2

Flash Flood Hazards

Dénes Lóczy, Szabolcs Czigány and Ervin Pirkhoffer
Institute of Environmental Sciences, University of Pécs
Hungary

1. Introduction

Climate change research has revealed that the frequency of extreme weather phenomena with increasing damage to human assets has been gradually growing worldwide (Intergovernmental Panel on Climate Change [IPCC], 2007). The likelihood of increasing frequency of heavy precipitation events is assessed as 'likely' for the last four decades of the 20th century and 'very likely' for the 21st century. This also means that over most regions of the Earth's land surface an ever growing proportion of total precipitation will fall in the form of heavy rainfalls (Burroughs, 2003). The intensification trend of tropical cyclone activity, observed in some regions since 1970, will probably also continue in the 21st century. As a consequence, rainfall events concentrated in time and space are expected to lead to serious local flooding in many parts of the world.

Floods are remarkable hydrometeorological phenomena and forceful agents of geomorphic evolution in most physical geographical belts and, from the viewpoint of human society, among the most important environmental hazards. Except for extreme environments, floodplains and the immediate surroundings of streams are usually densely inhabited areas and, therefore, they are of high vulnerability to floods. According to the European Environment Agency (EEA, 2010), floods rank as number one on the list of natural disasters in Europe over the past decade. Authors of the report claim that "the events resulting in the largest overall losses were the floods in Central Europe (2002, over EUR 20 billion), in Italy, France and the Swiss Alps (2000, about EUR 12 billion) and in the United Kingdom (2007, over EUR 4 billion)" (p. 8.). With accumulating knowledge on the water regime of major rivers, the inundation hazard from riverine floods can be defined with some precision. To estimate the magnitude of this hazard in small catchments, however, poses more problems.

2. Flash flood research

2.1 Definitions and approaches

Flash floods (synonym: storm-driven floods) can be defined from various aspects: as hydrometeorological phenomena, natural hazards or geomorphic agents. Inundations can be referred to four basic classes: riverine floods, excess water (from rising groundwater table), coastal floods and flash floods (Lóczy, 2010). Although riverine floods along major rivers remain to be the most severe natural hazard which threaten to inflict serious damage to human life and property, recently the latter classes have also attracted more attention in scientific circles.

From a hydrometeorological aspect, flash floods are best described as events involving ”too much water in too little time” (Grundfest & Ripps, 2000). This means that exceptionally high amounts of rainfall, combined with very efficient and rapid runoff on relatively small catchments, are typical of flash floods. A flash flood immediately follows the inducing storm event. The term ’flash’ itself indicates a sudden rapid hydrological response of a usually small catchment, where water levels may rise to their maximum within minutes or a few hours after the onset of the rain event. Flash floods are highly localized in space: they are restricted to basins of a few hundred square kilometres or less. They are also restricted in time: response times not exceeding a few hours or are even less. Therefore, extremely short time is left for warning (Georgakakos, 1987, 2006; Collier, 2007; Carpenter et al. 1999).

It is often emphasized that heavy rainfall is a necessary but not sufficient condition for inducing flash floods. Since the entire physical environment influences their origin, flash floods are proper subjects for physical geographical investigations (Czigány et al., 2008). For instance, soil moisture conditions prior to the rainfall events are major hydrological controls of flash flood generation (Norbiato et al., 2008; Czigány et al., 2010). It is only with knowledge on the topography, soils and human impact on the catchment (steep slopes, drainage density, impermeable surfaces, saturated soils and land use) that the flood/no flood threshold can be established with some precision. Anthropogenic influences are important because some basins respond particularly rapidly to intense rainfall in the wake of disturbances in the natural drainage (stream channelization, deforestation, housing development, fire etc.) (Norbiato et al., 2008). As hydrometeorological phenomena, flash floods are best characterized by their magnitude (total amount and intensity of inducing rainfall), return interval, total runoff and similar parameters.

As geomorphological phenomena flash floods are short-duration events caused by an abrupt rise in the discharge of a river or stream, which may have remarkable geomorphic impacts through erosion and sedimentation (Reid, 2004). Previously, some geomorphologists restricted this concept to the ephemeral streams of arid and semiarid areas (Reid et al., 1994), but now the view is more excepted that the ’flashy’ flood hydrographs of subtropical seasonal climates and even of humid temperate regions can also be covered in the flash flood category. There may be, however, significant differences in runoff generation and geomorphic consequences (Bull & Kirkby, 2002). The geomorphic consequences of flash floods are usually judged from the stream flood hydrograph, sediment load transported and sediment accumulation.

Flash floods are naturally not novel phenomena, the frequency of their occurrence, however, shows an increasing tendency. Until some recent disasters, flash floods have not been so intensively studied as conventional large riverine floods. In some particularly affected countries (e.g. in the United States and the United Kingdom), however, their research dates back to the 1970s and 80s (e.g. Grundfest, 1977, 1987; Georgakakos, 1987; Schmittner & Giresse, 1996; Carpentier et al., 1999; Pontrelli et al., 1999).

In the case of a sophisticated hydrological approach, in addition to precipitation, several environmental factors are also to be considered in flash flood modelling as boundary conditions. Soil characteristics (actual moisture content, permeability, ground surface alterations and vertical soil profile) influence runoff production and help define flash flood prone areas. Various catchment characteristics (e.g. size, shape, slope, land cover) also affect runoff and the potential occurrence of flash floods. Consequently, the approach towards flash flood hazard assessment should be substantially different from that applied for modelling inundations along large rivers, in coastal areas or in valleys and lowlands due to elevated groundwater levels (Czigány et al. 2011b – see also below).

