Journal of Arid Environments 112 (2015) 98–108

Contents lists available at ScienceDirect

Journal of Arid Environments

journal homepage: www.elsevier.com/locate/jaridenv

Rationale for flood prediction in karst endorheic areas

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ARTICLE INFO

Article history:
Received 7 May 2013
Received in revised form
18 February 2014
Accepted 22 May 2014
Available online 18 June 2014

Keywords:
Critical rainfall duration
Dryland hydrology
Endorheic basin
Karst system

ABSTRACT

A large karst area of South-Eastern Italy (Puglia) is characterized by endorheic basins, whose runoff does not discharge into the sea but converges toward internal lowlands and infiltrates or flows into underground cave systems through swallow holes. In such environment whenever intense rainfall events cover large areas and rainfall intensity exceeds the discharge capacity of sinks and swallow holes, significant volumes of runoff are produced and stored on surface causing floods and risks for people and goods. Most of these sinks are often at the end of small independent basins delimited by weak divides and, whenever water storage exceeds the overflow threshold, runoff contributes to downstream areas and, in cascade, large areas may contribute to deepest lowlands.

The observation of historical flood events suggests that in such areas traditional methods for the individuation of the design flood event, and in particular of critical rainfall duration, lack of applicability and the worst rainfall condition, for a fixed return time, should be searched accounting for soil hydraulic behaviour and groundwater dynamics. In this paper a rationale for the evaluation of the critical rainfall event and of the flood-prone area for given return period is proposed. A case study is presented showing that for high return period events a "multiple-reservoirs" mechanism is activated that affects the critical rainfall condition as well as the flood extent in the urban areas.

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1. Introduction

Traditional procedures for the identification of flood-prone areas for given return period are usually referred to exorheic basins, i.e. basins with a free surface outlet into an open sea (or lake or other stream). They typically evaluate the effects of a flood design hydrograph (Horritt and Bates, 2002; Kay et al., 2011; Romanowicz and Beven, 1997; Sarhadi et al., 2012) whose peak, representing the maximum streamflow-level, is considered the most critical factor. In facts, during the flood, a consistent threat for human lives and goods is represented by both the water level and the conveying force that characterizes flow velocity.

These procedures, quite often, are not suitable for karst areas, because they do not provide complete elements necessary to individuate areas flooded with fixed return period and the related risk (Bonacci et al., 2006; Mijatovíc, 1987). In some of these areas the risk due to the conveying force of discharge is less important because the weak slopes reduce flow velocity. On the other hand more importance should be given to other factors such as the water volume that can be stored in surface sinks and depressions, in order to account for the risk connected to high water depth.

The Puglia region in Southern Italy (Fig. 1) is mostly characterized by karst areas with irregular and apparently flat landscapes and quite permeable matrix of outcropping soils (Festa et al., 2012; Parise, 2011). In these areas it is often erroneously assumed that drainage of rainfall excess behaves in a natural way without significant risk. In fact, in many cases, when rainfall assumes particular space-time patterns, the drainage capacity of the swallow holes and the underlying karst system may be insufficient. In those cases the flood risk, with consistent water depths, of large lowlands with high population density is real.

A peculiar feature of these lands is provided by endorheic basins, i.e. drainage basins with a closed watershed divide and without free-surface outlet into an open sea. Within these basins runoff flows towards sink areas and reaches underground aquifers through percolation and filtration within the karst system. When rainfall intensity exceeds infiltration rate, large runoff volumes may be produced and routed towards lowlands.

The semi-arid climate that characterizes this region suggests to consider the Horton (infiltration excess) mechanism as the dominant process in runoff generation. The so-called Hortonian runoff (Beven, 2004a,b,c; 2006; Horton, 1931, 1933, 1936) was conceptually defined starting from the observation that the source of runoff is the portion of the basin where rainfall intensity exceeds the infiltration capacity of soil. In recent years many researchers have

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http://dx.doi.org/10.1016/j.jaridenv.2014.05.018
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been studying the hydrologic response of semi-arid basins considering that, besides the infiltration excess mechanism, floods can be triggered also by the saturation excess mechanism (Kirkby, 1978; Martinez-Mena et al., 1998), leading to two-components distribution of runoff (Fiorentino et al., 2011; Gioia et al., 2008, 2012; Iacobellis et al., 2011).

The hydrologic behaviour of endorheic areas in extreme events, as far as we know, is practically unexplored and, in particular, the hydrological literature does not provide any consolidated methodology for risk assessment and long term flood prediction specifically designed for this kind of environment. Moreover, despite the high risk of flooding of important areas including small-medium towns of Salento (Southern Puglia), there is not any available dataset of measured flows. Then, according to the definition provided by (Sivapalan et al., 2003), these basins have to be considered "ungauged basins" where rainfall time series are available and, consequently, non-conventional methods for calibrating (and validating) any proposed hydrological model (Biondi et al., 2011) shall be proposed and tested.

In this paper we focus on the evaluation of flood-prone areas which is particularly suited for urban areas placed in karst lowlands. In particular, in the context of flood risk evaluation, for such peculiar environment, we still suggest the use of traditional (and parsimonious) hydrological models, but they have to be casted in the correct framework, accounting for all critical factors that sensibly affect model result. With this purpose, in section 2, a rationale for providing flood-prone areas is described and organized in different tasks, including the sub-task to be performed for model assessment. A suitable hydrological model is described and the procedure to evaluate the critical rainfall event is defined. In section 3 a real case study is presented: the town of Copertino. In particular, the description of all surrounding endorheic areas that potentially contribute to flooding the town centre, with indication of divides, hydraulic connections and main swallow holes, is provided. The model assessment was performed exploiting measures and observations relative to the flood event of November 2004. In long-term prediction the flood-prone area for return period of 30 years is obtained. In section 4 we report additional comments and final remarks.

2. Rationale for model assessment and flood-prone areas evaluation

In a karst environment local situations may be quite different and heterogeneous depending on geomorphology, soil behaviour and groundwater dynamics. In some cases the karst bedrock is covered by a more or less deep layer of less permeable soil (in some cases practically impermeable) and runoff is drained by a surface stream-network system that ends into a natural swallow hole. Then, runoff is drained through the impermeable layer connecting the surface with the underlying aquifer. Obviously the swallow hole discharge capacity depends by its size and maintenance but can be also conditioned by the groundwater level oscillation. In fact, when the water table rises and approaches the surface, the swallow hole gets to hydraulic saturation and its discharge capacity is strongly reduced. Moreover, if wet soil moisture condition precedes a significant rainfall event, extensive overland runoff may be triggered and contribute to a flood event of consistent volume and peak flow. In such cases, when the flood peak exceeds the discharge capacity of the swallow holes, even large areas besides them may be flooded. Such areas remain flooded until runoff discharge decreases below the sinkholes drainage capacity and the stored water volume is then slowly released.

