HYDROLOGICAL PROCESSES
Hydrol. Process. **26**, 1478–1494 (2012)
Published online 16 September 2011 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/hyp.8272

Development of a thresholds approach for real-time flash flood prediction in complex geomorphological river basins

Nektarios N. Kourgialas, George P. Karatzas* and Nikolaos P. Nikolaidis
Department of Environmental Engineering - Technical University of Crete, Polytechneioupolis, 73100 Chania, Greece

Abstract:

Flash floods represent one of the deadliest and costliest natural disasters worldwide. The hydrological analysis of a flash flood event contributes in the understanding of the runoff creation process. This study presents the analysis of some flash flood events that took place in a complex geomorphological Mediterranean River basin. The objective of the present work is to develop the thresholds for a real-time flash flood forecasting model in a complex geomorphological watershed, based on high-frequency data from strategically located hydrological and meteorological telemetric stations. These stations provide hourly real-time data which were used to determine hydrological and meteorological parameters. The main characteristics of various hydrographs specified in this study were the runoff coefficients, lag time, time to peak, and the maximum potential retention. The estimation of these hydrometeorological parameters provides the necessary information in order to successfully manage flash floods events. Especially, the time to peak is the most significant hydrological parameter that affects the response time of an oncoming flash flood event. A study of the above parameters is essential for the specification of thresholds which are related to the geomorphological characteristics of the river basin, the rainfall accumulation of an event, the rainfall intensity, the threshold runoff through karstic area, the season during which the rainfall takes place and the time intervals between the rainstorms that affect the soil moisture conditions. All these factors are combined into a real-time-threshold flash flood prediction model. Historical flash flood events at the downstream are also used for the validation of the model. An application of the proposed model is presented for the Koiliaris River basin in Crete, Greece.

KEY WORDS flash floods; flash flood prediction; hydrographs; karstic areas; rainfall thresholds; soil conditions

Received 22 February 2011; Accepted 28 June 2011

INTRODUCTION

Floods that emanate from overflow river systems vary considerably regarding their magnitude and duration. In the case of large rivers, floods can occur long after the rainfall and last for days, weeks, or even months. In small river basins, which exhibit intense topography with thin and impenetrable soil, flash floods can also appear (Georgakakos, 1986). A flash flood is defined as a flood which follows shortly—within a few hours—after a heavy or excessive rainfall event. Flash floods can also occur due to rapid snow melting. The karst flash flood is a special kind of flash flood related to the structure and hydraulic properties of a karstic system and has been identified as one of the hazards in karstic terrains. The majority of the karst flash floods appear in arid and semi-arid areas (Marechal *et al*., 2008). The combination of basin characteristics, such as sparse vegetation, thin rock soils and steep slopes, and intensive short-term precipitation can create sharp peaks and narrow hydrographs with short time lags (Bonacci *et al*., 2006). In the Mediterranean area, where ephemeral streams are common fluvial systems, rainfall and runoff processes play a significant role in the generation of the flash floods (Camarasa Belmonte and Segura Beltran, 2001). Flash flood peaks are less anticipated than typical flood events and can cause extensive destruction, particularly when intense rainfall causes landslides (Lin, 1999). Flash flood water moves at very high speeds and can roll boulders, tear out trees, destroy buildings and constructions, and affect human lives. In flash floods, the sediment yield of individual events is large, but the small number of flash floods limits the mean annual sediment yield to low values in arid environments (Cohen and Laronne, 2005). According to Archer (1992), the flash flood can be considered as a wall of water that could have a height up to 6 m. Since flash floods happen suddenly and in most cases with minimal warning they are particularly dangerous.

Over the past decade, there have been an increasing number of flash flood events in many parts of the world, including the US, the European Union, and Australia (Hapuarachchi *et al*., 2011). For instance, the International Emergency Disasters Database (EM-DAT) reported an extreme flash flood event with huge impact that influenced the Piedmont region in the northwest of Italy. This serious flash flood event took place during the time period of 14–22 October 2000, caused 25 human deaths, and a total economic loss of approximately 5,655,000 euros. In the island of Crete, Greece (Figure 1), 49 serious flash flood events were recorded by the Civil Protection Service Office of Crete Region for the period of

* Correspondence to: George P. Karatzas, Department of Environmental Engineering - Technical University of Crete, Polytechneioupolis, 73100 Chania, Greece. E-mail: karatzas@mred.tuc.gr

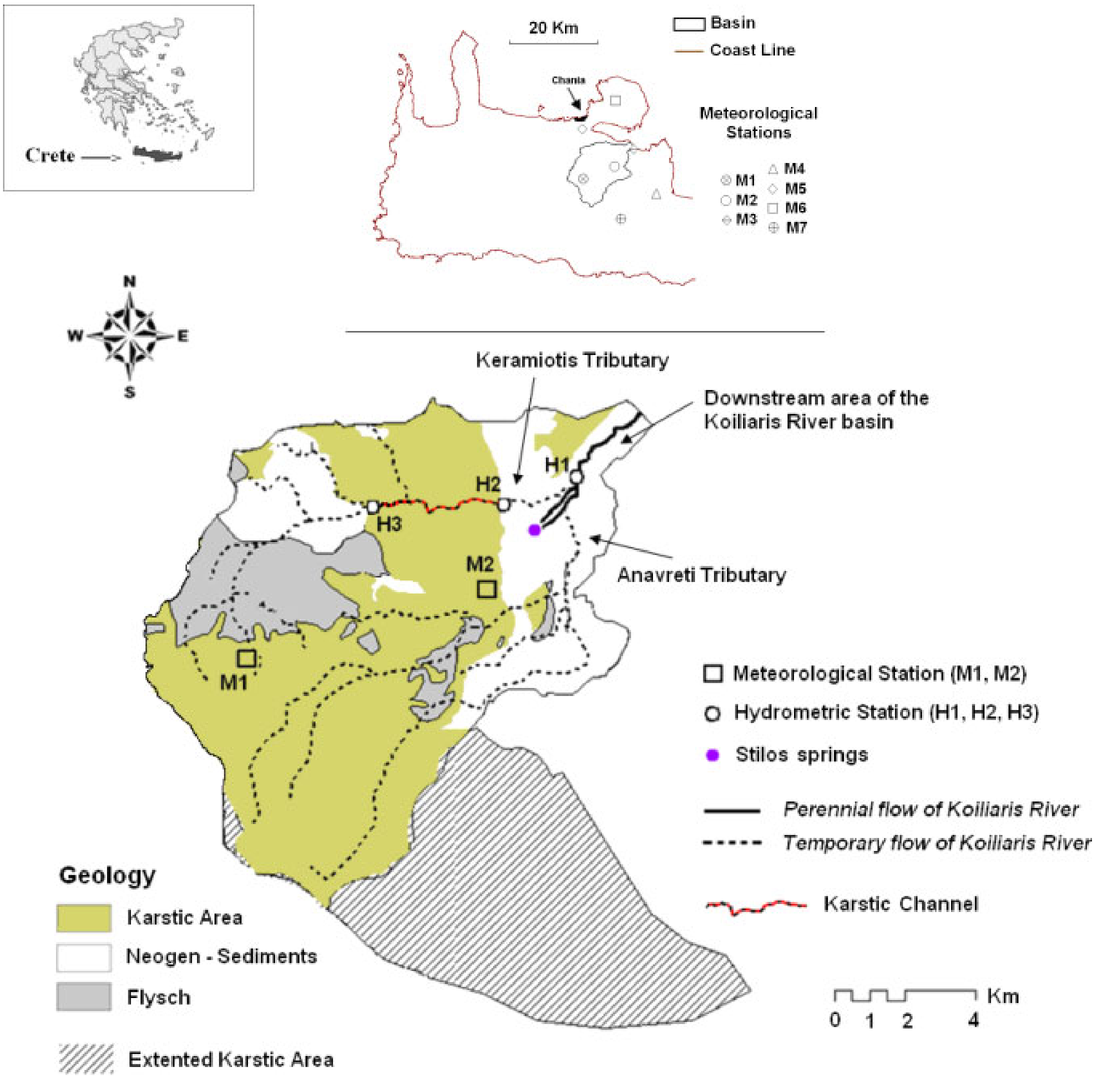

Figure 1. The geology and the hydrometeorological network of the Koiliaris River basin

1990–2007 (Koutroulis *et al*., 2010). On the basis of the Hellenic Agricultural Insurance Organization (ELGA) for this time period, the year 2000 was the most catastrophic one regarding flash flood damages. Specifically, on the island of Crete for that year the estimated total agricultural damage due to flash flood events was estimated to be 68,348,000 euros.

It is widely recognized that obtaining a reliable flood forecasting system is not an easy task, since rainfall is one of the most difficult elements of the hydrological cycle to forecast (French *et al*., 1992), and great uncertainties (due to initial conditions and numerical representation of the prediction equations) still affect the performances of both stochastic and deterministic rainfall prediction models. Interesting perspectives for the future are opened by numerical weather prediction models, but up to now they do not seem to be able to provide accurate rainfall forecasts at the temporal and spatial resolution required by many hydrologic applications (Brath, 1999). Weather radars can provide better spatial rainfall estimations. However, it has been demonstrated that the more intense the rainfall is, the less reliable the rainfall estimates from radar become (Younis *et al*., 2008). Basing on the above findings, the benefits from real-time precipitation data (meteorological station), in terms of efficiency of the flood forecast, are very important especially in small river basins (Toth *et al*., 2000; Kourgialas and Karatzas, 2011).

In general, a typical real-time flood forecasting system is based on a hydrological model, which requires a real-time series of hydro-information and a rainfall-runoff database to transform the flood forecast into a clear message of the oncoming flood danger. A flood warning system based on threshold levels can supplement the traditional flood forecasting systems. Specifically, the critical rainfall threshold levels provided by hydrologists, can be used by non-technical stakeholders as a simplified and quick recognition tool of an oncoming extreme flood event (Martina *et al*., 2006).

For an ungauged river basin, a method for predicting flash floods (called flash flood guidance) was developed by Georgakakos (2006). Flash flood guidance is a general term referring to the average rain required to fall over a specific area during a specific time in order to initiate localised and rapid flooding in small streams.