Flash floods are often associated with other natural hazards. Then their damage is partly due to the fact that they often trigger debris flows, i.e. hyperconcentrated flows, where the proportion of sediment load surpasses that of water discharge (Iverson, 1997). The particle size of the sediment swept at rates up to 20 m s^{-1} – confined within narrow valleys or erosion gullies – may range from clay to large blocks. The rainfall that produces flash floods often saturates entire hillslopes and subsequently may induce extensive slumps. Through blocking valleys and impounding stream flow, the slumps create suitable conditions for the next flood.

2.2 Flash floods in the world

Disastrous flash flood events can be cited from almost all continents. The majority of the 'classic', best documented events have been reported from the United States. Every year, riverine, coastal and flash floods are responsible for more fatalities than any other meteorological phenomenon in the Unites States. On the 30-year average, flood-related death toll totals 120 fatalities annually. From 1996 through 2003, 3000 flash flood events were documented in a year on average (Collier, 2007). Although some authors note that remarkable progress in research and warning have been made in the US and in some other countries (e.g. in the UK), flash floods are still among the most dangerous natural phenomena worldwide (Davis, 2001). Detailed documentation is available since the 1970s. In 1972 alone two disastrous floods were recorded in the US: 125 people were killed in Buffalo Creek, West Virginia, as a consequence of the failure of a coal-waste dam (Davies et al., 1972) and 238 people in Rapid City, South Dakota, where 380 mm rain fell within 6 hours (Davis, 2001). One of the best documented flash floods of all time occurred in the Thompson Canyon, Colorado, a small watershed (181 km^2) drained by one of the tributaries of the Colorado River. In 1976, 350 mm rain fell in less than six hours, flooding the narrow canyon floor (Caracena et al., 1979) and when the water level rose suddenly and unexpectedly by 6.5 m (Davis, 2001). 145 people were killed, 418 houses destroyed and 138 damaged. Total material damage amounted to USD 40 million.

A flash flood (well studied and even documented in videos, now on YouTube) took place in England, on the Cornwall Peninsula, in Boscastle, on August 16, 2004 (Golding, 2005). It provided an opportunity for the application of the land surface model called MOSES-PDM (Met Office Surface Exchange Scheme incorporating the Probability Distributed Model) to portray the evolution of soil moisture conditions from meteorological information (radar rainfall and satellite cloud observations). The entire rainfall event lasted for only about seven hours, but was very localized. The total 24-hour cumulative rainfall reached 200.4 mm at one location (Otterham) (Golding, 2005). In places upstream from Boscastle rainfall intensity reached 24 mm within 15 minutes, while in Boscastle 89 mm rain fell in an hour (Golding, 2005). The probability of such a high-intensity rainfall in Boscastle, at least according to the available statistical data, is 1 to 1,300. Antecedent high precipitation also influenced soil moisture and runoff on the higher portions of the catchment. The intense rainfall was followed by a 2-metre rise in the water level of the local Valency Stream, the discharge of which reached 180 m^3 s^{-1}, a value of an estimated return time of 400 years

(Bettess, 2005). During the Boscastle flash flood event, 100 residential homes were destroyed and 75 cars were swept to the sea. Due to the efficient assistance of the available rescue teams, no fatalities happened. This rare event resulted from a combination of hydrometeorological factors (Golding, 2005): unusually high rainfall efficiency (relative to the moisture content of the inflowing air) and the exceptionally long stay of intense storms over the same catchment.

For similar reasons, mountain environments in the Mediterranean are also seriously threatened by flash flooding (e.g. Borga et al., 2007). In the Aragonian Pyrenees, the catchment of the Barranco de Áras stream (only 19 km^2 in area) was affected by enduring (5-hour) rainfall with 500 mm h^{-1} peak intensity and an estimated 243 mm total amount on 6 August 1996. In the Biescas camp-site 87 people died because flash flooding of 600 m s^{-1} discharge was combined with a debris flow transporting 68,000 m^3 debris (Gutiérrez et al., 1998). The tragic underestimation of the capacity of check dams by engineers had also contributed to the disaster. In the French Côte d'Azur, in Draguignan (Var *département*) the 10 June 2010 flash flood killed 37 people in the town and its neighbourhood, caused blackouts and cut away the village from the world (Telegraph, 2010). It was triggered by a huge cloudburst (350 mm within 20 hours), unobserved in the area since 1827. (For a more complete overview of flash floods in Europe see Gaume et al., 2009.)

As it has been mentioned, however, arid and semiarid regions are the most favoured environments for flash flood generation (Reid et al., 1994). According to research in Israel (Cohen & Laronne, 2005), for instance, flash floods of arid regions involve both bedload and suspended sediment concentrations much higher than in the perennial rivers of humid environments. In arid or desert regions storms cut arroyos (intermittent gullies with flat floors and vertical walls). Flash flooding in an arroyo can occur in less than a minute, with enough power to wash away sections of pavement, large boulders, cars and even houses. Although the sediment yield of individual events is large, fortunately, flood events rarely occur and mean annual sediment yields remain low in arid environments (Graf, 2002).

The prediction of heavy rainfall and ensuing flash floods is particularly challenging in the tropical belt, especially on islands with intense, localized and mostly convective rainfalls (e.g. Kodama & Barnes, 1977). Devastating events have been reported from various Caribbean islands (Laing, 2004). During an El Niño winter, on 5–6 January 1992, heavy rainfall produced flash floods in Puerto Rico and caused 23 deaths and 88 million U.S. dollars in damage (National Oceanic and Atmospheric Administration, National Weather Service [NOAA NWS] 1992). At a few stations the amount of the rainfall, associated with a quasi-stationary front at the surface and an upper-level trough, was up to 500 mm (Laing, 2004).