In absence of an impermeable soil layer covering the karst bedrock, still similar processes may have place but the flood frequency significantly decreases even because soil is well drained by infiltration and the antecedent moisture conditions are usually dry.

Fig. 1. Endorheic areas and study area in Puglia, Southern Italy.

In some other cases, the final reach of the stream-network is not a swallow hole but a lowland area, which may be flooded as a bucket, without any other hydraulic connection, between the surface and the aquifer, than filtration or infiltration.

It also often happens that adjacent endorheic basins may produce connected flow patterns. In fact, if the common part of their divide is low, water may flow from one to the other using the lower part of the divide as a weir. In such a way runoff may flow from basin to basin as in multiple reservoir systems (Fig. 2). By means of such a mechanism also very large areas of hundreds square kilometres may become contributing, in cascade, toward deepest areas facing a very high risk of flooding.

As an important consequence of what is stated above, the total drainage basin area contributing to the flood is not constant, in principle, but may change during the rainfall event. If one studies the effects of a single rainfall event, he will first have to identify all the surrounding endorheic basins that could potentially contribute to the flood by overflow from basin to basin in cascade. Then he will have to verify if the overflow conditions from one sink to the following, in cascade, are reached or not. On the other hand, from the designer's perspective, according to this mechanism the overall effective contributing area may change with return period. In fact we may

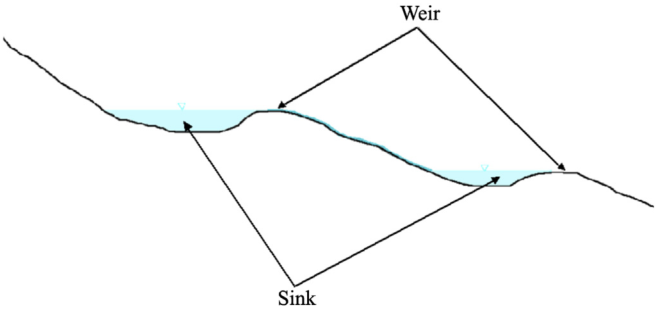

Fig. 2. Scheme of adjacent endhoreic basins behaving as multiple reservoirs.

have different endorheic basins that behave independently for low return periods. But for increasing return period the cascade mechanism could be activated being exceeded the critical threshold of storage and drainage capacity of the upstream sinks.

The first task to be performed starts from the detailed analysis of the flood-prone lowland including the identification of the watershed divide, soil features, storage and drainage capacity accounting also for the presence of swallow holes, drainage wells and other structures typical of the karst system. The empirical depth–volume relationship of the sink has to be evaluated providing the volume of water that can be stored in the sink below any corresponding level. Elaborating the depth–volume curve needs accurate topographic data for depth ranging from zero (lowest level within the sink) to the lowest point of the watershed divide. In fact, also the flood-prone lowland may behave, in extreme conditions, as a sink whose overflow crosses the lowest part of the divide as a weir. Let us call V_S the sink storage capacity i.e. the maximum volume of water that can be stored in such a sink below the lowest point of the watershed divide.

The geomorphological analysis includes detection of the areas outside the watershed divide in order to identify other sinks whose runoff volume, in critical events, may overtop such a weir-divide and contribute to flood the lowland. Obviously the analysis has to be further extended from basin to basin in the upstream direction in order to find the overall potential contributing area provided by the union of all the sub-basin that may, in cascade, contribute to flood the deepest lowland. Then, watershed, soil features, storage and drainage capacity have to be assessed for all the sub-basins that compound the overall potential contributing basin.

The second task is aimed at determining the hydrologic behaviour of the overall potential contributing area. For each of the sub-basins individuated in the first task, the runoff exceedance overflowing the weir-divide has to be evaluated for a given rainfall input. This hydrologic analysis has to begin from the headwater sub-basins, those that drain runoff from the upper reaches of the overall potential basin, and proceed, in cascade, towards the lower sub-basins and the flood-prone area considered.

Accounting for different types of rainfall input, we distinguish three different sub-tasks: (2.1) model assessment, which is based on the use of one or more single observed events; (2.2) model application for long-term prediction, which is based on the use of design rainfall events; and (2.3) model application for real time forecasting of floods, based on measured or predicted real time rainfall events. We do not develop real time forecasting in this paper because it requires a different level of both model complexity and real-world observation.

One of the most important requirements for the development of a correct model assessment procedure is the availability of observations from real extreme events in the area. The collection and analysis of observed rainfall and flood features is needed in order to choose a suitable hydrological model and verify its descriptive and predictive capability. In practice, for assessment purpose, the observed rainfall input is used in order to evaluate the runoff volume that reaches the flood-prone lowland. Then, the modelled runoff volume is compared with the volume of water in the real flooded area. At this stage it is also possible to perform the calibration of model parameters in order to achieve the best fit between modelled and observed flood volume.

In long-term prediction the rainfall input is provided by means of the rainfall Intensity Duration Frequency (IDF) curve for given return period. Thus, the hydrologic analysis has to be repeated for a consistent range of rainfall duration values. These should range from technical values close to zero up to the maximum routing time of the entire potential basin area, including the farthermost headwater sub-basin. The rainfall duration that produces the maximum runoff volume (V_R) in the flood-prone lowland will be the critical rainfall duration.

In the third task the runoff volume, V_R, available after the second task as the maximum runoff volume produced by the critical rainfall event, is used to provide the flood-prone area map for given return period. For this purpose V_R is compared with the volume of water that can be stored in the flood-prone lowland according to the volume–depth curve which was obtained in the first task. We remind here that V_S was defined as the sink storage capacity.

We have two different cases:

If $V_R < V_S$

- the runoff volume is stored in the sink without overflow. The flood water depth is obtained intersecting the volume–depth curve with the line of equation $V = V_R$. Hence, also the flood water surface, which is below the lowest point of the watershed divide, is determined.

If $V_R \geq V_S$

- the runoff volume exceeds (or is equal to) the storage capacity of the sink which is filled up while the runoff exceedance overflows the weir-divide. The flood water depth is obtained intersecting the volume–depth curve with the line of equation $V = V_S$. The flood water surface is placed at the same level of the lowest point of the watershed divide.

2.1. Hydrological model

According to the key design criteria above introduced, the critical rainfall event maximizes the runoff volume produced from the overall potential contributing basin. Then, the hydrological analysis to be performed requires the choice of a suitable hydrological model that has to be applied to each of the involved sub-basins in order to determine if the local sink is able to contain runoff volume or if the overflow volume contributes to runoff in the lower sub-basin.

We assume that runoff per time unit is equal to net rainfall, i.e. it is equal to rainfall intensity minus infiltration. Then, the runoff volume is obtained for any sub-basin by integrating in space and time the net rainfall intensity and adding the upstream overflow volume, if present. Besides infiltration we have to account also for the discharge capacity of single or multiple swallow holes that are inside the sub-basin.

We use, for long-term prediction, a design hyetograph with rainfall intensity, constant in space and time, evaluated by means of the IDF curve of assigned return period. Then, the evaluation of the maximum runoff volume is performed numerically by allowing rainfall duration to vary within 0.5 and 24 h.