Depending on the method, several factors are considered such as: precipitation from the previous days, the channel inundation especially in case of a temporary river expanding and contracting due to variation in the flow. Thus, apart from the rainfall data the detailed knowledge of the parameters involved in the form of the hydrographs is very important. The key to flash flood forecasting is to quickly identify when a flash flood is above a predetermined threshold level, where a bankfull flash flood can occur. Hence, flash flood forecasting does not require a complex numerical model that requires high computational time (Lin, 1999). The main task is to define a rainfall threshold which can generate a flash flood peak equal to or higher than the flooding flow. This threshold depends on the amount and duration of the rainfall event, as well as the soil moisture conditions (Martina *et al.*, 2006; Norbiato *et al.*, 2008; Javelle *et al.*, 2010). After dry periods, high rainfall intensities occur that fall over crusted or poor soils and induce Horton-type overland flow causing a very fast response (Moraitis *et al.*, 2010). In case of karstic channels the above mentioned rainfall threshold is related to the rainfall amount which is able to exceed the transmission losses by the karstic channel.

Hydrological processes in a complex hydrogeological river basin are related to rivers—tributaries with temporary and permanent flow, high mountainous karstic areas, springs, downstream karstic areas, and karstic channel parts. In a complex geomorphological watershed consisting of karst formation, the area of the river basin should be defined not only by the surface morphology of the basin (topography), but also by the extended karst that contributes to the flow (Bakalowicz, 2005). This fact, in combination with the unexpected behaviour of flash floods is making the prediction and forecasting of flash floods an extremely difficult task. Wireless technology with high-frequency telemetric hydrometeorological data in real time, can be used for the prediction of forthcoming floods in such areas (Moraitis *et al.*, 2010).

Up to the present, limited studies have been presented in the area of the flash flood forecasting in such complex geomorphological areas (Yates *et al.*, 2000). Thus, the objective of this paper is the development of an integrated thresholds method for flash flood prediction in a complex geomorphological area. This method is based on three steps: (1) the determination and the analysis of the hydrometeorological parameters that affect the flash flood hydrographs, (2) the evaluation of the accumulated rainfall thresholds per time, and (3) the assessment of the antecedent soil moisture conditions. The developed threshold methodology could be used as an easy tool for flood risk managers (e.g. Civil Protection Service Office) without modelling knowledge in order to predict an oncoming flash flood event. The proposed real-time flash flood prediction methodology can be applied in any river basin, especially in small and complex geomorphological river basins where the respond time is limited. Moreover, the present study highlights the importance of the detailed knowledge of the present hydrogeological system; this information is crucial for the strategical space planning of a real-time hydrometeorological network. In this way, the uncertainty in the development of flash flood prediction methodology can be reduced remarkably. All these approaches are applied to the Koiliaris River basin in Crete, Greece.

STUDY AREA AND HYDROMETEOROLOGICAL NETWORK

The Koiliaris River basin is located 15 km east of the city of Chania, Crete. The basin extends from the White Mountains (Lefka Ori) to the coastline. The area of the basin has been estimated to be 130 km^2. The elevations of the basin range from 0 to 2120 m a.m.s.l. The total length of the hydrological network of the Koiliaris River is 36 km. The Koiliaris River basin consists of two tributaries; the main Keramiotis, and the second smaller stream, Anavreti (Figure 1). The Keramiotis tributary is a temporary river because it crosses a karstic gorge (channel). The length of the Koiliaris River from the intersection point (where all the streams meet) to the discharge point is 3·3 km. This part of the Koiliaris River receives a constant flow from the karstic springs of Stilos. The karstic area that is included in the basin (green region) and the estimated extended karstic area (shaded region) both contribute to the discharge of the Stilos springs (Kourgialas *et al.*, 2010), (Figure 1). Thus, a portion of the water measured at the hydrological station H3 discharges at the Stilos springs (through the karstic area), and the rest flows to the hydrological station H2. The topography of the area is variable with an average topographic slope of 12%. The geology of the basin is mainly constituted by carbonates, quaternary-neogenic deposits, and flysch formations. As for the land uses, rangeland accounts for 58% (101 km^2) of the total watershed area, cultivated areas cover 29·4% (51 km^2), urban areas 2·8% (5 km^2), forests 8·5% (14·8 km^2), and aquatic areas 0·6% (1 km^2). The downstream area of the watershed is agricultural with main produce being oranges, olive oil, and vegetables.

The continuous meteorological data for the time period of 1975–2009 were used to determine the rainfall gradient of the Koiliaris River basin with respect to altitude and time. These data were obtained from seven meteorological stations (M1–M7), in and out of the basin, as shown in Figure 1. Specifically, the data for meteorological stations (M3–M7), correspond to the time period of 1975–2009, while for the telemetric meteorological stations (M1, M2) from the time period of 2007–2009, since they were initialized in 2007. The hydrometric station (H1) was installed in 2004, and the hydrometric stations H2, H3 in 2007, all telemetric, for flood event monitoring (Figure 1). Hydrometric station H1 is located just downstream of the tributary intersection point, while hydrometric stations H2 and H3 are strategically located at the inflow and outflow points, respectively, of a karstic gorge (channel) (Figure 1). Meteorological stations M1 and M2 are located at 1000 and 400 m a.m.s.l., respectively (Figure 1).

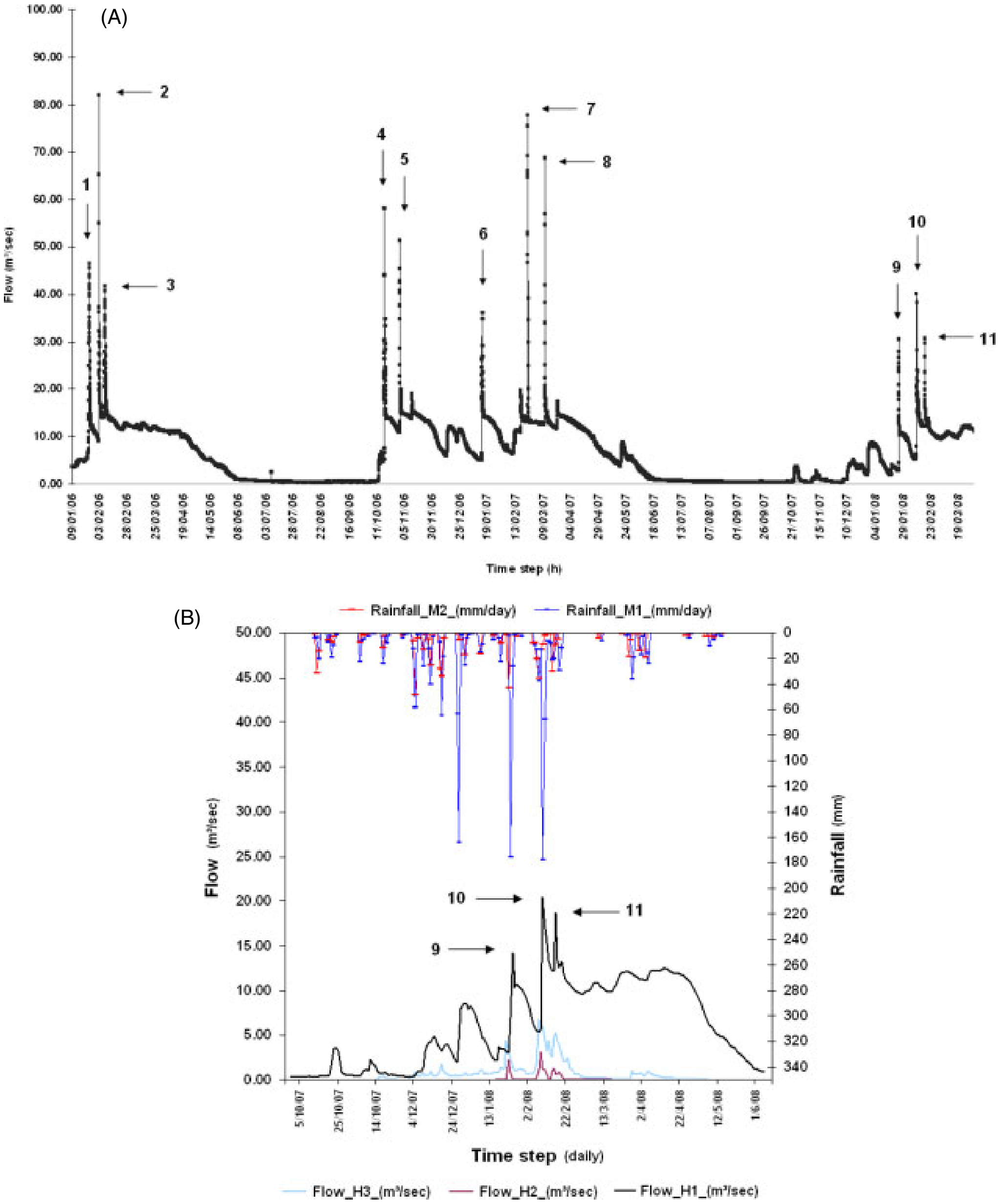

Figure 2. (A) The hourly flow data at station H1 and the 11 flash flood events; (B) The flash floods (9, 10, 11) and the corresponding daily hydrometrorological data from all stations

Stilos springs is the main discharge source in the Koiliaris River and the major discharge point of the karstic system of the White Mountains (Figure 1). On the basis of the authors' previous work, the total flow at the exit point of the basin outlet was estimated to be 136·29 million m^3/year. From this, 80% was contributed by the karstic flow through Stilos springs, while the net contribution of watershed flow (Keramiotis and Anavreti tributaries) to the river was only 20% of the total flow (Kourgialas *et al.*, 2010). The river hydrograph was characterized by peaks of quick and slow response. The quick response was mainly due to surface runoff and the slow response due to springs flow recession (Figure 2(A) and (B)), (Moraitis *et al.*, 2010). According to Figure 2(A), the river hydrograph is characterized by a series of flash floods peaks. These sharp peaks are mainly attributed to Keramiotis tributary during the rainy season (Kourgialas *et al.*, 2010; Moraitis *et al.*, 2010). The flood wave is generated in the upstream non-karst watershed and travels to the karstic area. Hydrometric station H3 reports the hydrological data of the upstream non-karst watershed, and station H2 the data of the downstream karstic area (Figure 1).

During the last 30 years, many extreme flash flood events have occurred in the basin, especially in the downstream area (Hydrometric station H1). Some of these flood events have been reported by the local authorities, but no flow data are available before the year 2004 since the first hydrometric station (H1) was installed during that year. Basing on historical data, the 5 overbank flash flood events that have been reported before 2004 are: (i) on 27 March 1988, (ii) on 7 December 2000, (iii) on 4 November 2001, (iv) on 10 December 2001, and (v) on 12 February 2003. The above historical extreme flash floods caused severe and extended damages in properties and constructions.

