their properties, is needed in order to achieve valid results. Using the SCS-CN method, in fact, the hydraulic conductivity of each shallow deposit has to be determined and then connected to each different lithology present in the area, in order to assign each soil to one of the different classes and calculate the value of the Curve Number. In addition, the lithology, shows different behaviour depending on whether or not it is capable of infiltrating water.

Soil use is another important aspect to take into account in calibrating the curve number; in fact, this may have a significant effect on the hydraulic characteristics of the study area (Koren *et alii*, 2000). For example, the impermeable areas, represented by buildings, car parks or industries, imply a run-off time reduction (Bean *et alii*, 2007). On the contrary forests or uncultivated natural areas delay or in some cases even cancel out the surface run-off (Zhang *et alii*. 2012).

Even the amount of precipitation and the hyetograph shape before the analysed event are important factors to take into consideration as well as the hydrological conditions prior to the event. As previously stated (Marchi *et alii*, 2010) the hydrological conditions before the event are very important as regards run-off coefficients even in the case of flash floods. The three storm events described and analysed in this paper have a different duration and intensity and present hyetographs with different shapes; this is mainly due to the hydrological period when the events occurred and also to the particular way in which they happened. The first event occurred in the late spring, when the soil moisture was very low, and is characterised by long duration and medium intensity, with a rainfall peak located in the final part of the storm. The second and third events occurred in the late winter, and show a more regular trend, with lower rain intensity. The hyetograph trend and the features of the rainfall affect the shape of the hydrograph, together with another important parameter, namely the variation in the piezometric level and its value before, during and after the precipitation. As presented in the results chapter, the behaviour of the hydrometric level before and after the peak is heavily influenced by the piezometric level, and this is particularly apparent when relating the graphs obtained by the HEC-HMS model to the measured one. In the first event (Fig. 4) a flash flood takes place after a long period of precipitation of medium intensity, necessary to increase the water content in the soil cover and to raise the groundwater level thereby recharging the aquifers feeding the water course. A single rainfall event of short duration (recorded in a single area of the basin, Figure 4a) can raise the level by about 4 meters. Without the first part of the rainfall (leading the watershed to critical conditions) it is likely that the effect of the single storm would not have been so significant. The second and third events (Figs 5 and 8) originate a comparable increase in the water stage (about 130 cm), but the shape of the hydrograph is very different, exhibiting a steeper curve in the latter case; in addition, the hyetograph shows the longer duration of the second storm compared with the third one, with double the amount of total rainfall.

The influence of the hydrological period and, therefore, of the groundwater level before and during the event, is apparent both in the first part of the late spring event (Fig. 4) when the groundwater (recharged during the first part of the precipitation) contributes to keeping the river stage high, and in the second part of the hydrograph (second and, above all, third event, late winter) where groundwater sustains the water stage after the peak.

These data and observations support the analysis of the HEC-HMS model output; in general, in fact, it is possible to notice a good correlation around the maximum level of the hydrograph, but there is scarce correspondence for lower levels which are represented by the base flow, strictly connected to groundwater behaviour and therefore to the variability of the piezometric level. In particular, the discrepancy visible in the hydrograph tails is more apparent during the recharge period (Fig. 8), when the groundwater mainly influences the hydrological behaviour of the water course.

The divergence between the results obtained by the hydrological model and the measured data, suggests taking into account the entire flood hydrograph, including the lower portion. Although this could seem negligible for risk prediction, this is not always the case. Most hydraulic works, in fact, are designed only on the basis of the maximum water stage expected in the watershed for a given time, and often underestimate any resilience strategies due to their cost (Vis *et alii*, 2003). In particular conditions the water stage may sometimes remain high for a longer period, and this possibility should be considered in the design and management of a watershed (Vitvar *et alii*, 2002).

In conclusion, this study shows that mathematical models, based on precipitation data, could provide a good representation of the flood when the hydrometric stage is at its maximum level, but the other parts of the hydrograph are often underestimates as the model does not represent the real soil and aquifer conditions before and after the flood event.

For this reason, the mathematical models should be improved by implementing some other parameters, for example: soil moisture before and after the event and/or the continuous record of the piezometric level during the entire hydrological year.

These factors could significantly improve flood events forecasts, making them more reliable and precise and extending the potential of the mathematical models. Furthermore, the suggested improvements could also be very important for the future development of scientific results involving the long-term behaviour of aquifers in the modelling process. Starting from these core concepts, public stakeholders (national and local authorities) and professionals should certainly be interested in accessing results that can be used to improve environmental management.

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