Journal of Hydrology 394 (2010) 245–255

Contents lists available at ScienceDirect

Journal of Hydrology

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

Flash flood prediction using an uncalibrated hydrological model and radar rainfall data in a Mediterranean watershed under changing hydrological conditions

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ARTICLE INFO

Keywords:
Flash floods
Hydrological model
Mediterranean climate
Urbanization
Weather radar
Convective rain

SUMMARY

Flash floods cause some of the most severe natural disasters in Europe but Mediterranean areas are especially vulnerable. They can cause devastating damage to property, infrastructures and loss of human life. The complexity of flash flood generation processes and their dependency on different factors related to watershed properties and rainfall characteristics make flash flood prediction a difficult task. In this study, as part of the EU-FLASH project, we used an uncalibrated hydrological model to simulate flow events in a 27 km^2 Mediterranean watershed in Israel to analyze and better understand the various factors influencing flows. The model is based on the well-known SCS curve number method for rainfall–runoff calculations and on the kinematic wave method for flow routing. Existing data available from maps, GIS and field studies were used to define model parameters, and no further calibration was conducted to obtain a better fit between computed and observed flow data. The model rainfall input was obtained from the high temporal and spatial resolution radar data adjusted to rain gauges. Twenty flow events that occurred within the study area over a 15 year period were analyzed. The model shows a generally good capability in predicting flash flood peak discharge in terms of their general level, classified as low, medium or high (all high level events were correctly predicted). It was found that the model mainly well predicts flash floods generated by intense, short-lived convective storm events while model performances for low and moderate flows generated by more widespread winter storms were quite poor. The degree of urban development was found to have a large impact on runoff amount and peak discharge, with higher sensitivity of moderate and low flow events relative to high flows. Flash flood generation was also found to be very sensitive to the temporal distribution of rain intensity within a specific storm event.

Introduction

Flash floods are considered a severe natural hazard and have had significant impacts on Man throughout history. They can destroy infrastructures, cause landslides, damage agricultural fields, and cause injury or death to both livestock and human kind. Mediterranean areas are considered to have high flash flood potential (Norbiato et al., 2008) and arid, semi-arid and Mediterranean areas in Israel often suffer from flash floods. For example, in December 1993 a flash flood in the Negev desert in southern Israel ended in loss of lives and heavy damage to infrastructures (Ziv et al., 2005); in October 1997 a heavy rain storm caused flash floods and nine deaths in Israel and six in Egypt (Dayan et al., 2001); and in April 2006 a flash flood caused the death of five persons and destroyed roads and houses in northern Israel (Morin et al., 2007).

Flash floods are defined as strong flows occurring shortly after rainfall (Gruntfest and Huber, 1991) and are usually generated by extreme rainfall events associated with convective storms with relatively high rain intensities. They differ from other kinds of floods in that they tend to develop in the same place and time of the rainstorm that caused them, which allows for short (minutes to a few hours) advance warnings issued but sometimes no alerts at all. Urbanization and population growth increase flash flood risk since there are far more people and infrastructures concentrated in flood prone zones. In addition, urban development creates conditions, such as impervious surfaces, conducive for rapid flood generation (Davis, 2001).

Flash floods can also be defined as an intensive hydrological watershed response to excess rainfall. The response includes a strong and fast runoff flow that occurs immediately after a given rainfall event. The factors that affect flash flood generation are very complex and mainly include characteristics of the rain (intensity, duration, amount, and time-space distribution) and physical and

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doi:10.1016/j.jhydrol.2010.03.021

hydrological characteristics of the watershed (area, length, slopes, shape, type of soil and land use, vegetation, antecedent conditions, and others).

Recently, there is evidence to support the claim that due to global warming, extreme rainfall events are becoming increasingly frequent in the eastern Mediterranean region (Alpert et al., 2002). Other evidence points to an increase in extreme rainfall events accompanied by a decrease in the total amount of rain (Alpert et al., 2004). A possible consequence of this precipitation trend will be an increase in flash flood occurrence. Arid, semi-arid and Mediterranean regions are particularly vulnerable to such change due to water management issues, soil erosion and flash flood impacts (Alpert et al., 2002).

Recent efforts have been directed at predicting the occurrence of flash floods based on lightning activity in the preceding convective rain event. The EU-FLASH project (Price et al., 2007) showed that lightning can potentially be used as a precursor for extreme rain events. Yair et al. (2010) and Lynn and Yair (2010) have developed an index that can be used to evaluate the probability of Mediterranean flash floods based on lightning activity. Such modeling efforts underline the importance of flash flood prediction.

Yet, and due to the complexity of hydrological processes generating flash floods, our ability to predict them is quite limited and depends on various factors such as the availability of rainfall information, its accuracy and spatiotemporal resolution, soil moisture estimation, surface parameters and the ability of hydrological models to represent the complex processes involved in flash flood generation (Yatheendradas et al., 2008).