METHODOLOGY

Hydrograph analysis

The information related to flash flood events in the Koiliaris River basin is based on data collected at the three hydrometric stations and on the analysis of the obtained hydrographs. In many of the flash flood studies presented in the past the hydrograph analysis has been based on daily data (Camarasa Belmonte and Segura Beltran, 2001; Rusjan *et al.*, 2009). However, daily data are sufficient for a detailed flash flood analysis only in case of long-time databases (many decades). For this reason, hourly rainfall and hydrological data were used for the flash flood analysis in the present study. The hourly flow data from hydrometric station H1 for the time period of 1 September 2006–31 May 2008 are shown in Figure 2(A). Eleven flash flood events appear in this figure. The highest flash flood event was recorded on 4 February 2006 (flash flood event 2). During this flood event the hourly flow reached 83 m^3/s.

The main meteorological and hydrological parameters considered in this work were the accumulated value of the rainfall that generates the flood, the rainfall duration, the maximum discharge value and water level of the flood event, the runoff coefficients, the lag, the time to peak, and the maximum potential retention. The majority of these parameters are recorded directly from the stations (meteorological or hydrometric). However, parameters such as the runoff coefficients (C), the time to peak (t_p), the lag time (t_l), and the maximum potential retention (S) are specified from the final form of the hydrographs and the geomorphological characteristics of the river basin (Viessman *et al.*, 1989; Green and Nelson, 2002).

The most important factors in the creation of a flash flood event in a small river basin with complex geomorphology are the rainfall intensity and the total volume of rainfall and the soil conditions before the rainfall event (Camarasa Belmonte and Segura Beltran, 2001; Carmi and Berliner, 2008). Basing on this, parameters that describe the geomorphological characteristics of the river basin and the general characteristics of the rainfall can affect the final shape of the hydrograph peaks. The preliminary hydrographic analysis in a threshold flash flood forecasting system is necessary in order to establish some initial river assessment values as warning levels. Specifically, based on hydrographic analysis, some parameters such as the flow peak, the direct flow, and the available time for responding (beginning of the rainfall until the threshold is exceeded), can be determined. In this work, the developed flash flood thresholds model was based on the determination of the basic hydrometeorological parameters, with emphasis to the time to peak. The proposed flash flood prediction model is presented in the following sections.

Development of a threshold flash flood prediction model for complex geomorphological river basins

In order to develop a flash flood forecasting model applied to complex basins it is important to make some assumptions that simplify the proposed methodology:

A. In a complex river system, where more than one tributary exists (as in our case), one could determine that which is mainly responsible for the flash flood events by estimating the kinetic energy and sediment yield transfer of each tributary. Specifically, for each tributary, two parameters are computed and compared: (i) stream power, and (ii) sediment yield. These parameters characterize flash flood waves of high velocities and high rates of sediment transport that cause severe damage. The stream power is the product of discharge and energy slope and can be defined as the rate of energy supply at the channel bed which is available for overcoming friction and transporting sediment (McEwen, 1994).
B. For a better estimation of the water volume flowing to the river, the meteorological data should be selected at a station that is located in the upstream area of the selected tributary and is adjacent to its source of water supply. Also, the time to peak of a flash flood event in the downstream area should be sufficient in order to minimize the damages. Finally, it is important that the selected meteorological station records the data in a real-time basis.

In the present study, the Koiliaris River has two tributaries: the main Keramiotis, and the smaller stream, Anavreti. For these two tributaries, the stream power and the sediment yield (including the mean sediment concentration) were computed for all flash flood events, using the stream power equation and the Hillslope Erosion Model as they were presented by Petit *et al.*, 2005 and Wilson *et al.*, 2001, respectively. On the basis of the above, the Keramiotis tributary appears to have higher kinetic energy and sediment yield transfer compared, on average of 25–30%, in comparison to the Anavreti, for all the studied flash flood events. Thus, the Keramiotis tributary is considered as the one that is most responsible for flash flood events. The meteorological station M1 was selected as the one that is located in the upstream area of Keramiotis and is adjacent to its source of water supply. Moreover, the meteorological station M1 is located in the karstic area of White Mountains that contributes to the discharge of Stilos springs and provides the necessary rainfall information that affects the flow in Keramiotis tributary and the discharge of Stilos springs. All data from stations M1 and M2 are recorded on a real-time basis in a central computer system at the Technical University of Crete, Department of Environmental Engineering.

Flooding flow prediction. For the flash flood prediction model it is essential to define the flooding flow (bankfull discharge) in a river, i.e. the river flow when the banks are completely covered with water (Carpenter *et al.*, 1999). Flows equal to or higher than the flooding flow can cause small or large destructions (infrastructures, agriculture) and human losses. For the study area, the flooding flow was related to the one at hydrometric station H1 (downstream area). In order to assess the flooding flow using stage records at a gauged site, the water level–discharge relationship (rating curve) can be employed. However, the rating curve reliability depends on the availability of high stage velocity measurements which in many cases are very difficult to be performed (Moramarco *et al.*, 2004),

In order to determine the flooding flow two techniques can be applied: (1) Rating curve technique. The rating curve (H (water level) *vs* Q (flow discharge)) represents the hydraulic behaviour of the river channel at a given section. (2) Empirical technique. This technique is mainly applied in cases where measurements of H and Q are not available or are of low precision due to the difficulties of taking them at high levels and high water velocities. In this technique, the bankfull discharge is computed from channel geometry and roughness characteristics using empirical equations (Carpenter *et al.*, 1999).

The next step of the present study was to relate the bankfull flow at station H1 (downstream area) to the river flow at station H2 (exit point of the karstic channel). The purpose of this was an attempt to have an earlier 'alert' for an upcoming flood event in the downstream area. In a previous authors' work (Kourgialas, *et al.*, 2008; Kourgialas, *et al.*, 2010), the hydrograph peaks recorded on an hourly basis at station H2 (Q_{H2}) can be computed using a linear regression equation, that relates the flow discharge peaks of stations H1 and H2, as follows:

$$Q_{H2} = 0{\cdot}378 \times Q_{H1} - 3{\cdot}48, \quad R^2 = 0{\cdot}82 \tag{1}$$

where

Q_{H2} = peak discharge at hydrometric station H2 (m^3/h),
Q_{H1} = peak discharge at hydrometric station H1 (m^3/h).

Linear regression was used considering that stations H1 and H2 are located relatively close and the difference between their peak flow values is due to the spring flow that is discharged in the upstream area of station H1. The reliability of the obtained results using Equation (1) is supported by three factors: (1) the existence of a four-year continuous and high-resolution hydrological monitoring of the behaviour of the springs, (2) the geological evidence of two types of karst in the area (Plakenkalt and Tripali limestones), and (3)the consistency in time of the response of this karstic system that contributes to the discharge of Stilos springs. For Q_{H1} equal to the flooding flow, Equation (1) yields the critical discharge at station H2, $Q_{crit} = Q_{H2}$. When the flow at hydrometric station H2 is higher than a critical flow, Q_{crit}, then the downstream area of the Koiliaris River basin is expected to have a flooding flow. The next step is to estimate the accumulated rainfall volume (at station M1) that can create the critical flow, Q_{crit}, at station H2.

The accumulated rainfall for a specific rainfall duration. In the karstic channel of the Keramiotis tributary, all the water in the beginning of a storm event disappears because of the high infiltration rate. The surface runoff commences only when a threshold soil absorption level (P_0) is reached, which is defined in karstic areas by the following mathematical relationships presented by Camarasa and Tilford (2002).

$$\sum Peff = 0 \quad \text{for} \quad \sum P \le P_0, \tag{2}$$

$$\sum Peff = \frac{\left(\sum P - P_0\right)^2}{\sum P + 4P_0} \quad \text{for} \quad \sum P > P_0, \tag{3}$$

$$i = \frac{\left(\sum P - P_0\right)^2}{t_R \times \left(\sum P + 4P_0\right)} \quad \text{for} \quad \sum P > P_0, \tag{4}$$

where

$\sum Peff$ = The effective rainfall (mm),
$\sum P$ = The accumulated rainfall from the beginning of the rainfall event (mm),
P_0 = The runoff threshold through karstic area (mm), and
i = The average effective rainfall intensity (mm/h).

Equation (4) is obtained by dividing both parts of Equation (3), by the duration of the effective rainfall, t_R.

Karst limestones have a high infiltration rate, while finer textures (silt, clay, and calcretes) favour surface runoff. The runoff thresholds vary significantly for different events in the same basin, depending on the season. Specifically, the coefficient P_0 appears to have a high value during winter, a moderate value during autumn and spring, and a low value during summer (Camarasa Belmonte and Segura Beltran, 2001). This behaviour is attributed to the type of rain and the behaviour of the soil. During summer, spring, and autumn, intense convective showers alter the soil structure rapidly, exceed the infiltration capacity, and generate Hortonian flows, while in winter, the rain is less intense but more persistent, and the system responds more gradually.

The quantification of the P_0 threshold term, below which no surface flow exists, determines the amount of rainfall, at station M1 necessary to create surface flow at station H2. The term P_0 can be estimated using the linear equation between accumulated rainfalls and the corresponding surface runoffs. In this work, the method of Osborn and Lane (1969) was applied. The method is based on the linear equation

$$Q = a \times P \pm b, \tag{5}$$

Where

Q = total runoff (m^3/s),
P = total precipitation (mm), and
a, b = arithmetic values, depending on the characteristics of the linear equation.

For $Q = 0$, Equation (5) determines the term P_0.

Herein, the runoff threshold term P_0, at the exit point of the karstic channel, was computed using the linear relation between the total rainfall (meteorological station M1) and the total surface runoff (hydrometric station H2). This linear relation was applied separately for the three seasons: autumn, winter, and spring. The summer season was not considered since there is no flow at station H2. Basing on the above findings, the variability of the system is embedded in the runoff threshold term P_0, where the coefficient of determination (R^2) of Equation (5) should have a value close to 1.

After the threshold term (P_0) is computed, in order to estimate the accumulated rainfall ($\sum P$), using Equation (4), the knowledge of the effective rainfall intensity (i) is needed. This can be computed as follows.

The mathematical expression relating the critical flow (Q_{crit}), at the exit point of the karstic channel (hydrometric station H2), with the effective rainfall intensity (i), is given by the following equation (Carpenter *et al.*, 1999).

$$Q_{crit} = \frac{2{\cdot}42 \times i \times t_R \times A}{\Pi^{0{\cdot}4} \times (1 - 0{\cdot}218 \times t_R/\Pi^{0{\cdot}4})}, \quad (6)$$

where the parameters Π in Equation (8) is defined as

$$\Pi = \frac{L^{2{\cdot}5}}{i \times A \times R_L \times \omega^{1{\cdot}5}}, \quad (7)$$

and ω in Equation (9) is

$$\omega = \frac{S_c^{0{\cdot}5}}{n \times B^{2/3}} \quad (8)$$

where

Q_{crit} = The critical flow (m^3/s) at hydrometric station H2 that can generate flooding flow in the downstream area of the Koiliaris River basin,
A = The drainage area (km^2),
t_R = The duration of effective rainfall (h),
L = The main stream length (Keramiotis tributary) (km),
i = The effective rainfall intensity (cm/h),
R_L = Horton's length ratio (dimensionless),
S_c = The local channel slope (dimensionless),
n = The Manning's roughness coefficient, and
B = The top width (m).