The hydrologic model exploits a spatially-distributed parameterization and evaluates the infiltration capacity in time $f(t)$ according to the classic Horton equation (Horton, 1940):

$$f(t) = f_c + (f_o - f_c)e^{-t/k} \tag{1}$$

where f_o is potential infiltration capacity at time 0; f_c is the asymptotic infiltration rate; k is a time constant.

The three model parameters should be calibrated based on direct observations on the studied basin, in particular its soil and land-use. Nevertheless, for application to semi-distributed models, it is feasible to use values reported in literature, in particular we referred to handbook values in Table 1 which were evaluated (Maione, 1995) with reference to the classification of the Soil Conservation Service (SCS, 1972). This includes groups A, B, C and D, based on the infiltration capacity of the bare soil in average soil moisture antecedent condition:

Table 1
Handbook values of parameters f_c, f_o and k for different SCS groups.

SCS Group	f_c [mm/h]	f_o [mm/h]	k [min]
A	25.4	250	30
B	12.7	200	30
C	6.3	125	30
D	2.5	76	30

Group A – Soils with high potential infiltration (low runoff) after prolonged wetting. Sand, loamy sand, or sandy loam.
Group B – Soils with moderate potential infiltration (moderate runoff). Silt loam or loam.
Group C – Soils with low potential infiltration (moderate runoff) Sandy clay loam.
Group D – Soils with very low potential infiltration (high runoff). Clay loam, silty clay loam, sandy clay, silty clay, or clay.

We do not consider the variability of parameters due to land-use except for urban areas that are reclassified as belonging to group D. We use f_c values from Table 1 while parameters f_o and k are evaluated by model calibration with reference to four SCS groups.

The evaluation of the real infiltration is performed comparing rain intensity and infiltration capacity after determining the ponding time from equations:

$$\int_0^{t_p} i(t)dt = F(t_p - t_o); \quad i(t) = f(t_p - t_o) \tag{2}$$

where $i(t)$ is time-dependent rainfall intensity, $F(t)$ is cumulative infiltration and t_o is a time constant that allows to find:

$$F_r(t_p) = F(t_p - t_o) \tag{3}$$

where $F_r(t)$ is cumulative real infiltration.

If rainfall intensity is constant the above equations become:

$$it_p = F(t_p - t_o); \; i = f(t_p - t_o). \tag{4}$$

Such a case is displayed in Fig. 3 with reference to a rainfall event of duration 3 h and a soil type of Group D.

A flood peak concentration model is also needed and we used the classic lag and route method (Pilgrim and Cordery, 1992) characterized by the following assumptions: (i) runoff flows over the basin surface following an invariant path dependent only by the point where it generates; (ii) water velocity is constant in time and (iii) discharge is obtained by summing contributions coming from upstream source areas.

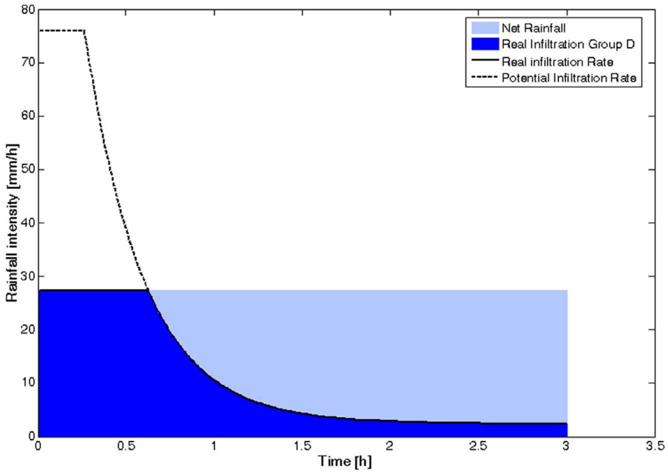

Fig. 3. Design hyetograph of constant intensity (duration 3 h) and Horton infiltration for Group D.

The application of such methodology is described in the following case study section and includes the calibration of the hydrological model above reported which was performed exploiting the flooded areas observed after an historical flood event.

3. Case study: the town of Copertino

In this section we report results of the model application to the town of Copertino, placed in a karst endorheic area (Fig. 1) in Salento, the southernmost part of the Puglia region, in Southern Italy. Such a case is emblematic of the processes above described and involves an urban area placed in the sink of an endorheic area that receives overflows from other adjacent sinks.

Climate is of the Mediterranean type, with mild temperatures in winter and hot-dry summer. The mean annual temperature ranges between about 15 °C and 20 °C with peaks of 40 °C observed in July and August. Mean annual rainfall is about 590 mm, while mean annual reference evapo-transpiration is about 1100 mm. All climate variables, including rainfall, show a strong inter-annual variability and seasonality. The town population is estimated at about 24,000 with a population density of about 420 inhabitants/km^2.

The Geology of Salento reports different outcropping carbonate rocks, including the Cretaceous limestone, the Oligocene, Miocene, and Plio-Pleistocene calcarenites, and the middle-upper Pleistocene terraced marine deposits (Festa et al., 2012). Depending on characteristics of soluble rocks, age and activity of karstic phenomena, the all region is strongly affected by the presence of sinkholes, and vertical structures, showing a great variety of size and morphology (Bruno et al., 2008).

3.1. Geomorphological analysis and detection of the overall potential contributing basin (task 1)

The endorheic area of Copertino covers 22.3 km^2 and can be divided, morphologically, in four sub-basins (sub-basins 1, 2, 3 and 4 in Fig. 4a). It has an elongated shape in direction (North-West) – (South-East) and, looking at soil characteristics, could be divided in two parts. The first, Northern part (sub-basins 1 and 2.1) is less permeable, while the second one (sub-basins 2.2, 2.3, 3 and 4) has outcropping fractured limestone of moderate permeability (according to the SCS classification).

The basin of Copertino may exchange flows with the adjacent endorheic basin of Leverano, (so called because it includes the homonymous urban area, see Fig. 4a) of 34.3 km^2. In fact, the watershed-divide between these two basins presents a concave shape with a lower sector that, for intense and prolonged rainfall events, allows water to flow from Leverano to Copertino.

With regard to this behaviour it is worth to mention that within the lower area of the Leverano basin is located a large swallow hole, which is called “Le Arche” from the name of the surrounding land. Despite the morphology and the size of the hole, its discharge capacity is strongly reduced by sediments and vegetation. Within such lowland area we estimate, from the available DEM at resolution 20 m × 20 m, a discharge capacity of about 500,000 m^3 where water could be stored before overflowing toward Copertino. We assigned a null drainage capacity to the swallow hole in fact, probably due to absence of hydraulic maintenance in the latest years, a little permanent pond is present in the area.