High relief often generates heavy rainfall through orographic lift or by creating persistent low-level convergence which induces new convection (Weston & Roy, 1994). Such hydrometeorological and other environmental conditions were associated with another deadly flash flood, too, that occurred in Jamaica on 3–4 January 1998. The northeastern region was affected by heavy rainfall, which induced both flash floods and mudslides which caused five deaths and more than nine million U.S. dollars in damage to property, agriculture, and infrastructure (Laing, 2004). The situation was aggravated by antecedent rainfall from a strong cold front, currents of moist air masses at lower and higher topographic levels. Similarly to the Puerto Rico event, orographic lifting contributed to the disaster also here. The steep slopes of Blue Mountain ridge enhanced and localized convection over the region. In addition to antecedent rainfall, land-use practices (e.g. floodplain encroachment) also increase flood hazards.

Some examples of flash floods can also be cited from a continent infamous of rather extreme spatial and temporal variations in weather conditions, Australia. The most frequent cause of flash flooding is slow-moving thunderstorms. These systems, related to the El Niño–Southern Oscillaton (ENSO) circulation pattern, can involve strong updrafts of air which suspend huge amounts of rain before releasing a deluge onto the ground (Allan, 1993). Water in creeks, drains and natural watercourses can rise at dangerous rates. On the evening of 26 January 1971, seven people died in Canberra as flash flood waters from a nearby thunderstorm flooded roadways near a drainage channel. It was estimated that around 95 mm of rain fell in one hour during the event. On another occasion, in Sydney on 7 November 1984, 127 mm fell in one hour leading to damage of around AUD 128 million (in July 1996 terms) (Australian Government, Bureau of Meteorology [AG BoM]). In the drier ('outback') regions of Australia flash floods are more common, but – the vulnerability being lower – their documentation is not so good.

Flash floods are increasingly observed in urban areas, where the surface is unable to absorb large amounts of water in a short period. In urban areas the hazard is exacerbated by various – and not exclusively physical – contributing factors and vulnerability is significantly higher – often because of the sudden rise of water levels. For instance, many cities of Latin America show uncontrolled and disorganized urban growth (Stevaux & Latrubesse, 2010) with infrastructure and production systems (railways, roads, plants) concentrated in densely populated valleys. Disasters are produced by a combination of tropical storms inducing flash floods and landslides and urban occupation of the valleys. It is often emphasized that the increased proportion of impervious urban surfaces and the limited drainage capacity are responsible for flooding. A storm on December 14–16, 1999, caused catastrophic landslides and flooding along a 40-km coastal strip north of Caracas, in the coastal state of Vargas, Venezuela with its extremely steep and rugged topography (mountains 2700 m high within about 6–10 km of the coast) (Brandes, 2000). The rivers and streams of this mountainous region drain to the north and emerge from steep canyons onto alluvial fans before emptying into the Caribbean Sea. Damage to communities and infrastructure was so serious because here little flat area is available for development with the exception of the alluvial fans. In Vargas state probably almost 50,000 people were killed, more than 8000 individual residences, and 700 apartment buildings were destroyed or damaged and total economic losses are estimated at USD 1.79 billion (Wieczorek et al., 2001). On average, at least one or two major flash-flood or landslide events per century have been recorded in this region since Spanish occupation in the 17th century.

2.3 Flash floods in Hungary

Until very recently flood hazard research in Hungary had focused on riverine floods, particularly those along the two major rivers, the Danube and its main tributary, the Tisza (Lóczy & Juhász, 1996; Lóczy, 2010). There are relatively few papers published on flash flood events in Hungary (Gyenizse & Vass, 1998; Fábián et al., 2009). In the mainly lowland and hill environments of Hungary flash floods do not appear a major hazard. Another reason is the lack of appropriate monitoring systems in the flash flood affected catchments (Vass, 1997). In the wake of the events of the first decade in the 21st century, however, flash flood related disasters and their consequences have been appearing more and more frequently in the Hungarian media.

Some recent events that made news took place in the Mátra Mountains (North-Hungary) in 1999 (Koris & Winter, 1999) and again on 18 April 2005 (Horváth, 2005). The rainfall resulted from an atmospheric complex of several convective cells transporting moist air like a conveyor belt against the mountain slopes. Huge boulders of volcanic rock were transported by the local stream (Fig. 1). As an aftermath of the flood, slumps in 500 m length along the undercut bank are regularly generated.

Fig. 1. Deposits of debris flow after the Mátrakeresztes flash flood (by permission of the Nógrád County Disaster Prevention Directorate)

Some of the most disastrous events in Hungary occurred on 15–16 May 2010, when a strong cyclone reached the Carpathian Basin. Hitherto virtually unknown stream names (e.g. Hábi Canal, Bükkösd Stream and Baranya Canal) appeared in the media. The ensuing floods caused significant economic losses in Southern Transdanubia (Southwest-Hungary), a region of mostly dissected hill topography and a dense drainage network (Fig. 2). Daily precipitation amounts, intensities and stream stages broke records and cumulative precipitation locally exceeded 300 mm in the Kapos drainage basin during May and June. In Csikóstőttős village 65 people were evacuated. A one metre high flood swept away a children's camp in Szekszárd, where firemen assisted to evacuate the campers. On 16 June 2010 182 mm of rainfall fell on the village of Iklódbördőce in the Zala Hills (Southwest-Hungary) and caused a mudflow. Estimated by the insurance companies, the May and June events caused ca HUF 100 billion (EUR 360 million) economic losses, at least 3,100 residential homes were damaged and the agricultural damage totals ca HUF 30 billion (EUR 110 million). A summary of water-related damage recorded by insurance companies shows the distribution of insurance events in Southern Transdanubia between 1980 and 2005 (Fig. 3). In the light of the 2010 floods, the number of events presented here seems to be underestimated (property insurance was probably not comprehensive), but the map is informative of the zones of highest flood risk.