For the determination of the parameter R_L, the follow equation was employed (Tarboton, 1996).

$$R_L = \frac{L_w}{L_{w-1}} \quad (9)$$

where

L_w = the mean length of streams of the Keramiotis tributary (km), and
w = the stream order (measurement of branch of the Keramiotis tributary).

The parameter (w) can be calculated based on the system of Strahler number (a numerical measure of its branching complexity), (Strahler, 1952).

Combining Equations (6), (7), and (8) the following equation is obtained.

$$Q_{crit} \times \left(\frac{L^{2{\cdot}5}}{A \times R_L \times a^{1{\cdot}5}}\right)^{0{\cdot}4} - Q_{crit} \times 0{\cdot}218 \times t_R \times i^{0{\cdot}4} - 2{\cdot}42 \times i^{1{\cdot}4} \times t_R \times A = 0 \quad (10)$$

The effective rainfall intensity, i, for the different intervals times, t_R, can be determined by solving Equation (10) using numerical methods.

By substituting the three different values of P_0 (P_{0_Winter}, P_{0_Spring}, P_{0_Autumn}) in Equation (4), and the computed effective rainfall intensity, i, for times t_R = 0·5, 1, 2, 3, 4, ... 20 h, the total seasonal rainfall (ΣP_{Winter}, ΣP_{Spring}, ΣP_{Autumn}), at the meteorological station M1, was determined. As was mentioned earlier, these values are directly related to critical flow Q_{crit}, at station H2 for the three different seasons of winter, spring, and autumn. Thus, the highest permissible values (threshold) of accumulated rainfall for specific rainfall duration per season, above which it is very likely to have a bankfull flash flood phenomenon in the downstream area of the basin, can be specified.

The antecedent soil moisture conditions. Physical properties of the soil surface change significantly during rainfall (continuous or intermittent rainstorms). As a result of surface sealing the soil moisture, the infiltration rate and the soil roughness can change. The created soil crust on the upper zone of the soil has a catalytic role in these changes and is related directly to the soil moisture conditions. This soil crust can be generated in different degrees during continuous rainfall as well as during intermittent rainfall. Mainly in arid regions, the surface runoff is frequently generated as a result of the crust development on the soil surface. The soil crust is a thin layer of greater, higher shear strength, finer pores, and lower hydraulic conductivity than the underlying soil (Carmi and Berliner, 2008).

The generation of the soil crust can be affected by the rainstorm interval times. According to Fohrer *et al.*, (1999), the infiltration rate is higher in the beginning of each interval though the decrease of infiltration rate (due to pre-sealed conditions) is much steeper than during a continuous rainfall. Thus, in the case of continuous rainfall (short interval times between the rainstorms) even small amounts of rainfall can create fast and important surface runoff (Fohrer *et al.*, 1999).

Apart from that, the levelling effect of the raindrop impact is even more distinctive in rainstorms. This

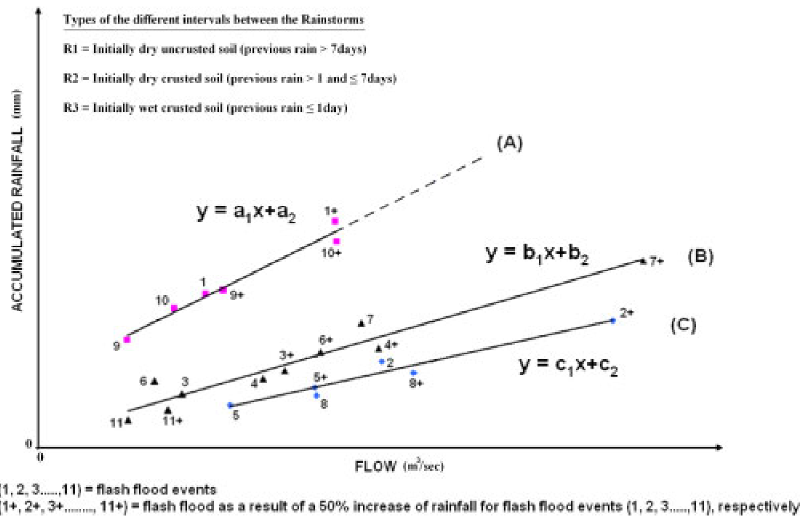

Figure 3. Accumulated rainfall *versus* the corresponding flow peaks, considering the antecedent soil moisture conditions

change in surface roughness could have an effect on runoff velocity, on transport capacity, and on the reduction of the lag time of a flash flood event. Basing on this, it is obvious that apart from the amount and the intensity of rainfall, the time interval between two successive rainfalls can play a significant role in the creation of crust in the surface soil. This crust can affect, positively, the generation of surface runoff and increase the flood danger.

Considering all the above, the 11 flash flood events (Figure 2(A)) were classified according to the interval time between the rainfall event that caused each flash flood and the immediately former one. As a result, three curves concerning the accumulated rainfall and the corresponding flow peaks for each flash flood were generated (Figure 3). The first curve (A) expresses the flash flood peaks that took place in dry uncrusted soil R1 (previous rain >7 days). This curve represents the flow peaks 1, 9, and 10. The second curve (B) expresses the flash flood peaks that took place in dry crusted soil R2 (previous rain >1 and ≤7 days). This curve represents the flow peaks 11, 6, 3, 4, and 7. The third curve (C) expresses the flash flood peaks that took place in wet crusted soil R3 (previous rain ≤1 day). This curve represents the flow peaks 5, 8, and 2.

In the above methodology, all the peaks of the 11 flash flood events that were used to develop the curves A, B, and C were below the bankfull discharge. In order to increase the accuracy in these curves it was considered that flash flood peaks of overbank flows must be included. These peaks of overbank flow can be created using the modelling framework based on the Hydrological Simulation Program—FORTRAN (HSPF)—for any geomorphological river basin. This framework for the Koiliaris River basin has been already calibrated and validated in previous work by the authors (Kourgialas *et al.*, 2008; Kourgialas *et al.*, 2010). The modelling framework based on the HSPF model can be used as a supplementary tool only for cases where limited flash flood peak data exist. The purpose of this study is the development of a simple threshold methodology for flash flood prediction and not the development of a flash flood forecasting system based on a complex hydrological model.

On the basis of the above, the 11 flash floods were simulated (a continuous simulation) considering a uniformly 50% hourly rainfall increase for each event. As a result 11 new flash flood peaks were generated denoted as (1+, 2+ ... 11+), as they are shown in Figure 3. The final three curves are shown in Figure 3. Considering the bankfull flow, at station H1, the rainfall thresholds related to the antecedent soil moisture conditions can be determined. The final step of the proposed methodology is the combination of the previously defined thresholds, that effect the generation of a flood event at the downstream area, (the accumulated rainfall for a specific rainfall duration and the antecedent soil moisture conditions), in an integrated graphic, in which the danger from an oncoming flash flood event can be predicted.

RESULTS AND DISCUSSION

Analysis of the output hydrographs

The discharge hydrograph analysis at the three gauged river sites, H1, H2, and H3, is presented in this section. The hydrologic analysis was performed using hourly data for flood events 9, 10, and 11 that occurred between 13 January 2008 and 13 March 2008 at each of the 3 hydrometric stations (Figure 2(B)). Overall, 9 flash floods were studied. Six of these flood events were recorded in the non-karstic area (data from stations H1 and H3) and 3 were at the exit point of the karstic channel (data from station H2). A rainfall data analysis related to these 9 flood events was also performed using the meteorological data of station M1.

Figure 4 shows the flood hydrographs of the 3 hydrometric stations for the flash flood event 9. The hourly rainfall data from the meteorological station M1 (indicated by the grey solid line) are also presented. In this figure, (A) and (C) show the hydrographs for stations