Notwithstanding the remarkable volume that could be stored in the area it is possible to hypothesize that in past events (in

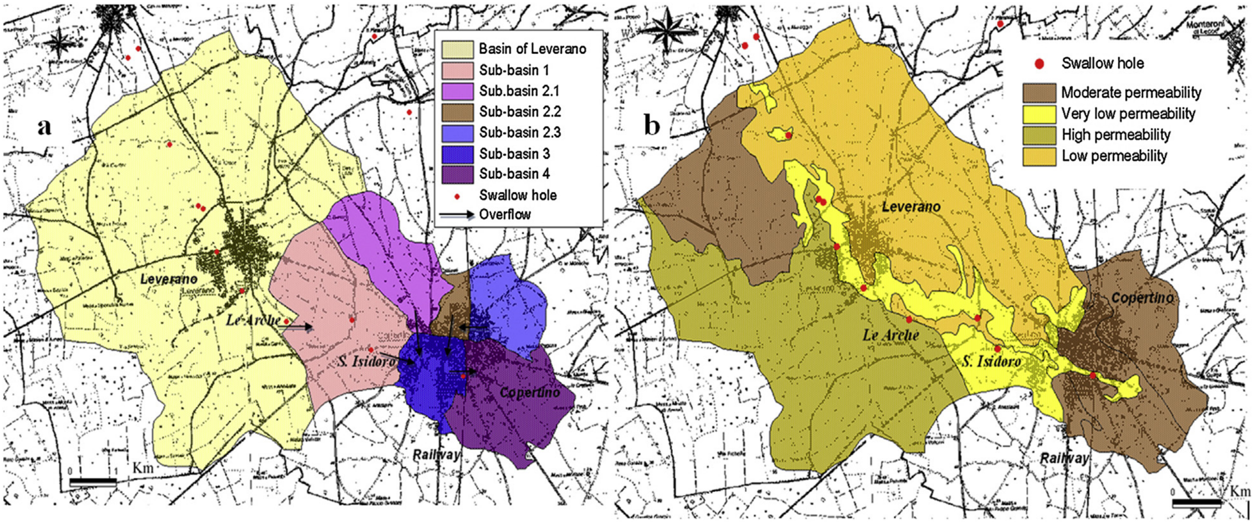

Fig. 4. a: Endorheic basins of Copertino and Leverano and b: Soil permeability.

particular during the extreme event in 2004 which is described in the following section) a significant overflow from the basin of Leverano interested the basin of Copertino with a dramatic worsening of the hydraulic risk.

The upper part of the Copertino area is compound by sub-basins 1, 2 and 3. The sub-basin n. 1 includes a natural swallow hole (in the following called S. Isidoro), which is also practically filled by earth and vegetation. Previous studies report a maximum discharge capacity of the swallow hole of about 0.1 m^3/s. The basin has soils of low permeability (Fig. 4b) and is placed North-West of the urban area. The storage capacity of the sink is about 450,000 m^3 in the area of the S. Isidoro swallow hole. The sub-basin area covers 6.5 km^2 with minimum height of 32.4 m a.s.l. and the sub-basin divide lowest point is at 33.2 m a.s.l. which is the overflow threshold toward basin n. 3 which includes part of the city centre.

The sub-basin n. 2 includes an area North-East of Copertino and its divide crosses a medieval castle which dominates the old town of Copertino. The basin area of 6.6 km^2, has low permeable soils, a lowest point at 32.3 m a.s.l. and at least one overflow threshold toward the city centre (basin n. 3). Sub-basin n. 2 is compound by three smaller sub-basins: 2.1 and 2.2. They have storage capacities respectively of 165,000 m^3 and 132,000 m^3 and both may overflow toward sub-basin 3. Sub-basin 2.3 has a storage capacity of 55,000 m^3 and may overflow toward basin 2.2.

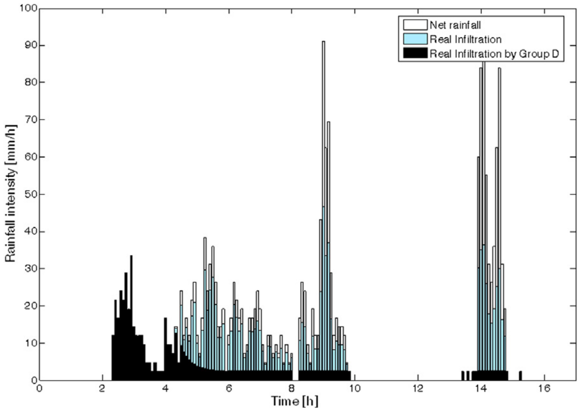

Fig. 5. Rainfall event of the 13th November 2004 recorded at the raingauge of Copertino and Horton infiltration.

Sub-basin n. 3 includes almost the entire old town of Copertino and is crossed by a railway. The area of sub-basin n. 3 is 1.9 km^2, with soils of low permeability and may receive overflows from all the above mentioned basins. Close to the train station a natural swallow hole is present, located inside a large settling-basin. The maximum drainage capacity of the swallow hole is estimated in about 0.6 m^3/s. Beside the concrete wall of the settling-basin, a street-tunnel runs below the railway. The total storage capacity, of about 530,000 m^3, includes both the settling-basin and the street-tunnel that has been repeatedly flooded during significant extreme events. The depth–volume relationship of the sink is shown in Fig. 10a. The lowest point of the watershed divide of basin n. 3 is located at the end of the tunnel in the outbound direction and, according to local authorities, it has been never reached by water.

Sub-basins n. 2.1, 2.2, 2.3 and 3 are also provided with independent sewer systems that, for sub-basins 2.1, 2.2 and 2.3 drain into a network of small wells placed inside the same sub-basins in the lowest areas. The sewer system of sub-basin n. 3 drains into the settle basin close to the street-tunnel. The discharge capacity of the draining wells is unknown but their efficiency is probably very low

Fig. 6. Traces of the overflow from the Leverano basin into sub-basin n. 1.

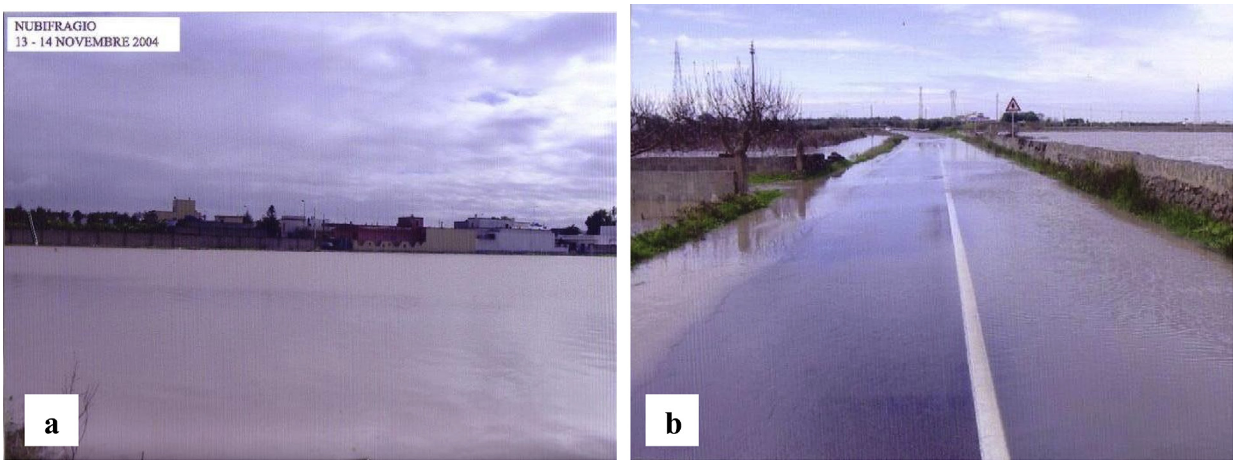

Fig. 7. Flooding in sub-basin n. 1 close to the S. Isidoro swallow hole (on the left) and traces of the overflow into sub-basin n. 3 (on the right).