3. Flash flood modelling

3.1 Objectives

The above mentioned events directed the attention of water management experts and of the wider public to flash flood hazard. Consequently, flood prevention needs to be also

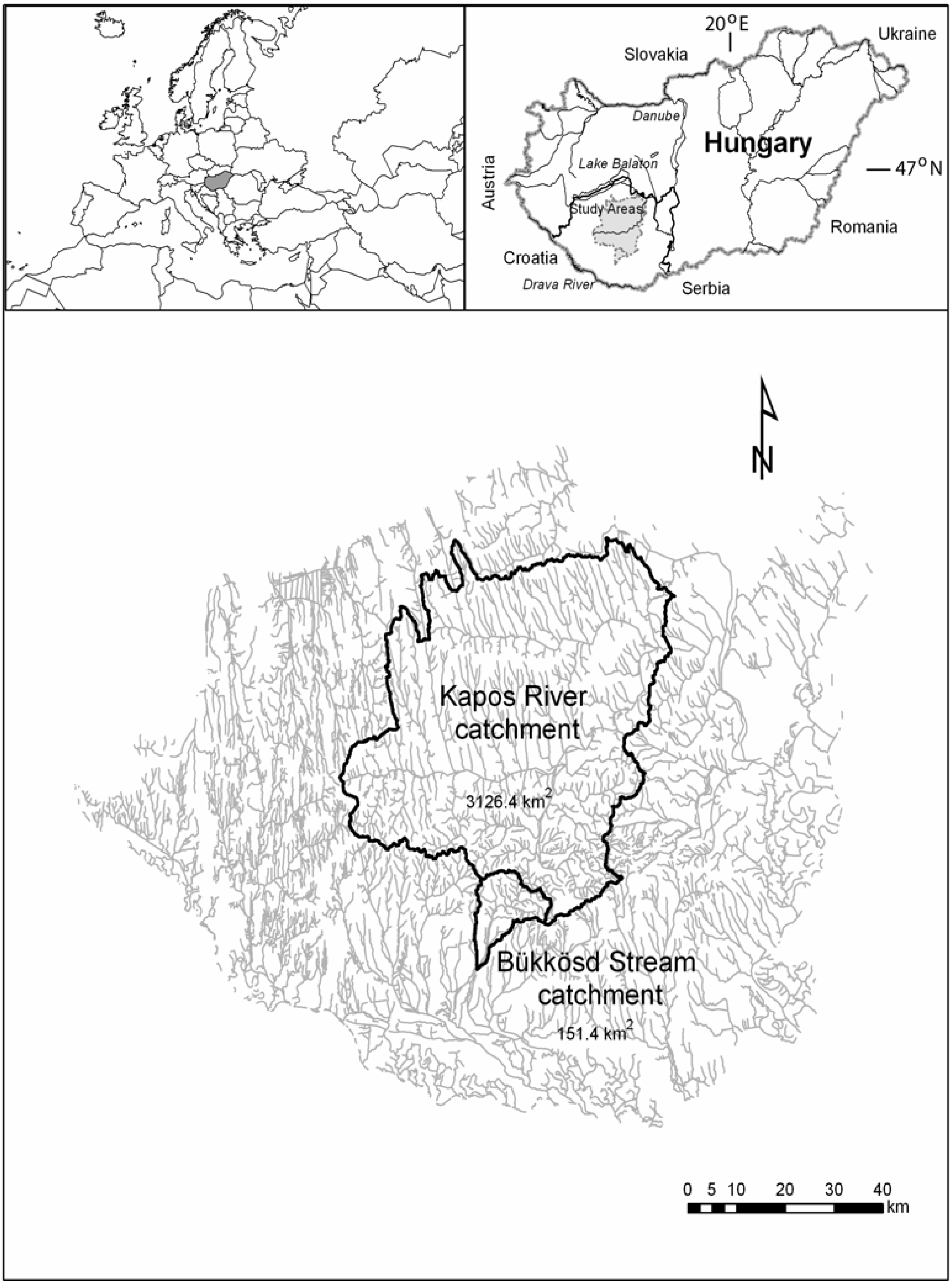


Fig. 2. The drainage network of Southern Transdanubia with the catchments studied and an inserted location map (from the river network database of Hungary)

extended to the previously neglected small mountainous catchments at relatively low elevations, which cover ca 30 per cent of the entire land area of Hungary, while the cumulative length of streams total more than 20,000 km (Kaliczka, 1998). It is recognized that flood assessment and prevention measures, such as the presently planned and constructed nationwide Flood Risk Information System (abbreviated from the Hungarian as ÁKIR), a model and software-based flood prediction system, also have to cover minor catchments potentially affected by flash floods (Pászthory & Szigeti, 2009).