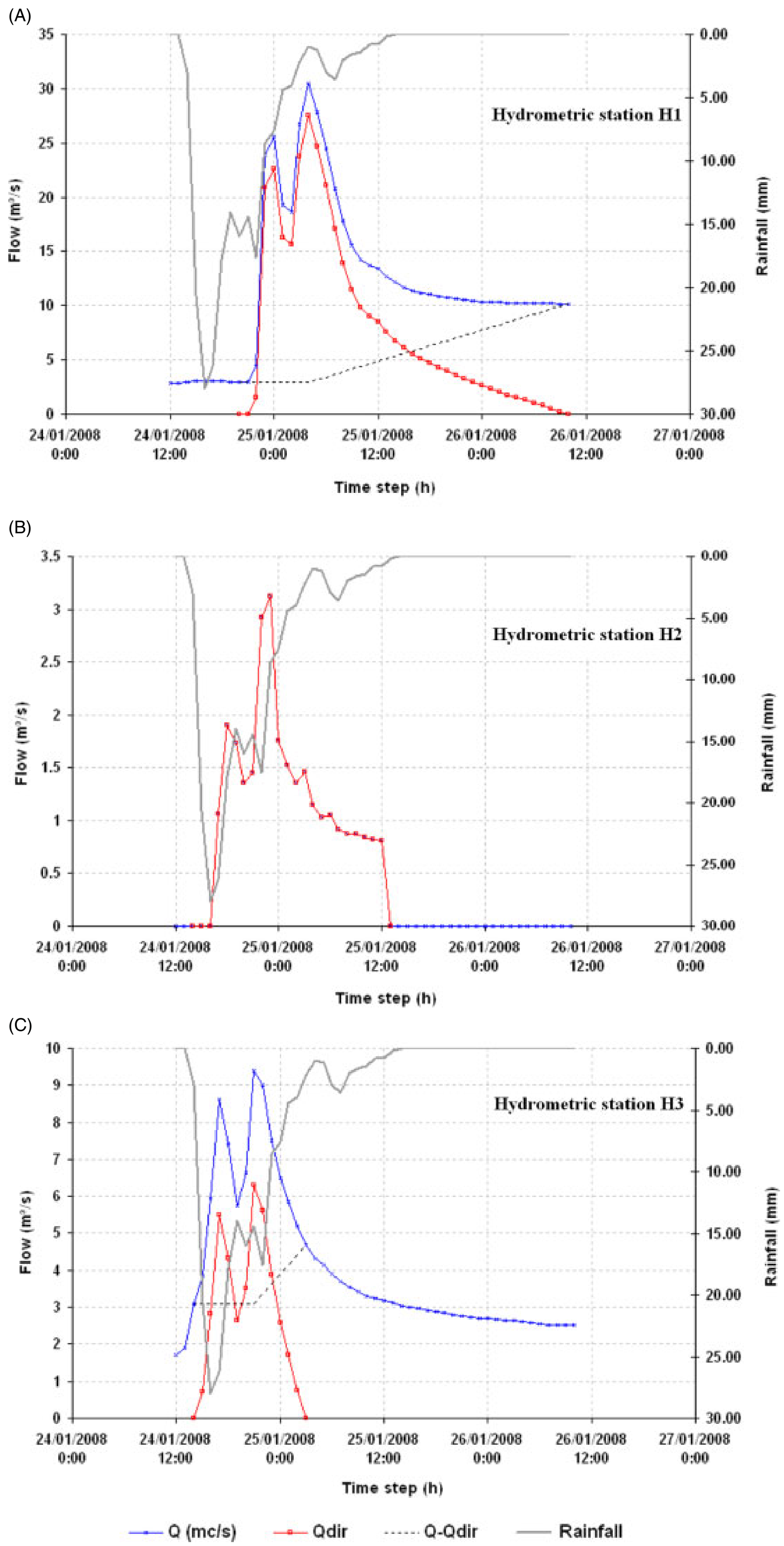

Figure 4. The hourly hydrographs for the three flood events at stations H1, H2, and H3 on 24–25 January 2008

H1 and H3 and represent the flash flood events at the non-karstic area, while (B) shows the hydrograph of station H2 that represents the flash flood event at the exit point of the karstic channel. The observed flow Q (indicated by the blue line), the direct flow Q_{dir} (indicated by the red solid line), and the basic flow $Q–Q_{dir}$ (indicated by the black dotted line) were graphically determined in all hydrographs. The direct flow was estimated using a hydrograph analysis based on the concave baseflow separation method (McCuen, 1989). Table I shows the rainfall characteristics for the three flood events at the meteorological station M1. The statistical parameters such as the average intensity, the standard deviation, the variance and the coefficient of variation of each rainfall event are also considered.

The flood wave has been increased downstream (station H1) due to the incoming flow from the two tributaries and the discharge from Stilos springs that are located upstream and close to station H1. Thus, the flash flood event that was recorded at station H1 represents the excess flow from the entire basin. Basing on Figure 4(A), the rising limb appeared to be abrupt and the recession limb lasted for a longer time. At the end of the flash flood event the base flow was much higher than at the beginning as a result of the delay and the discharge of accumulated water that was stored in the entire basin during the precipitation. In the same figure, (B) shows the hydrograph of a flash flood event recorded at station H2 which is relatively simple since there is no baseflow. The shape of this hydrograph was very sharp with a short base time, and steep rising and recession limbs, typical for karst flashy streams. Finally, (C) shows the flash flood hydrograph, obtained at station H3 where the rising limb was steep with almost the same duration as the recession limb. The hydrological parameters of the flood events obtained from the hydrograph analysis, are presented in Table I.

The flash flood that took place at station H2 has a lower maximum flood discharge than the other two stations (H1, H3). This is due to the combination of the high permeability of the karstic channel and the high value of the maximum potential retention of the karstic area (Table I). This results in the reduction of the flood wave travelling downstream. An interesting point is the runoff coefficient (defined as the ratio of the runoff volume to the rainfall volume), which for flash floods 9 and 10 is very low, while for flash flood 11, is very high and equal to 59·5%. The explanation of this phenomenon is attributed to the interval time between the rain that caused the flash flood event and the previous rainfall event. For flash floods 9 and 10 the interval time from the previous rainfall was very long, a fact that caused a high infiltration rate in the soil surface, while for flash flood 11 the interval time was very short, causing a low infiltration rate and a high runoff coefficient.

As shown in Table I, for all cases, the estimated time to peak (t_p), (obtained from a flood hydrograph analysis as the time from the beginning of the storm to the time when peak flow occurred), for station H1 is greater than 19 h, which can be considered as a sufficient time for the prediction and mitigation of an oncoming flood event in the downstream area of the Koiliaris River basin. It is obvious that the determination of the time to peak is very important for the flash flood prediction. For this reason, it will be useful to study the relationship between the time to peak (t_p) and the corresponding rainfall characteristics. Table I shows the rainfall characteristics that caused the three flash flood events. These rainfall events have different characteristics regarding the amount of rainfall, the duration and the average intensity. The rainfall that caused flash flood 9 had a large volume of rainfall, moderate duration, and very high intensity. The rainfall that caused flash flood 10 had a very large volume of rainfall, long duration, and moderate intensity. Lastly, the rainfall that caused flash flood event 11 had a small rainfall volume, short duration, and moderate intensity. On the basis of the above analysis, when the rainfall intensity is very high, the time to peak becomes shorter, while when the rainfall intensity is moderate or low, the time to peak is related directly to the duration of the rainfall.

The developed thresholds flash flood prediction model and the final results

As it was reported in the sub-section on 'Flooding flow prediction', the flooding flow can be estimated using two different techniques. In the present study, the first technique was used for the determination of the flooding flow in the hydrometric station H1. Using continuous measurements for high, moderate, and low flows, for the time period of 2004–2010, a two-part rating curve was defined (Kourgialas, 2010).

A. When the water level (H) at hydrometric station H1 is lower or equal to 0·4 m then the flow discharge (Q), is computed as

$$Q = 7 \times H^{2\cdot 1} \qquad (11)$$

B. When the water level (H) at hydrometric station H1 is higher than 0·4 m then the flow discharge (Q) is defined as

$$Q = 29\cdot 54 \times H - 10\cdot 782, \quad R^2 = 0\cdot 99 \qquad (12)$$

Equations (11) and (12) were used for various flow measurements during the seven year period (2004–2010). Moreover, the river bed at station H1 (cross-section) is stable, while the river banks are almost vertical and constructed by drystone walls. Basing on the above, the two-part rating curve is invariably up to bankfull flow for the station H1. Therefore, it can be used with accuracy for extreme flows as it is the flooding flow at this location.

On the basis of Equation (12), when the cross-section of the hydrometric station H1 is completely covered with water, the hydraulic depth is equal to 3·4 m, thus, the flooding flow Q_{flood} will be 92 m^3/s.

For a value of $Q_{(H1)} = 92$ m^3/sec, the surface flow (Q_{crit}) at the exit point of the karstic channel (hydrometric

Table I. The rainfall-hydrological characteristics for flood events 9, 10, and 11

Meteorological characteristics during flash lood event (Meteorological Station M1)	Flash flood 9			Flash flood 10			Flash flood 11		
Total mean rainfall (mm)	200			256·10			41		
Rainfall duration (h)	24			54			11		
Average intensity (mm/h)	8·33			4·57			3·15		
Max intensity (mm/h)	28			13·20			5·80		
Standard deviation (mm)	7·44			3·43			1·8		
Variance (mm^2)	55·35			11·76			3·24		
Coefficient of variation (%)	89·31			75·05			57·14		
Hydrological characteristics (Stations H1, H2, H3)	**H1**	**H2**	**H3**	**H1**	**H2**	**H3**	**H1**	**H2**	**H3**
River–Tributary	Koiliaris	Keramiotis	Keramiotis	Koiliaris	Keramiotis	Keramiotis	Koiliaris	Keramiotis	Keramiotis
Basin Area (km^2)	130	38·2	21·15	130	38·2	21·15	130	38·2	21·15
CN	60·58	55·52	64·44	60·58	55·52	64·44	60·58	55·52	64·44
S (maximum potential retention) (mm)	165·3	203·5	140·2	165·3	203·5	140·2	165·3	203·5	140·2
Total runoff depth (mm)	15·58	2·64	31·66	21·96	15·87	58·03	24·4	2·52	17·94
Direct runoff depth (mm)	8·64	2·64	6·88	8·61	7·17	12·58	2·63	2·52	7·62
Direct runoff depth (in 10^6 m^3)	1·12	0·1	0·15	1·12	0·27	0·27	0·36	0·1	0·16
Peak discharge (m^3/s)	30·5	3·1	9·4	40·1	21·6	23·5	30·8	9·2	15·8
Peak of direct discharge (m^3/s)	27·6	3·1	6·3	34·7	21·6	20·8	18·6	9·2	14·3
Peak water level (m)	0·86	0·55	0·8	1·1	0·85	1·55	1	0·2	0·4
Time to peak discharge	25/1/2008, 4·00	24/1/2008, 23·00	24/1/2008, 21·00	11/2/2008, 00·00	10/2/2008, 23·00	10/2/2008, 22·00	17/2/2008, 8·00	16/2/2008, 19·00	16/2/2008, 18·00
Runoff coefficient for total runoff	0·078	0·013	0·158	0·086	0·062	0·227	0·595	0·061	0·437
Runoff coefficient for direct runoff	0·043	0·013	0·034	0·034	0·028	0·050	0·064	0·061	0·186
Mq (Mass centre of direct discharge) (h)	20·7	14	9·2	34·6	25·9	24·3	39·4	13·4	11·8
Mp (Mass centre of direct mean rainfall) (h)	8·9	8·9	8·9	24·1	24·1	24·1	23·4	10·4	10·4
T (Time of direct runoff) (h)	37	20	13	48	6	23	27	4	8
t_l (Lag time (h)), [$t_l = Mq - Mp$]	11·7	5	0·3	10·5	1·8	0·1	16·1	3·0	1·4
t_p (Time to peak) (h)	19	8·33	7	25	24	20	21	9	8