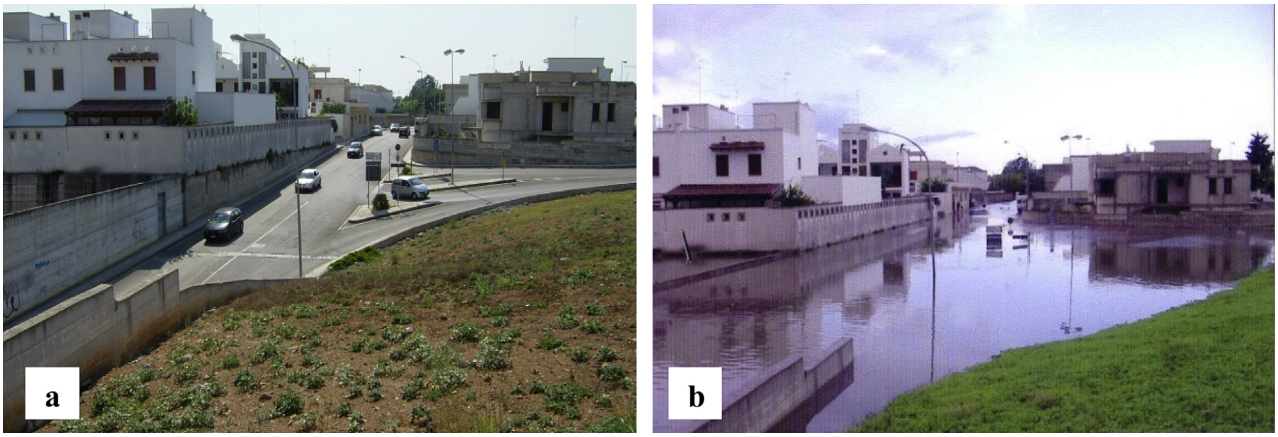

Fig. 8. Basin n. 3, view from above of the street-tunnel in normal conditions (on the left) and during the flood of 2004 (on the right).

due to scarce maintenance and to saturation due to the water table rise from the underlying aquifer.

Sub-basin n. 4 (7.3 km^2) is placed South-West of the urban area. It has low permeability, the lowest point is at 31.3 m a.s.l. and according to the available historical information it was never interested by overflows from sub-basin n. 3.

3.2. *Model assessment (sub-task 2.1)*

3.2.1. *Analysis of the flood event of November 2004*

The urban area of Copertino was subject to a remarkable flood event on the 13th of November 2004. The following information is available:

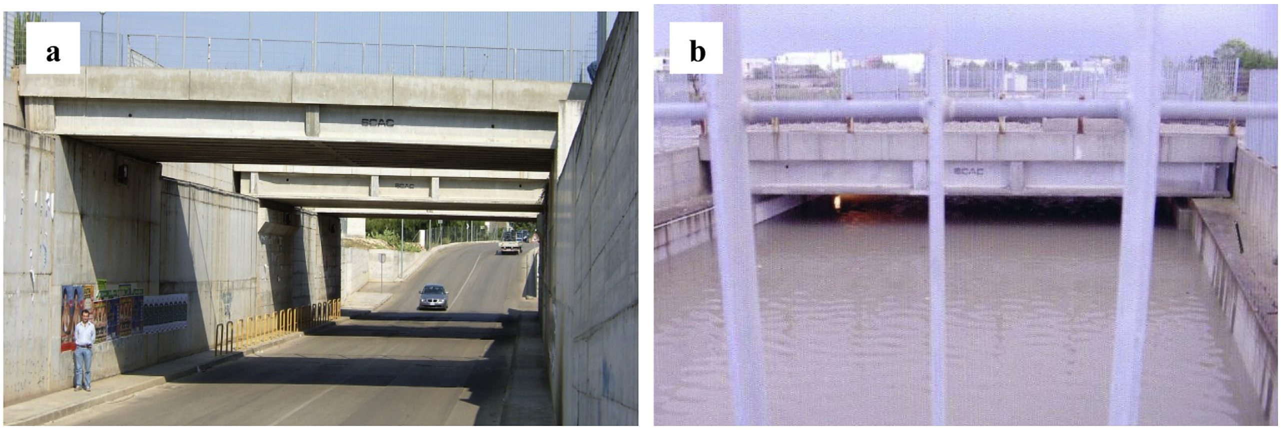

Fig. 9. Basin n. 3, view from below of the street-tunnel in normal conditions (on the left) and during the flood of 2004 (on the right).

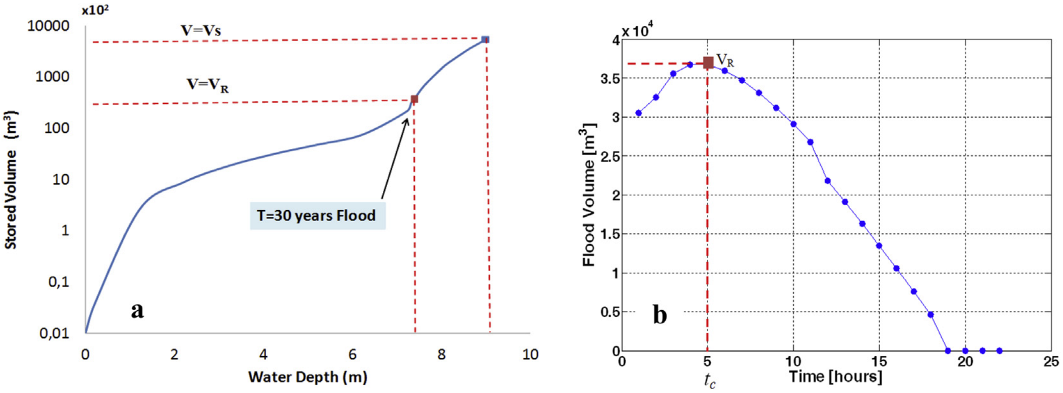

Fig. 10. a: Depth–volume curve for basin 3. b: Curve of flood volumes for sub-basin 3, for $T = 30$ years and rainfall duration ranging from 0.5 to 24 h.