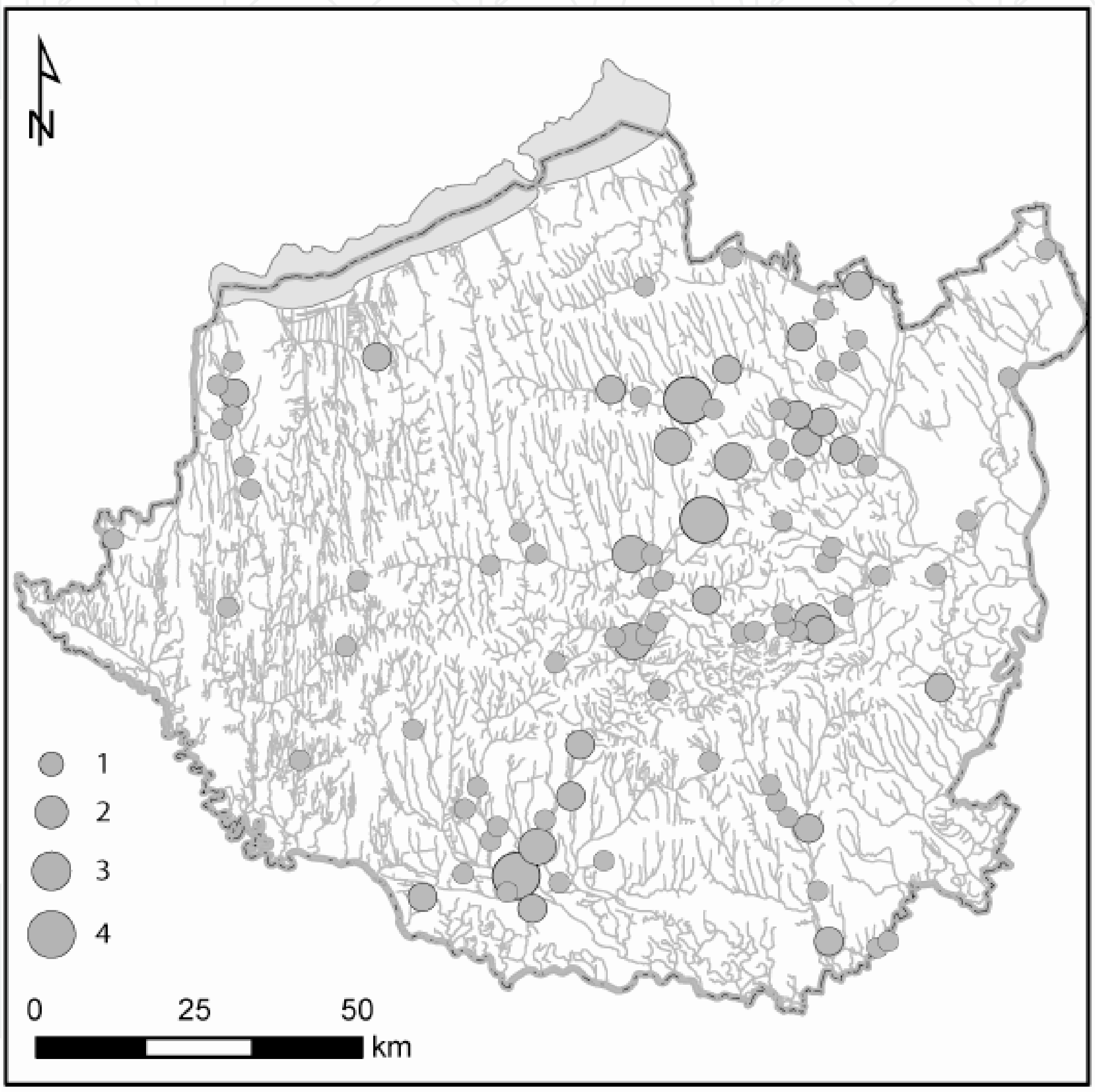


Fig. 3. Water-related events with damage to property in Southern Transdanubia, 1980–2005, based on insurance data (after Varannai, 2005). The map shows the number of occurrences

In the following part of this chapter a proposed flood risk assessment mapping procedure and numerical flood forecasting system are outlined. Our objective is to identify flash flood risk in order to promote the development of a flood warning system and to mitigate flood-related life and property losses. The screening of the country's territory for flash flood hazard and rating the risk in the various regions would also help insurance companies in estimating expectable damage.

3.2 International models

The modelling of flash flood hazards requires a more complex approach than that of large riverine floods as more environmental factors have to be considered and regularly monitored. Flood modelling serves flood forecasting, i.e. the estimation of future flood conditions, while flood warning means the information of the public on the timing and location of a flood event allowing them sufficient time to take preparatory actions. A Decision Support System (DSS) in flood management assists authorities to make decisions based on forecast information (the expected characteristics of the flood, the number of inhabitants threatened and the evacuation infrastructure available) (Maarten et al., 2007).

Given the significance of catchment properties in the generation of floods, distributed hydrological models seem to be best suited for the purpose of flash flood prediction. These models of various levels of complexity are built on a grid-based network, small subbasins or triangulated irregular networks (TINs). Some frequently used examples of physically based, distributed hydrological models (cited by Paudel 2010, see references there) are

- Gridded Surface/Subsurface Hydrologic Analysis (GSSHA), developed by the US Army Corps of Engineers Engineering Research and Development Center (USACE-ERDC);
- Modular Modeling System (MMS) – US Geological Survey;
- Hydrology Lab's Research Modeling System (HLRMS) – National Weather Service Hydrology Laboratory;
- Vflo™ – Institute of Environmental Sciences, University of Oklahoma – Institute of Environmental and Natural Sciences, Lancaster University, UK;
- MIKE-SHE – Danish Hydraulic Institute;
- Hydrologic Research Center Distributed Hydrologic Model (HRCDHM) – Hydrologic Research Center;
- Soil and Water Assessment Tool (SWAT) - US Department of Agriculture, Agriculture Research Service (USDA-ARS)
- TIN-based Real-Time Integrated Basin Simulator (tRIBS) – Massachusetts Institute of Technology;
- Variable Infiltration Capacity (VIC) – University of Washington.

The US Army Corps of Engineers (USACE) has played a vital role in the development and application of hydrological models in the Unites States since the early 1960s. USACE models are extensively used throughout the world. As a well-established standard model, HEC-HMS is widely used in the United States and worldwide for the simulation of surface runoff. For the mapping of inundated areas the models HEC-RAS, HEC-GeoRAS and ArcGIS 9.1 are useful. The HEC-HMS is designed to simulate the precipitation-induced runoff processes in catchments of dendritic drainage pattern. It is applicable in a wide range of geographical areas, equally for large drainage basins and small catchment for solving the widest possible range of problems (water availability, urban drainage, flow forecasting, future urbanization impact, reservoir spillway design, flood damage reduction, floodplain regulation etc.) (US Army Corps of Engineers, 2005).