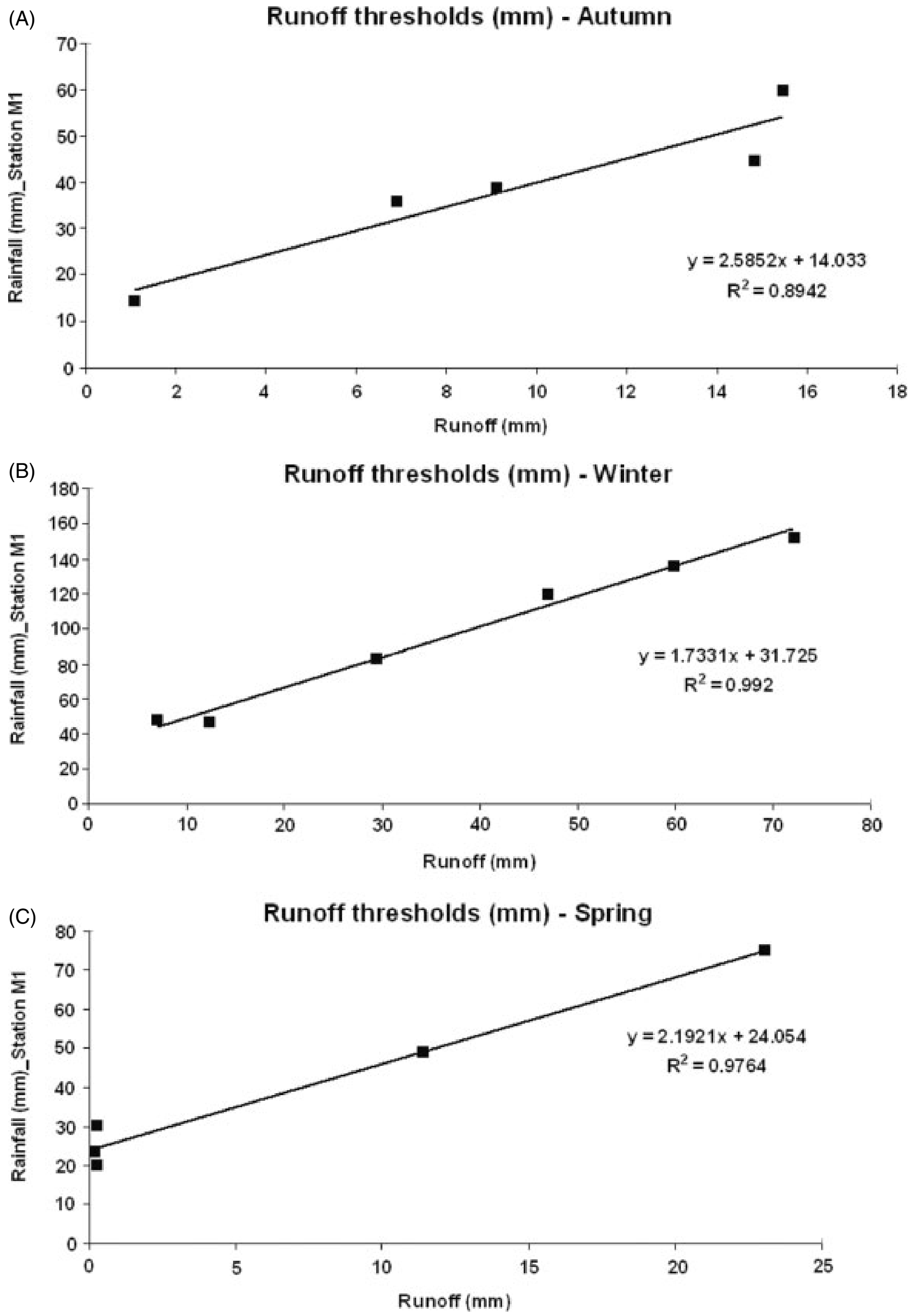

Figure 5. The determination of factor P_o for the three seasons (Autumn, Winter, Spring)

station H2) is $Q_{crit} = Q_{(H2)} = 31{\cdot}3$ m^3/s (Equation (1)). Thus, when the flow at hydrometric station H2 is higher than 31·3 m^3/s then the downstream area of the Koiliaris River basin is expected to have a flooding flow.

The quantification of the threshold soil absorption level P_0 was performed at the exit point of the karstic channel for the time period of 1 September 2006–31 August 2008. Using Equation (5) the linear relationship of total rainfall *versus* runoff is presented for each season in Figure 5. Basing on Figure 5, in order to have surface runoff at the exit point of the karstic channel in autumn, winter, and spring, the total height of rainfall has to be higher than or equal to: $P_{0\_Autumn} = 14$ mm, $P_{0\_Winter} = 31{\cdot}7$ mm, and $P_{0\_Spring} = 24{\cdot}1$ mm, respectively. The final graphical representation of the accumulated rainfall thresholds for a specific rainfall duration and season is presented in Figure 6(B).

For a bankfull flash flood of 92 m^3/s (hydrometric station H1), (Figure 6(A)), the maximum accumulated rainfall ($\sum P$) related to the antecedent soil moisture, above which a flash flood phenomenon can occur is: 505 mm for curve (A), 245 mm for curve (B), and 155 mm for curve (C). Figure 6(B) shows the combination of the thresholds results related to the accumulated rainfall and the antecedent soil moisture conditions for the flash flood prediction. Specifically, lines R1, R2, R3 show the maximum

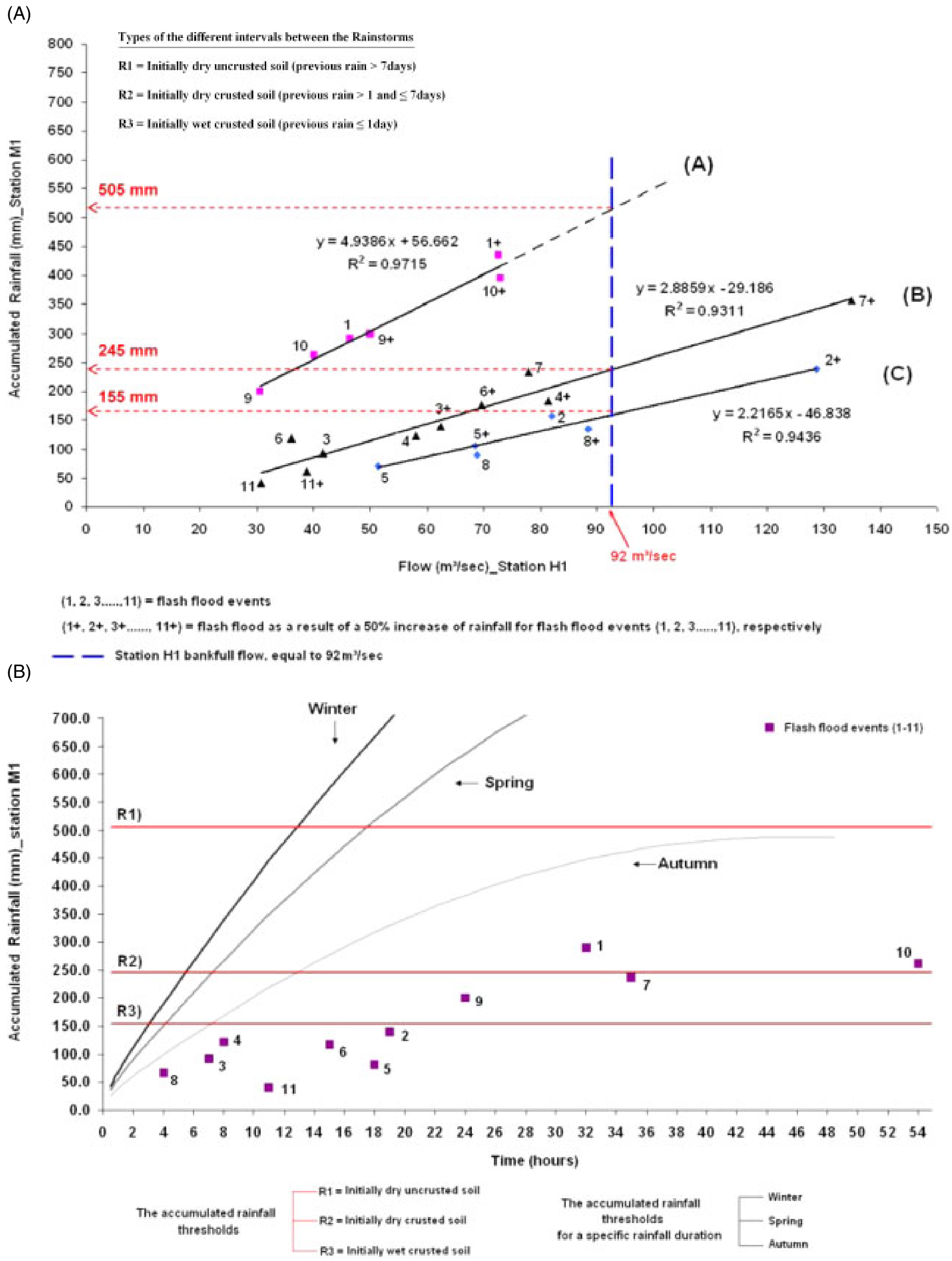

Figure 6. (A) A graphical representation of the accumulated rainfall (station M1) and the corresponding flow peaks (station H1) for each observed flash flood; (B) The graphical combination of the flash flood thresholds and the justification of flash floods (1–11) with the developed flash flood prediction model

permitted accumulated rainfall related to the antecedent soil moisture which are 505, 245, and 155 mm, representing the bankfull values of curves (A), (B), and (C), respectively. The curves, Winter, Spring and Autumn show the maximum permitted rainfall intensity related to the season and have been obtained using Equation (4).

Combining lines R1, R2, R3 with curves Winter, Spring, and Autumn, 9 combinations (R1–Winter, R2–Winter, R3–Winter, R1–Spring, R2–Spring, R3–Spring, R1–Autumn, R2–Autumn, and R3–Autumn) are created depending on the season and the time interval between the study rainfall and the previous rainfall. Thus, if a point is located inside the area, enclosed by the appropriate pair of curve-lines (thresholds), then the danger of an oncoming hazardous flash flood at hydrometric station H1 will be minimal (Figure 6(B)). Table II shows the rainfall characteristics of the 11 flash floods and the soil moisture conditions before the rainfalls. Using the data of Table II and Figure 6(B) the performance of the flash flood prediction model can be verified. For all the 11 flash flood events the model yields a correct prediction. Specifically, for flash flood events 2 and 7, during which

Table II. The rainfall characteristics and soil condition for the recorded flash flood events 1–11

Flash flood	1	2	3	4	5	6	7	8	9	10	11
Accumulated rainfall (mm)	290·6	140·0	93·2	122·5	80·9	117·8	237·6	67·0	200·0	256·1	41·0
Duration of rainfall (h)	32	19	7	8	18	15	35	4	24	54	11
Season	Winter	Winter	Winter	Autumn	Autumn	Winter	Winter	Spring	Winter	Winter	Winter
Antecedent soil moisture	R1	R3	R2	R2	R3	R2	R2	R3	R1	R1	R2

the hourly flow peaks were close enough to the bankfull flow, the proposed flash flood prediction model shows that their marks are located very close to the boundary of the area enclosed by the rainfall intensity–soil moisture curves (Figure 6(B)).