A hydrological model used for flash flood modeling and prediction is inevitably an abstraction of reality. The use of a model is necessary since the use of hydrological measurements can be very limited (Beven, 1989) and insufficient.

One of the main questions when approaching flash flood modeling is the model's degree of complexity (Michaud and Sorooshian, 1994). The more complex a model, the better it may represent the complexity of real hydrological systems, though it will not necessarily allow for better flood prediction when compared to a simpler model. Using multiple model parameters can increase the uncertainty of prediction (Perrin et al., 2001) but demands a complicated calibration procedure in order to decrease uncertainty. Robust, uncalibrated models, on the other hand, can produce good results and can be applied over ungauged areas (Lange et al., 1999), although they do not pretend to represent in detail all the hydrological processes, or their full spatiotemporal distribution. Comparing a complex and a simple model with and without calibration, Michaud and Sorooshian (1994) concluded that, for a semi-arid area, a complex model that demanded a much longer running and calibration procedure gave similar results to those from a simple model.

A calibration procedure required for a complex model can increase its level of uncertainty (Beven, 1989) and make it less robust. This is particularly important when intending to employ the model to various areas and watersheds. For this purpose a more flexible model is required.

One of the objectives of the current work is to use a relatively simple and flexible model that can later be applied over gauged as well as ungauged watersheds. Hence the model employed here is based on the commonly used SCS curve number (SCS–CN) method (S.C.S., 1964) for excess rainfall computation, combined with the kinematic wave method for flow routing. The SCS method was originally developed in the United States for the purpose of estimating runoff volumes over small agricultural watersheds with a sole parameter, the curve number (CN), representing hydrological soil characteristics such as soil type, land use and antecedent moisture conditions. The SCS–CN method is widely used particularly because of its simplicity and minimal data requirements. Despite this, it has some unclear aspects and disadvantages (Ponce and Hawkins, 1996). An apparently weak point of the method is its sensitivity to its sole parameter – the CN, although this may be a reflection of the natural variability. For the objectives of this study, the method was developed for medium-sized agricultural fields; it is stable, requires no calibration and therefore suits the goals here.

During the past four decades, the SCS–CN method has been developed, modified and used in different versions for a variety of purposes. King et al. (1999) compared the SCS–CN method with the popular Green and Ampt infiltration model, applying both methods over a 21.3 km^2 watershed. The authors indicate that the SCS–CN method gave reasonable results for annual, monthly and daily simulations (King et al., 1999). Mishra et al. (2005) examined the basic SCS–CN method and a modified multi-parameter SCS based method applied to a variety of watersheds and differing in size and rain properties, and found that although the modified method generally performed better, the basic method was appropriate for high rainfall events. Ponce and Hawkins (1996) reviewed the empirical and conceptual foundations of the method and indicated that it performed best in agricultural sites, and was better suited for storm rainfall–runoff estimates in streams with negligible base flow such as for ephemeral streams in semi-arid and arid regions. The method gave the best results for small and medium size watersheds (Ponce and Hawkins, 1996). Other studies have used the SCS–CN for simulations of single events (Borga et al., 2007), or for long-term runoff calculations such as Mishra and Singh (2004) who developed a modified SCS–CN method for long-term simulations. The method has also been used for various types and sizes of watersheds and in different climate conditions including arid and semi-arid regions (Rawls and Brakensiek, 1986; Mishra et al., 2005; Ali and Sharda, 2008).

Based on one, relatively easy to evaluate parameter that represents land and soil characteristics, the method is often used for evaluating the effect of land use changes on the water regime. Harbor (1994) used the SCS–CN method to develop a way to assess the effect of land use changes on surface runoff for planning purposes. Suggesting different development scenarios, the author found that a several percent increase in curve numbers leads to hundreds of percent increase in average annual runoff. Many other studies have dealt with the effect of urbanization and development on flood regimes (Moglen and Beighley, 2002; Camorani et al., 2005; Wu et al., 2007).

In this work, aimed at improving flash flood predictions in ungauged Mediterranean watersheds, we focus on identifying the peak flow discharge. The objectives are to: (1) examine the application of a robust uncalibrated model on a Mediterranean medium-sized watershed, (2) simulate the effect of land use changes and urban development on flash flood intensity, and (3) examine the effect of intra-storm rain intensity distribution on flash flood generation.

Study area

The study region is in northeastern Israel on the eastern coast of the Mediterranean Sea (Fig. 1a). The Merhavia watershed studied in this work (Fig. 1b) is located in the upper part of the Harod drainage basin (Fig. 1) that continues flowing further downstream into the Jordan River, and includes a hydro-climatic gradient with a Mediterranean climate at its western edge that gradually becomes semi-arid and arid moving eastwards. Merhavia is a 27 km^2 watershed, with elevation ranging from 10 to 500 m.a.s.l, and an average hillslope gradient of 5%. Soils of the area are mainly eroded alluvial soils, which were up until the beginning of the 20th