The default model used in the European Flood Forecasting System (EFFS) is LISFLOOD (De Roo et al. 2000), a physically based catchment model, developed for the European river basins. As a rainfall-runoff model it has inputs of data on topography, precipitation amounts and intensities, antecedent soil moisture, land use type and soil type in the form of maps (topography, drainage network, CORINE land cover, soil depth, soil class). The meteorological variables required are rainfall, potential evaporation (for bare soil, closed canopy and water surfaces) and daily mean air temperature (De Roo et al., 2000).

3.3 Methods

3.3.1 Differences between the modelling of riverine and flash floods

Conventional large riverine floods and flash floods do not only differ in their general characteristics but also in their time of concentration (T_c or lag time) and duration of flood peaks. As it has been mentioned, for flash floods T_c is not more than 6 hours (NOAA definition). This extremely short lead time makes warning and prevention very difficult. In unexplored and ungauged catchments the single source of information is field surveys. Flood reconstruction is often only possible from the falling limb of the hydrograph or by assessing the aftermaths of the event (including the study of deposits – Costa, 1983).

As far as the triggering process is concerned, flash floods are generally associated with intense and convective rainfalls – often further enhanced by orographic effects (Horváth, 2005). Large riverine floods, on the other hand, are often preceded by days of incessant rainfall over hundred or thousand square kilometres affecting several drainage basins. It is to be noted here that in humid continental environments flash floods do not only occur in the summer, but rain-on-snow events may also generate winter flash floods (as shown for Southwest-Hungary by Pirkhoffer et al., 2009a,b; Czigány et al., 2010).

For flash flood modelling and forecasting usually an area of 10 to 200 km^2 is selected, i.e. about one or two orders of magnitude less than for large riverine floods. During flash floods peak flow may exceed baseflow several hundred times - although peak discharge only lasts for a few hours. Moreover, as flash floods are usually triggered on the upper reaches of the stream, where the channel is narrow, stage increase is even more pronounced than flow changes. Figure 4 shows an idealized, rapidly rising and slowly attenuating hydrograph, typical of many hill regions, where T_c is extremely short. The second flow peak, triggered by a moderate rainfall, is due to higher soil moisture. The time of residence in the reservoirs (e.g. canopy or surface storage) of the hydrological cycle is usually much shorter for flash floods. Rainfall intensity largely exceeds infiltration rate, and, thus, excess runoff into intermittent streams reach the beds of permanent rivers, where a rapid rise of water will be observed (Fig. 4.).

Numerical modelling is further complicated by a plethora of environmental factors to be considered during the simulation process. Judging from the available data on documented flash floods, it can be claimed that built-up areas of the highest risk are located along the boundaries of areas of higher elevation and adjacent lowlands as well as at the abrupt narrowing of river valleys (bottlenecks). As periodically water-filled gullies often function as preferential flow paths during convective rainstorms, adequate knowledge on topography is essential for highly accurate flash flood prediction.

3.3.2 Runoff modelling

In case studies and pilot catchments we used 50-m and 10-m Digital Elevation Models (DEMs) based on topographic maps. In the field TOPCON HiPER Pro RTK GNSS high-precision GPS and SOKKIA surveying instruments were employed to improve the spatial resolution of the generated DEM to 1 m. This, however, was achieved only locally – usually in the immediate vicinity of watercourses.

Surface runoff was simulated using HEC-HMS, which has the advantage of working with distributed precipitation data available from weather radar and a continuous soil-moisture-accounting model (Pirkhoffer et al., 2009b). Radar images and various meteorological data were obtained from the Hungarian Meteorological Service (OMSz), while hydrological data (e.g. water stage and discharge) were received from the Research Institute for Environmental Protection and Water Management (VITUKI Rt.), the South-Transdanubian Environmental Protection and Water Management Directorate (DDKÖVIZIG) and the MECSEKÉRC Rt., a successor enterprise to the former uranium mining company. To obtain field data we monitored soil moisture (using Time Domain Reflectrometry technique), canopy cover and precipitation at 14 monitoring stations in a 1.7 km² pilot catchment (Pirkhoffer et al., 2009b; Czigány et al., 2010). Runoff output data were then compared with observed flow.

3.3.3 Rapid screening and GIS-based risk assessment

The first comprehensive, but least detailed type of approach to flash flood modelling is rapid screening that usually employs ARC GIS and SGA GIS softwares (Pirkhoffer et al., 2009b; Czigány et al., 2011a). The input data for this analysis comprise various topographical, geological, soil and land use parameters. Rapid screening models serve to delineate the area with a natural hazard or rate vulnerability and risk in that area (Cobby et al., 2009; Czigány et al., 2008) in order provide a general overview of its level for experts, decision-makers and the public.