- A record of the rainfall time series with time step of 5 min measured at the raingauge station of Copertino from the Servizio Idrografico e Mareografico, Regione Puglia. (Table 2 and Fig. 5);
- The flooded urban areas and relative volumes are known and documented by photographic reports; such data provide the necessary information for a non-conventional model assessment.

During the month of November 2004 also other significant rainfall events, besides the one of the 13th, were observed. On the 8th of November a rainfall event typical of the Autumn season occurred, with a peak of 41.8 mm. In following days only very small precipitation was observed and no rainfall was recorded in the second half of the month.

On the 13th of November 2004, in particular, 177.2 mm of rainfall were measured corresponding to a return period of about 400 years. Precipitation started 15 min past 2 a.m. and proceeded almost continuously until 5 min to 10 a.m. producing an observed rainfall depth of 126.2 mm. At 20 min past 1 p.m. it rained again and (after a strong peak) it stopped at about 3 p.m. determining other 49.6 mm of rainfall; up to the end of the day only other 1.4 mm were measured.

In order to provide further information about the basin response, it is worth noting that, on the 14th of November, a total rainfall depth of 25.6 mm, recorded in two steps (the first one at 6 a.m., the second at 3 p.m.), did not produced any variation of the flooded areas observed after the rainfall in previous days.

Starting at 30 min past 3 p.m. of the 13th of November local authorities realized a continuous monitoring of the flooded areas in the town centre and documented the state of the areas by means of several photographs. Such photographic documentation was precious in order to individuate five areas that for their extension and position could be considered as damaged by the flood.

The first one of these areas is located in the basin of Leverano whose overflow into basin n. 1 contributed to the flood nearby the S. Isidoro swallow hole. This is the second flooded area that approaches the urban area of Copertino. Fig. 6, which was shot a few hours after the peak, shows a water level slightly above the street that separates the basin of Leverano from basin n. 1. Traces of the overflow from basin n. 1 into sub-basin 3 are visible in Fig. 7.

Table 2
Rainfall time series (mm) recorded on the 13th November 2004 at the raingauge in Copertino. The table reports rainfall depths in intervals of 5 min.

	0÷5	5÷10	10÷15	15÷20	20÷25	25÷30	30÷35	35÷40	40÷45	45÷50	50÷55	55÷60
0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	1.0	1.8	1.4	2.0	1.8	2.4	1.6	2.8	1.2
3	1.0	1.0	1.0	0.8	0.4	0.4	0.2	0.4	0.2	0.2	0.2	1.4
4	0.8	0.8	0.6	1.2	0.4	2.0	1.0	1.4	1.0	1.8	2.2	1.0
5	0.6	1.4	3.2	2.0	2.6	3.0	2.2	1.2	1.2	1.6	0.2	1.0
6	1.4	2.2	1.8	1.4	1.6	0.6	0.8	1.4	1.4	1.6	2.0	1.6
7	0.8	0.4	1.0	1.0	0.6	0.8	0.6	1.0	0.4	0.8	0.4	0.8
8	0	0	1.4	2.2	2.0	0.8	0.4	1.6	1.0	1.0	3.6	7.6
9	5.2	5.8	2.4	1.0	1.4	1.2	1.2	1.0	0.4	0.2	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0.2	0	0.2	0	0.2	0.2	5.0	7.0
14	7.8	4.6	2.6	2.2	3.0	5.2	7.0	2.6	1.6	0.2	0	0
15	0	0	0.2	0	0	0	0	0	0	0	0	0
16	0.2	0.4	0	0	0	0	0	0	0	0.6	0.2	0
17	0	0.2	0.2	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0.2	0
19	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0.2	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0

The third and fourth flooded areas were placed in two sites not too far. They were interested by contributions coming from their respective watersheds (sub-basins 2.2 and 2.3 above described) without reciprocal influence because the railway placed between them runs higher than the streets level. According to local authorities both the sub-basins did not produce overflow into other sub-basins. The flooded areas, of limited extension, had water depth of about 0.5 m. Nevertheless they were critical because a high traffic urban road connecting the hospital and the urban centre was flooded.

Finally, the flood interested the urban area covering the streets and the street-tunnel beside the settling-basin in basin 3 (Figs. 8 and 9). The entity of this flooding and the related risk were particularly high. The water depth reached about 4 m with respect to the bottom of the tunnel, representing a serious risk for human lives. The water level reached 31.5 m a.s.l., hence, there was not overflow (as confirmed by local authorities) from sub-basin n. 3 into sub-basin n. 4.

According to what above exposed, we implemented the hydrologic model considering the overall potential contributing basin as composed by the union of the basin of Leverano and sub-basins n. 1, 2 and 3.

3.2.2. Model parameterization

The availability of a DEM (20 m × 20 m) of the endorheic area of Copertino allowed to determine, for all the considered sub-basins, the runoff patterns up to the different outlets, and to evaluate their lengths. Corresponding lag times were evaluated assuming as a function of the soil coverage a higher velocity (1.0 m/s) for urban areas where soil is considered impermeable and the drainage is also assured by the existent sewers and a lower velocity (0.1 m/s) over the surrounding areas not urbanized.

Exploiting the water levels observed in the photographs of the flood and by means of the DEM, we determined the flood water volume useful to calibrate the model and evaluated the influence of the parameters f_o and k of the Horton equation before mentioned. We decided to keep literature values for the saturation infiltration rate f_c and calibrated the values of k and f_o because they mostly depend on the moisture condition antecedent the rainfall event. We obtained by calibration the values of k and f_o reported in Table 3. All the calibrated values show higher values than those from handbooks indicating that the antecedent moisture condition was probably dry.

In practice we reproduced the effects of the event of November 2004, obtaining runoff storage volumes that were consistently close to the observed values for all the considered flooded areas. The procedure of calibration considered first the parameters of sub-basins n. 2.2 and 2.3 whose behaviour was hydrologically independent from the other sub-basins in the considered historical event. In fact they reported observed flooded areas with volume of 41,000 and 7,465 m^3 (see Table 4) without any contribution from (nor into) other sub-basins. Moreover, both sub-basins are characterized by the presence of soils belonging to only two classes of permeability: Group B and Group D. The hydrological behaviour of all other basins is not independent on each other provided that the basin of Leverano produced overflow into sub-basin n. 1 as well as, sub-basins n.1 and n. 2.1 toward basin n. 3. Thus the parameters k and f_o of Group A and Group C were obtained by considering that: (i) runoff exceeded the storage capacity of the basin of Leverano characterized by presence all SCS Groups; (ii) runoff exceeded the storage capacity of the sub-basin n. 2.1 characterized only by Groups C and D; (iii) sub-basin n. 1, characterized by Groups A, B and C received overflow from the basin of Leverano and also exceeded the proper sink threshold with overflow into sub-basin n.3; (iv) sub-basin n. 3, characterized by Groups B, C and D, received overflows from sub-basin n. 1 and n. 2.1 and reached a stored volume of about 200,000 m^{3}well below its full capacity.