The validation of the developed model. The last step of the present study was the validation of the flash flood prediction model using field data for five historical flash flood events presented in the section on 'study area and hydrometeorological network' with flows over the bankfull at downstream area (cross-section of station H1). All field data were for flash flood events before the installation of the meteorological station M1 and the hydrological station H1. In order to overcome the lack of data at station M1, the hourly rainfall data (duration and accumulated rainfall) that caused the above extreme events were estimated using available data from the surrounding stations. The rainfall accumulated data at station M1 were estimated using the existing rainfall gradient for the Koiliaris River basin. As mentioned in the section on 'study area and hydrometeorological network', in order to determine the rainfall gradient of the Koiliaris River basin, the meteorological data from 7 meteorological stations, for the period of 1975–2009 were used. The developed rainfall gradient is

$$Y = 0{\cdot}7105 \times X + 578{\cdot}37, \quad R^2 = 0{\cdot}94 \tag{13}$$

where

Y = Accumulated rainfall (mm), and X = Elevation (m)

Basing on Equation (13), the missing rainfall characteristics at station M1 can be estimated for the 5 reported historical flash flood events, of the section. These 5 flood events were numbered as flood events 12 through 16. Table III presents the estimated accumulated rainfall values that caused the 5 extreme overbank flash flood events, as well as the soil moisture conditions before the rainfalls. Flash flood events 12–16 were used for the validation of the proposed flash flood prediction model. As is shown in Figure 7, the marks of all the extreme hydrological events are located outside the boundary of the area enclosed by the corresponding pair of rainfall intensity–soil moisture curves. For example, the most extreme reported flash flood event was event 15 and took place on 10 December 2001, causing severe and extended damages in properties and constructions. As is shown in Figure 7, the mark of event 15 is located far beyond the boundary of the area enclosed between the pair of line (R3) and Winter curve that characterized this event, which validates the proposed model. Similarly, the mark of the extreme flash flood event 16 that took place on 4 November 2001, is located outside the area that is enclosed between the appropriate pair of line, R2 and Autumn curve (Figure 7). The importance of point 16 is noted because it shows the benefit of the proposed methodology that combines two kinds of thresholds (the accumulated rainfall for a specific rainfall duration and the antecedent soil moisture conditions). For the specific case if we only use the rainfall threshold (R2), without considering the Autumn curve threshold, the specific overbank flood event would not have been classified as a bankfull flow. Also, if the rainfall threshold had not been considered and the same event had occurred during spring or winter then it would not have been classified as a bankfull flow event by the proposed methodology.

For the time period of 1 December 2008–15 March 2009 at hydrometric station H1, another high flash flood event (17) was recorded, but it was below the bankfull. This flash flood took place on 25 February 2009 at 19 : 00. The accumulated rainfall that caused this flash flood was 126·6 mm, the rainfall duration was 27 h, and the time between this event and the previous one was less than one day (Line (R3)). For an additional validation of the proposed flash flood prediction model the characteristics of flash flood event 17 were used. The rainfall characteristics of this specific flash flood are enclosed in the area between line R3 and the Winter curve. The peak discharge of flash flood 17 was 59·5 m^3/s, which is relatively close to the bankfull flash flood flow (92 m^3/s). Figure 7 shows the mark of flash flood 17, which appears to be close to, but below the red threshold line, R3.

The proposed flash flood threshold method can be transferable to any river basin according to the geomorphological characteristics of the area and the availability of field measurements. Specifically, the proposed method was designed to include several models which are combined to describe the entire hydrological process of flash flood generation in complex geomorphological environments where temporary and permanent tributaries, karstic terrains, springs, and karstic channels exist. In each case, all or some of these models can be used and adjusted appropriately in order to predict the flash flood event.

Flash flooding is a complex and inherently uncertain phenomenon with its forecast also uncertain. The uncertainty of a flash flood forecast has three main sources: (a) measurement uncertainty, (b) meteorological forecasting uncertainty, and (c) hydrological model uncertainty (Krzysztofowicz, 2001). The first source depends on the data quality, the second is affected by model

Table III. The rainfall characteristics and soil condition for the reported historical-overbank flash floods 12–16, and for the flash flood event 17

Flash flood	12	13	14	15	16	17
Accumulated rainfall (mm)	176·0	295·0	268·0	426·0	232·2	126·6
Duration of rainfall (h)	50	48	30	60	10	27
Season	Winter 12/2/2003	Spring 27/3/1988	Winter 07/12/2000	Winter 10/12/2001	Autumn 04/11/2001	Winter 25/2/2009
Antecedent soil moisture	R3	R3	R2	R3	R2	R3

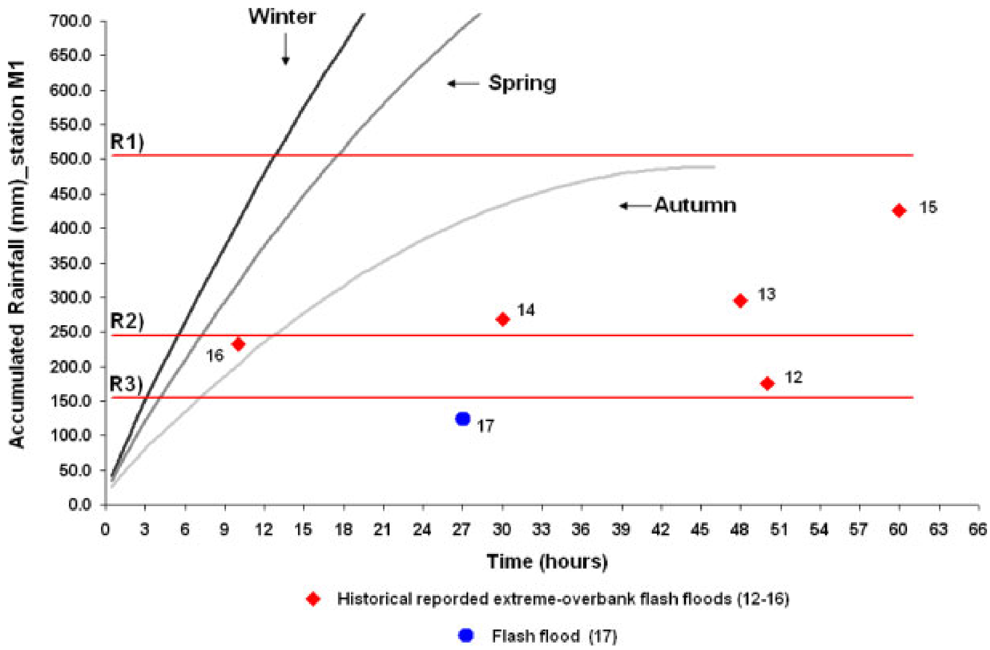

Figure 7. The validation of the proposed flash flood prediction model

uncertainty as well as data quality, and the third is more model-specific. Uncertainty estimates are important for decision making in flash flood warning. During the past two decades, new methods have been introduced to estimate the forecast uncertainty (Beven and Binley, 1992; Krzysztofowicz, 1999) and for making probabilistic forecasts (Krzysztofowicz, 2002; Ntelekos *et al*., 2006; Chen and Yu, 2007). On the basis of these studies, the largest source of uncertainty in quantitative flash flood forecasting is errors in the rainfall field.

The proposed methodology for real-time flash flood prediction in a complex hydrogeological system is capturing the processes operating in the basin using different methods such as measurements indices, regression models, and conceptual threshold approaches. The underlying principle in developing threshold methodology for real-time flash flood prediction was based on high-resolution field data collected at points within the watershed where the intersection of geologic and morphologic systems occur. Each conceptual model of the proposed methodology was calibrated with a unique hydrologic dataset in order to capture the hydrologic variability of the response of the system. The calibration and validation flood datasets that were selected for the present study represent different and extreme hydrological conditions to ensure that we get the right answers for the right reasons (Kirchner, 2006; Brocca *et al*., 2011). This approach was used in order to minimize the uncertainty inherent in the results and establish evidence for the uniqueness of the proposed parameterisation. The historical flood databases used in this study for a 35-year time period (1975–2010), obtained from the Civil Protection Service Office of Crete Region, capture the most extreme hydrological events in the island of Crete in the last century.

On the basis of the above, the combined uncertainty in the proposed threshold methodology for the Koiliaris River basin is small enough due to: (a) the small size of the basin, (b) the short distance between the meteorological stations, (c) the availability of real-time measurements, (d) the reliability of the rainfall gradient exhibiting a very strong correlation coefficient, (e) the satisfactory calibration and validation process, and (f) the detailed knowledge of the hydrogeological system that generates the flash flood events and can lead to the establishment of a strategically located real-time hydrometeorological network. By whatever means, the continuation of hydrological monitoring in the study area in the future is necessary to ensure the low level of uncertainty in the flash flood prediction. It is obvious that a good uncertainty estimate of flash flood forecasts adds credibility to the forecast system. However, the development of methodologies capable of incorporating flash flood forecast uncertainty into the decision-making process remains a major challenge.

CONCLUSIONS

In the present work, a new approach is presented for the prediction of flash flood events. The developed model considers the quantity and duration of rainfall, the season during which the event takes place, and the time interval between the rainfall that causes the flood event and the previous rainfall. In the past, the hydrological behaviour of the Koiliaris River basin has been characterized by several flash flood events. Moreover, the existence of fractured and karstified substrates is responsible for specific flash floods at the exit point of the karstic channel. In this paper, the hydrological response of three hydrometric stations was studied for three specific floods using hydrograph analysis. In all cases, the hydrographs are very sharp, with steep rises and short lag times. According to the hydrographs, only a small part of the rainfall is converted to runoff, especially in the karstic area (hydrometric station H2) where the runoff coefficient was equal to 1·3% (flash flood 9). These high transmission losses along the karstic channel play a significant role to the prevention of a severe flood event in the downstream area (hydrometric station H1). In the absence of the karstic area in the middle of the Keramiotis tributary, the flood wave would increase the possibility of catastrophic flash floods in the downstream area of the Koiliaris River. Therefore, the determination of the main hydrometeorological parameters is very important for the management of flash flood events. In order to avoid a high flash flood event a flash flood threshold prediction model was proposed. The usefulness of this model is related directly to the time to peak of a flash flood event, at hydrometric station H1. In the present study, in all cases, the time to peak was more than 19 h, which is sufficient time to avoid the catastrophic effects of a flood. The proposed model was validated with six flash flood events of the Koiliaris River basin. The knowledge, in real time, of the above parameters of the flash flood prediction model and the combination of these, can be a useful tool to mitigate the high flash flood events in the downstream area of a complex geomorphological river basin.