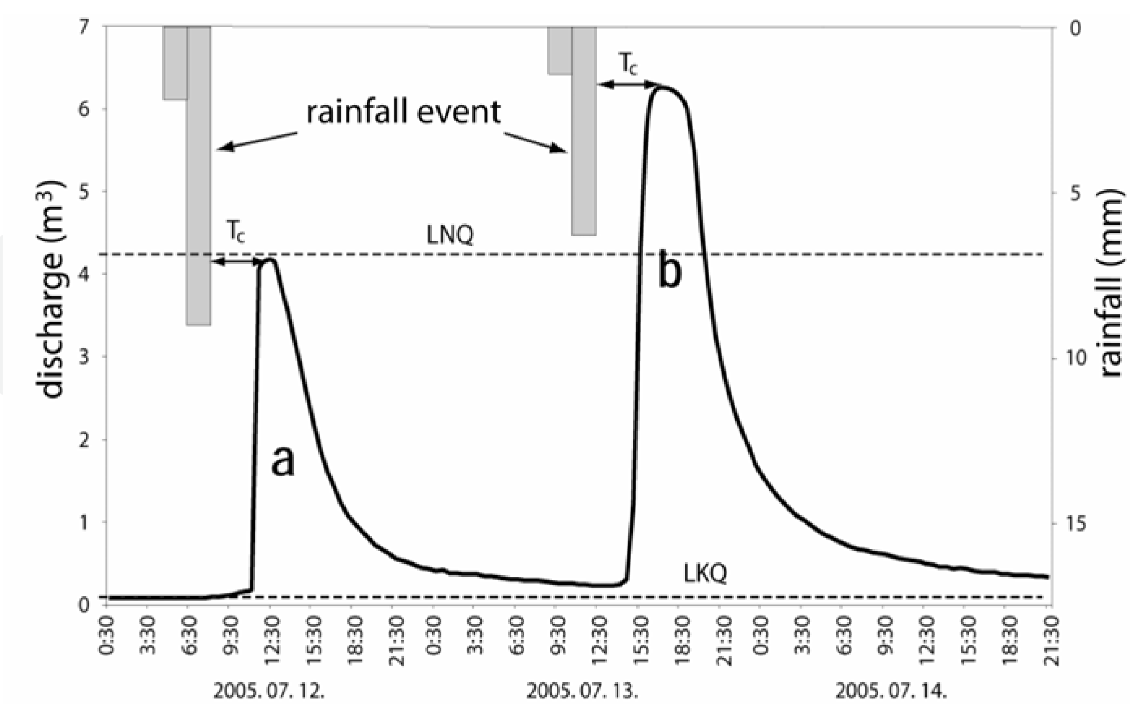


Fig. 4. Hydrograph of a typical flash flood (a) and that of a flood event with saturated soils (b). T_c = time of concentration; LNQ = maximum discharge; LKQ = minimum discharge

First, the catchments potentially affected by flash floods are identified. In the next step, risk assessment has to be carried out individually for each catchment as catchment properties influence flood level and stream behaviour. The impacts of floods are most pronounced along the watercourses and at the outflow point of the catchment. Therefore, all catchments are assigned with a unique ID number and the outflow points (usually in built-up areas) receive the same ID.

There are two approaches available for flood risk assessment: the first is based on passive factors, i.e. those which do not change significantly with time, while the second method focuses on the active factors, i.e. those which show significant variations with time (precipitation, canopy cover and soil moisture content). Passive environmental factors are determined with relatively high accuracy; spatially and temporally correct data on active factors, however, are difficult to obtain (Bálint & Szlávik, 2001).

The environmental factors incorporated in the 1:100,000 risk map are classified into five categories: topographical parameters (derived from the DEM), drainage netwok (from the river network database of Hungary), land cover (from CORINE Land Cover 2000), soils (from the AGROTOPO Hungarian soil database) and hydrological conditions. The three topographical properties were average slope, slope range and valley density for the catchment. Four soil parameters, which influence surface runoff, infiltration and interception were considered: soil depth, physical soil type, the ratio of barren/vegetation-covered surfaces (in limestone areas). Data on the hydrological factors contributing to flash flood generation were borrowed from the river network database of Hungary, created in accordance with the Water Framework Directive of the European Union. As confluences (number of tributary rivers) are prone to enhance the magnitude of flash floods (also proven during the Mátrakeresztes flash flood event – Horváth, 2005), first the number of stream confluences per unit area (1 km^2) were determined. Then drainage density was incorporated in the model.

GIS-based risk mapping represents a transitional type of models. It is closely related to rapid screening, but already points towards numerical analyses. The basic difference from rapid screening is that flooding in this case is not directly associated with a given rainfall event. Rainfalls are incorporated in a rather hypothetical manner: the extent of flooding is determined from a threshold height above the valley floor or the mean stream stage.

GIS models are primarily based on topography: all parameters, including runoff, T_c and drainage network, are derived from a topographic map or a DEM (Digital Elevation Model). The spatial resolution is at least 5 or 10 m. (Errors tend to be significant: between the calculated and the actual watercourses may reach 100 m.) The models which ignore infiltration and the canopy effect and define runoff direction and volume exclusively from topographic models are called impervious surface (IS) models. However, to obtain a true picture of runoff behaviour, the impact of soils and land use (Fig. 5a) cannot be neglected. Figure 5b clearly show the differences in runoff according to IS models with light colours, while the black zones indicate runoff also influenced by soils and land use.

Channel widths vary greatly in areas of high relief, ranging from 0.5 m to dozens of metres. When the spatial resolution of the topographic map exceeds channel width, a channel as a physical entity will not be shown on the final output map but a theoretical centerline represents the stream (valley inundation model). In this case, however, we have to define the valley floor through visual interpretation, wherever possible, including bottlenecks and broader floodplains (Fig. 5c). As it has been mentioned flood levels are approximated by height above the channel (Fig. 5d).

Flood risk was determined by the complex, superimposed impact of the 50-m resolution input grid databases of passive factors through appropriate weighting. Figure 5 summarizes the major elements of a GIS based runoff model and its mapping possibilities. Obviously, the number of included input parameters will determine the accuracy of the output vulnerability map.