Table 3
Calibrated values of parameters f_o and k for different SCS groups.

SCS group	f_o [mm/h]	k [min]
A	302.50	50
B	242.00	40
C	151.25	30
D	91.96	20

Table 4
Hydraulic features of lowland sinks.

Sub-basin	Discharge capacity of swallow holes (m^3/s)	Storage capacity V_S (m^3)	Runoff stored on event of 11/13/2004 (m^3)	Runoff volume with $T = 30$ years (m^3)
Leverano	–	500,000	500,000	72,000
1	0.1	450,000	450,000	150,000
2.1	–	165,000	165,000	33,000
2.2	–	1320,000	41,000	13,000
2.3	–	55,000	7,465	1,078
3	0.6	530,000	200,000	37,000

3.3. Evaluation of flood-prone areas for assigned return period (sub-task 2.2 and task 3)

Following model calibration, the map of flood-prone areas for given return period was obtained after evaluating the flood volume. The latter was obtained finding the critical rainfall duration which maximizes runoff volume (Fig. 10b).

The rainfall intensity–duration–frequency (IDF) curve was estimated by regional analysis of the annual maxima of rainfall intensity performed with probabilistic model based on the use of a Two Component Extreme Value Distribution (Rossi et al., 1984), Maximum Likelihood estimator and hierarchical estimation of regional model parameters (Fiorentino et al., 1987). In particular, the IDF curve with return period of 30 years is (Castorani and Iacobellis, 2001):

$$i = 67.4t^{-0.822} \tag{5}$$

where i is rainfall intensity (in mm/hours) and t is duration (in hours).

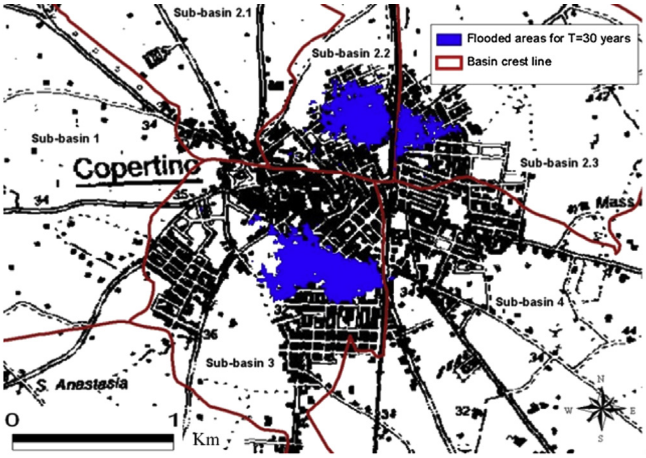

Fig. 11. Flood-prone area for $T = 30$ years in sub-basins 2.2, 2.3 and 3.

According to the observed behaviour of the Copertino basin during the rainfall event of November 2004, we referred to rainfall intensity for duration ranging between 0.5 and 24 h. Then we evaluated the critical duration and the correspondent maximum value of the flood volume. For a return time of 30 years we obtained the flood volumes reported in Table 4.

The above values were obtained considering rainfall events characterized by constant intensity (as in Fig. 3). Values slightly different from those above reported were obtained by using different design hyetographs and for this reason we do not present the relative values.

By means of the depth-volume curve (Fig. 10a) we found the flood depth corresponding to the flood volume and with available DEM we found the areas covering volumes corresponding to those reported in Table 4. In Fig. 11 we show areas subject to flood risk, with return time 30 years, in sub-basins 2.2, 2.3 and 3 that involve flooding of urban areas. A safety factor of 0.3 m was summed to the relative heights in order to individuate the areas prone to flooding for return period of 30 years. Adopting the safe factor above mentioned we found areas with extension very close to those observed in the event of November 2004.

4. Final remarks

We propose a methodology for the assessment of flood-prone areas, suited for a semi-arid, karst environment in Southern Italy. In particular we focused on the individuation of the critical rainfall of assigned return period producing the design flood event.

In this framework a detailed geomorphological analysis is needed in order to assess if there is chance to overflow from one sub-basin to another considering that, depending on the intensity and duration of the rainfall event, the drainage area may change with strong non-linearity.

In such a case the overall behaviour of adjacent endorheic basins can be assimilated to multiple reservoirs whose flooded area depends on the geomorphology of the lowlands and on the volume of surface stored water. Hence we searched for the critical rainfall event duration as the one that produces the maximum water volume (not the maximum discharge) for assigned return period.

We used a simple semi-distributed hydrological model which is composed by two classical modules: the first one uses the Horton infiltration model and evaluates runoff; the second one uses a simple routing scheme and allows for the individuation of the critical flood hydrograph.

The most difficult task is provided by the calibration of the hydrological model due to the absence of continuous measurements of discharge. In particular, the model parameters were calibrated in order to reproduce a runoff volume equal to the volume of water stored in the observed flooded areas. For such a purpose we used a digital elevation model (DEM) of the basin with scale 1:5000. The same DEM was improved by means of a dense sample of elevation measurements of the flooded areas.

In the process of parameters calibration, we kept handbook values of the asymptotic infiltration rate f_c of the Horton equation and changed the parameters k and f_0 that depend on the antecedent moisture condition.

We used the SCS-CN soil classification for model parameterization but we did not use the SCS-CN method because we found it unsuitable for these areas. In fact the SCS-CN method, originally developed by the US Department of Agriculture Soil Conservation Service and documented in detail in the National Engineering Handbook (SCS, 1972), is based on the assumption that:

$$\frac{V}{(P - I_a)} = \frac{F}{S} \tag{6}$$

where V is runoff volume, P is rainfall volume, I_a is initial absorption, F is real infiltration volume and S is potential maximum soil moisture retention after runoff begins. Following Equation (6), the SCS-CN method provides that, when soil reaches saturation (i.e. $F = S$), runoff (V) is equal to rainfall (P) minus initial adsorption I_a. In other words, as also shown in Fig. 12, the SCS-CN method produces an infiltration rate that, in time during the rainfall event, always tends asymptotically to zero. This kind of behaviour is physically unconsistent in karst areas where the asymptotic infiltration rate