Flash flood prediction methods are becoming more and more important nowadays because of the observed increase of hydrological extreme events. However, limited studies have been presented in the field of flash flood predictions in small and complex basins (where the response time is short). The benefit of this study is the creation of an easy-to-use method, by developing a threshold methodology that could be used by flood risk managers without modelling knowledge. The proposed methodology can be applied in any river basin as a useful tool for civil protection activity. On the basis of this methodology, if a weather alert provides information on the maximum rainfall expected in the next 24 h, then, if the antecedent wetness conditions are known it would be simple for the local authorities to determine whether or not an oncoming flash flood can occur. Thus, the response–warning time can be reduced and, consequently, the mitigation time can be increased, reducing the effects of a flash flood event. The limits of this methodology are: (a) the necessity of a detailed hydrogeological knowledge of the river basin, (b) the collection of historical flood data, and (c) the establishment of a real-time hydrometeorological network at strategic locations in the basin. At the same time, the above limits minimize the uncertainty in the proposed flash flood prediction methodology.

ACKNOWLEDGEMENTS

The present work would not have been feasible without the real-time data from the telemetric hydrometeorological network in the Koiliaris River basin. The financial support for the installation of these hydrometeorological stations was mainly provided by the research project 'Monitoring, forcasting and best practices for FLOOD Mitigation and prevEntion in the CADSES region (FLOODMED)' EU Community—INTERREG III B CADSES NEIGHBOURHOOD PROGRAMME. Also, the authors would like to thank the anonymous reviewers who provided helpful comments for the improvement of this manuscript.

REFERENCES

Archer D. 1992. Walls of water. *Circulation—British Hydrological Society Newsletter Society* **44**: 1–3.
Bakalowicz M. 2005. Karst groundwater: a challenge for new resources. *Hydrogeology Journal* **13**(1): 148–160.
Beven KJ, Binley A. 1992. The future of distributed models: model calibration and uncertainty prediction. *Hydrological Processes* **6**: 279–298.
Bonacci O, Ljubenkov I, Roje-Bonacci T. 2006. Karst flash floods: an example from the Dinaric karst (Croatia). *Natural Hazards and Earth System Sciences* **6**(2): 195–203.
Brath A. 1999. On the role of numerical weather prediction models in real-time flood forecasting. In *Proceedings of the International Workshop on River Basin Modeling: Management and Flood Mitigation*. September 25–26, 1997, Monselice (Italy), 249–259.
Brocca L, Melone F, Moramarco T. 2011. Distributed rainfall-runoff modelling for flood frequency estimation and flood forecasting. *Hydrological Processes*, DOI: 10.1002/hyp.8042.
Camarasa AM, Tilford AK. 2002. Rainfall—runoff modelling of ephemeral streams in the Valencia region (eastern Spain). *Hydrological Processes* **16**(17): 3329–3344.
Camarasa Belmonte AM, Segura Beltran F. 2001. Flood events in Mediterranean ephemeral streams (ramblas) in Valencia region, Spain. *Catena* **45**(3): 229–249.
Carmi G, Berliner P. 2008. The effect of soil crust on the generation of runoff on small plots in an arid environment. *Catena* **74**(1): 37–42.
Carpenter TM, Sperfslage JA, Georgakakos KP, Sweeney T, Fread DL. 1999. National threshold runoff estimation utilizing GIS in support of operational flash flood warning systems. *Journal of Hydrology* **224**(1): 21–44.
Chen ST, Yu PS. 2007. Real-time probabilistic forecasting of flood stages. *Journal of Hydrology* **340**: 63–77.
Cohen H, Laronne JB. 2005. High rates of sediment transport by flashfloods in the Southern Judean Desert, Israel. *Hydrological Processes* **19**: 1687–1702.
EM-DAT: The OFDA/CRED International Disaster Database (www.emdat.net), Universite catholique de Louvain—Brussels—Belgium.
Fohrer N, Berkenhagen J, Hecker ML, Rudolph A. 1999. Changing soil and surface conditions during rainfall Single rainstorm/subsequent rainstorms. *Catena* **37**(3): 355–375.
French MN, Krajewski WF, Cuykendall RR. 1992. Rainfall forecasting in space and time using a neural network. *Journal of Hydrology* **137**: 1–31.

Georgakakos KP. 1986. On the design of national, real-time warning systems with capability for site-specific, flash–flood forecasts. *Bulletin American Meteorological Society*, vol. **67**(10): no.
Georgakakos KP. 2006. Analytical results for operational flash flood guidance. *Journal of Hydrology* **317**(1): 81–103.
Green JI, Nelson EJ. 2002. Calculation of time of concentration for hydrologic design and analysis using geographic information system vector objects. *Journal of Hydroinformatics* **4**(2): 75–81.
Hapuarachchi HAP, Wang QJ, Pagano TC. 2011. A review of advances in flash flood forecasting. *Hydrological Processes*, DOI: 10.1002/hyp.8040.
Hellenic Agricultural Insurance Organization (ELGA), Statistical Bulletin for flood damages (www.elga.gr).
Javelle P, Fouchier C, Arnaud P, Lavabre J. 2010. Flash flood warning at ungauged locations using radar rainfall and antecedent soil moisture estimations. *Journal of Hydrology* **394**(1): 267–274.
Kirchner WJ. 2006. Getting the right answers for the right reasons: linking measurements, analysis, and models to advance the science of hydrology. *Water Resources Research* **42**: W03S04, DOI: 10.1029/2005WR004362.
Kourgialas NN. 2010. *Integrated Management-Forecast and Mitigation of Floods in Complex Geomorphological Regions with use of Mathematical Models and GIS*, PhD Dissertation. Environmental Engineering, Technical University of Crete.
Kourgialas NN, Karatzas GP. 2011. Flood management and a GIS modelling method to assess flood-hazard areas–a case study. *Hydrological Sciences Journal* **56**(2): 212–225.
Kourgialas NN, Karatzas PG, Nikolaidis PN. 2008. Simulation of the flow in the Koiliaris River basin (Greece) using a combination of GIS, the HSPF model and a Karstic–Snow melt model. *4th Biennial International Congress of iEMSs*, Barcelona Spain, vol. 1, 512–520.
Kourgialas NN, Karatzas GP, Nikolaidis NP. 2010. An integrated framework for the hydrologic simulation of a complex geomorphological river basin. *Journal of Hydrology* **381**: 308–321.
Koutroulis AG, Tsanis IK, Daliakopoulos IN. 2010. Seasonality of floods and their hydrometeorologic characteristics in the island of Crete. *Journal of Hydrology* **394**(1): 90–100.
Krzysztofowicz R. 1999. Bayesian theory of probabilistic forecasting via deterministic hydrologic model. *Water Resources Research* **35**(9): 2739–2750.
Krzysztofowicz R. 2001. The case for probabilistic forecasting in hydrology. *Journal of Hydrology* **249**(1): 2–9.
Krzysztofowicz R. 2002. Bayesian system for probabilistic river stage forecasting. *Journal of Hydrology* **268**: 16–40.
Lin X. 1999. *Flash floods in arid and semi-arid zones.* IHP-V Technical Documents in Hydrology, no. 23.
Marechal JC, Ladouche B, Dorfliger N. 2008. Karst flash flooding in a Mediterranean karst, the example of Fontaine de Nimes. *Engineering Geology* **99**(3): 138–146.
Martina M LV, Todini E, Libralon A. 2006. A Bayesian decision approach to rainfall thresholds based flood warning, *Hydrological and Earth System Sciences* **10**: 413–426, DOI: 10.5194/hess-10-413-2006, 2006.
McCuen RH. 1989. *Hydrologic Analysis and Design.* Prentice Hall, Englewood Cliffs: New Jersey, USA; 355–360.
McEwen LJ. 1994. Channel planform adjustment and stream power variations on the middle River Coe, West Grampian Highlands, Scotland. *Catena* **21**: 357–374.
Moraitis D, Efstathiou D, Stamati F, Tzoraki O, Nikolaidis NP, Schnoor JL, Vozinakis K. 2010. High frequency monitoring for the identification of hydrological and biochemical processes in a Mediterranean river basin. *Journal of Hydrology* **389**: 127–136.
Moramarco T, Saltalippi C, Singh VP. 2004. Estimation of mean velocity in natural channels based on Chiu's velocity distribution equation. *Journal of Hydrologic Engineering* **9**(1): 42–50.
Norbiato D, Borga M, Esposti SD, Gaume E, Anquetin S. 2008. Flash flood warning based on rainfall thresholds and soil moisture conditions: An assessment for gauged and ungauged basins. *Journal of Hydrology* **362**: 274–290.
Ntelekos AA, Georgakakos KP, Krajewski WF. 2006. On the Uncertainties of Flash Flood Guidance: Toward Probabilistic Forecasting of Flash Floods. *Journal of Hydrometeorology* **7**: 896–915.
Osborn HB, Lane LJ. 1969. Precipitation–runoff relation for very small semiarid rangeland watersheds. *Water Resources Research* **52**: 419–425.
Petit F, Gob F, Houbrechts G, Assani AA. 2005. Critical specific stream power in gravel-bed rivers. *Geomorphology* **69**(1): 92–101.
Rusjan S, Kobold M, Mikoš M. 2009. Characteristics of the extreme rainfall event and consequent flash floods in W Slovenia in September 2007. *Natural Hazards and Earth System Sciences* **9**(3): 947–956.
Strahler AN. 1952. Hypsometric (area-altitude) analysis of erosional topology. *Geological Society of America Bulletin* **63**(11): 1117–1142.
Tarboton DG. 1996. Fractal river networks, Horton's laws and Tokunaga cyclicity. *Journal of Hydrology* **187**(1): 105–117.
Toth E, Brath A, Montanari A. 2000. Comparison of short-term rainfall prediction models for real-time flood forecasting. *Journal of Hydrology* **239**: 132–147.
Viessman W, Lewis GL, Knapp JW. 1989. *Introduction to Hydrology.* Harper and Row: New York; 780.
Wilson CJ, Carey JW, Beeson PC, Gard MO, Lane LJ. 2001. A GIS-based hillslope erosion and sediment delivery model and its application in the Cerro Grande burn area. *Hydrological Processes* **15**(15): 2995–3010.
Yates DN, Warner TT, Leavesley GH. 2000. Prediction of a Flash Flood in Complex Terrain. Part II: A Comparison of Flood Discharge Simulations Using Rainfall Input from Radar, a Dynamic Model, and an Automated Algorithmic System. *Journal of Applied Meteorology* **39**(6): 815–825.
Younis J, Anquetin S, Thielen J. 2008. The benefit of high-resolution operational weather forecasts for flash flood warning. *Hydrological and Earth System Sciences* **12**: 1039–1051.