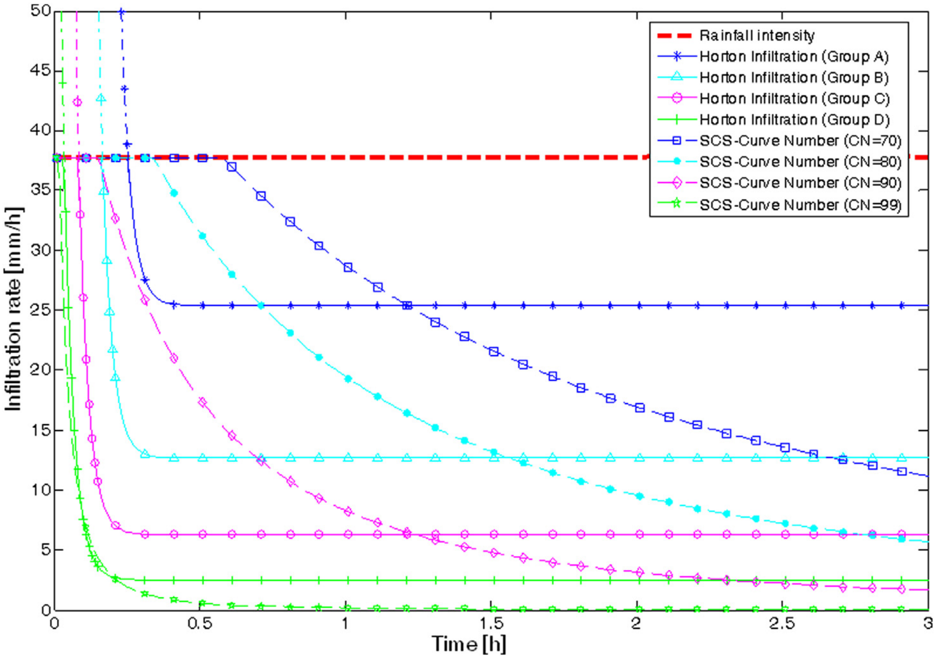

Fig. 12. Comparison between patterns of the Horton and SCS-CN infiltration rates, in time, during a rainfall event of 3 h, obtained for a rainfall event of $T = 200$ years.

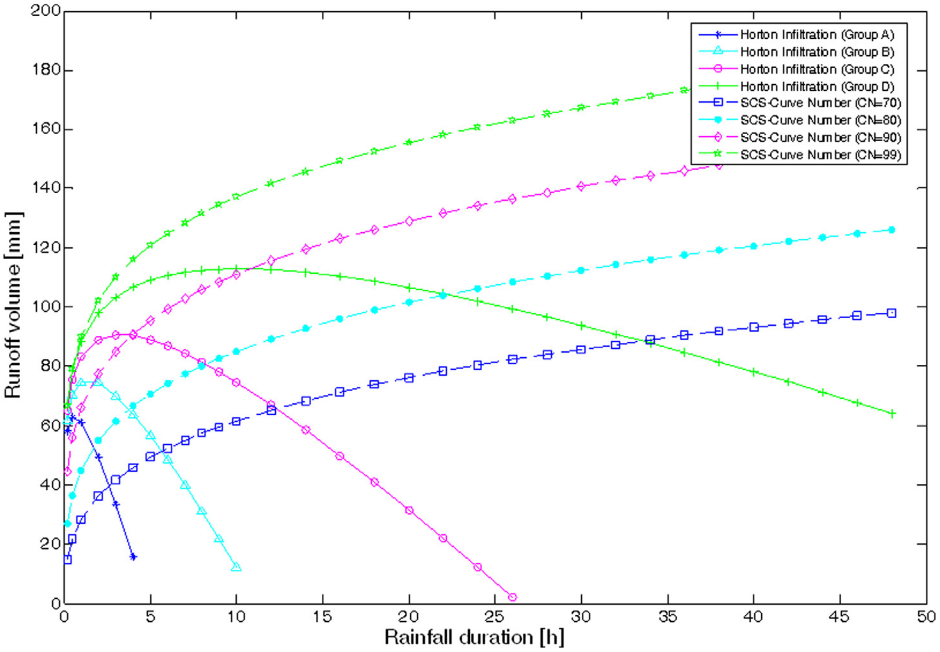

Fig. 13. Comparison between Horton and SCS-CN runoff volume curves obtained for rainfall events of $T = 200$ years and different rainfall durations.

can be very high and always plays an important role. On the other hand, as a consequence of a null asymptotic infiltration rate, the proposed procedure that aims to find the maximum runoff volume, would not be applicable. In fact, as shown in Fig. 13, when using the SCS-CN the volume of runoff diverges and the maximum does not exist for any rainfall duration. Nevertheless the direct observation of the real processes confirms that critical rainfall values exist and are found in the range of duration between 1 and 24 h.

The most important findings from this paper can be summarised by the following statements:

- determining flood-prone areas in one endorheic basin needs a preliminary geomorphological analysis of surrounding areas in order to find the overall potential contributing basin to the flood-prone area;
- the effective overall contributing basin may change during a rainfall event, and may be different from event to event, depending on the event return period;
- accurate information about sinks, swallow holes, draining wells, terrain shape, soil permeability and drainage capacity is necessary to assess the hydrological behaviour of these areas;
- the critical rainfall event can be obtained by numerical analysis, searching within a suitable range of rainfall duration, as the one that maximizes the runoff volume in the flood-prone lowland accounting for the effective overall contributing basin;
- the use of parsimonious hydrological models and traditional assumptions, such as a space-time homogeneous rainfall field, is still admittable but, in principle, the use of different design hyetographs and/or different spatial rainfall patterns could be recommended;
- in order to model soil infiltration we used the traditional Horton model, other choices could be made nevertheless, we showed that the well known SCS-Curve Number method, which is probably today the foremost worldwide-accepted model in catchment hydrology, is not suitable for application to endorheic basins;
- time of runoff concentration and propagation is also crucial for model performances, especially if swallow holes and draining wells provide a significant drainage capacity;
- model assessment always has to include, as much as possible, elements for testing the model descriptive ability based on the comparison with real event observation.

Some more considerations can be made with reference to the relevance of such results for flood management and risk mitigation. In this paper, as we said in section 2, we have not developed the sub-tasks 2.3 devoted to real-time forecasting but most of the considerations we have made for long-term prediction may obviously affect (and lead to significant improvements of) the emergency procedures for civil protection. In particular:

- the entire modelling framework and the results of the case study suggest that particular attention has to be paid also to prolonged rainfall of medium intensity that could trigger flooding of minor consistency (i.e.: water depth less than 50 cm) and produce high risk affecting urban areas, traffic roads or streets connecting important centres such as hospitals, schools, etc;
- a now-casting system could significantly benefit from the observation of weir points where the overflow from basin to basin may occur;
- continuous and careful maintenance of the largest swallow holes is also a crucial point. In fact, preserving their discharge capacity and increasing the runoff volume that could be stored in their proximity, in extra-urban areas, could sensibly decrease the flood risk.

Finally, more insights about model performance and sensitivity to parameterization will be objective of future research. In particular, the role of velocity in flow routing, the identification of CN group soil, the antecedent moisture condition, to mention some of the key parameters of the hydrological model, deserve specific investigation in order to evaluate prediction uncertainty.

Acknowledgements

The authors are grateful to the Servizio Idrografico e Mareografico, Regione Puglia, for providing the Copertino rainfall record and to local authorities responsible for civil protection of Comune di Copertino. The authors acknowledge the editor support and the constructive comments and suggestions provided by anonymous reviewers.

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