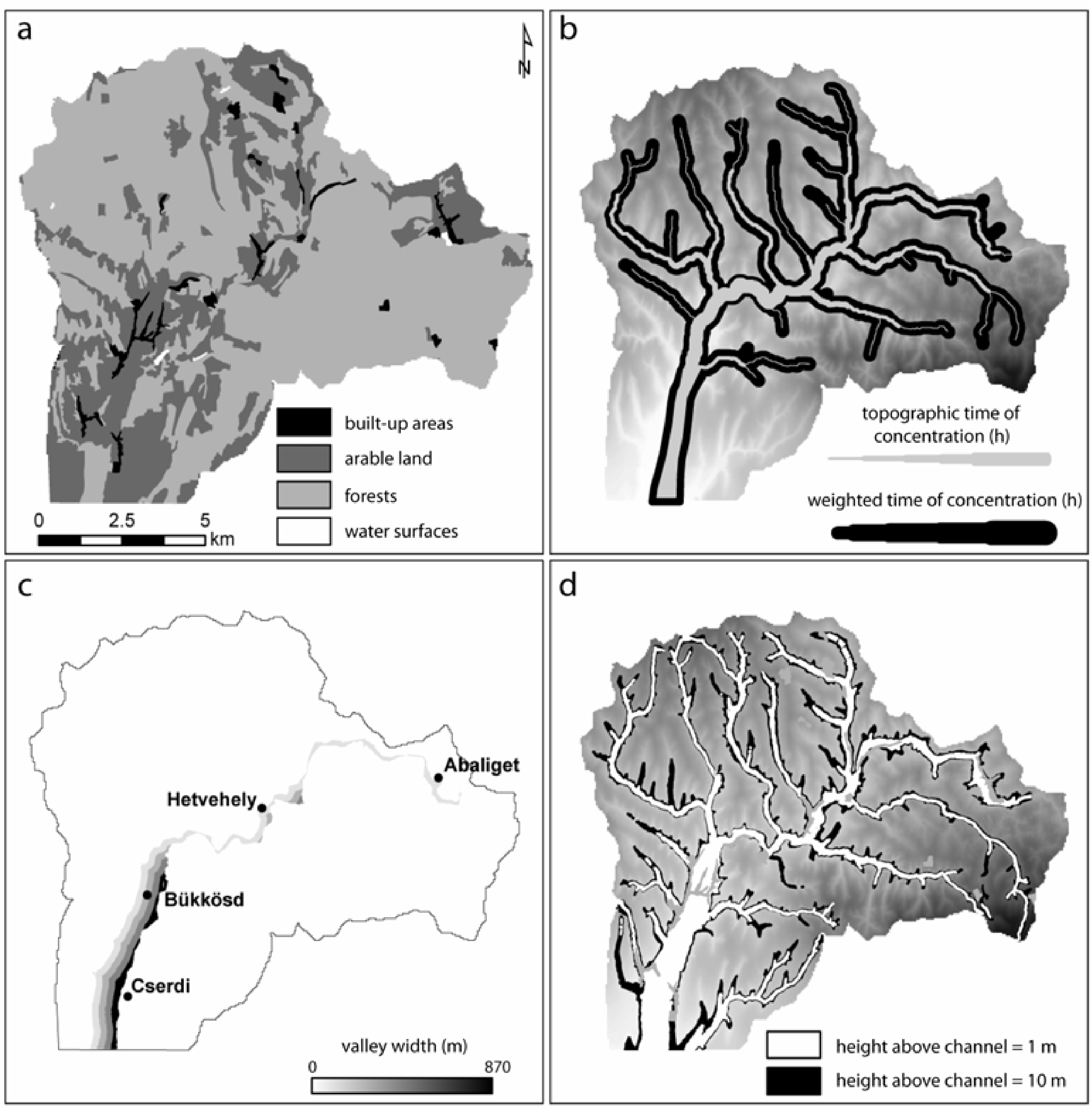


Fig. 5. Parameters for the construction of GIS inundation maps: a. land cover; b. time of runoff concentration; c. valley width; d. height above channel

3.4 Discussion

3.4.1 Correlation between rainfall and flood levels

As mentioned above, the primary triggering factors of flash floods are high-intensity convective rainfalls that are often associated with supercells. Below we discuss the spatial and temporal features of the heaviest rainfall event (in the second half of May and early June 2010) in Southern Transdanubia. The attention this event attracted helped us collect the necessary input data for the analyses.

Insurance only covers property damage in Hungary if rainfall events exceed 30 mm daily precipitation, officially confirmed by the Hungarian Meteorological Service (Varannai, 2005). The average of at least one event exceeding 30 mm occurs each year in the study area. The actual number of events in this category is shown in Table 1.

A persistent waving low-pressure system dominated in the central and western part of the Mediterranean and Central and Eastern Europe in mid-May and stayed in this region for three to four days. Similarly, the Carpathian basin was affected by moist air masses generating extensive, prolonged and relatively high-intensity precipitation on 14 to 17 May. The second half of May was characterized by local but intense showers and downpours. The 15 and 16 May flash floods were typical from a hydrological viewpoint, but unusual from a meteorological aspect as typical convective cells were not observed in this period. However, the soils were saturated in the upper and steep portions of the catchments of the Baranya and Hábi Canals and the Bükkösd Stream prior to the event, in early May.

Meteorological station	Number of rainy days above 30 mm precipitation	Number of rainy days	Cumulative precipitation (mm)
Siófok	3	21	257.9
Sellye	4	23	274.5
Sátorhely	2	22	177.3
Sármellék	2	23	204.2
Pécs	3	25	253.6
Árpádtető	5	24	385.0
Nemeskisfalud	3	24	273.2
Nagykanizsa	2	22	251.0
Kisbárapáti	2	25	185.1
Keszthely	3	24	385.5
Kaposvár	3	22	226.7
Iregszemcse	2	26	226.7
Iklódbördőce	4	22	285.6
Homokszentgyörgy	1	22	175.1
Fonyód	3	27	278.3
Bátaapáti	3	25	308.0

Table 1. Selected rainfall properties of the studied area between May 1 and June 16, 2010

Therefore, the soils acted as an impervious surface triggering extreme surface runoff. Soil moisture content only slightly decreased in the following two-week period, thus the second storm with less cumulative rainfall induced flash floods again on 31 May and 1 June. Over the period of 1 May to 16 June the cumulative number of rainy days reached at least 21 at all rain gauges operated by the Hungarian Meteorological Service in Southwest-Hungary (Table 1 and Fig. 6). Groundwater tables in the observation wells of the area indicated a mean rise of 1 to 1.2 m over the entire region (DDKÖVIZIG, 2010).

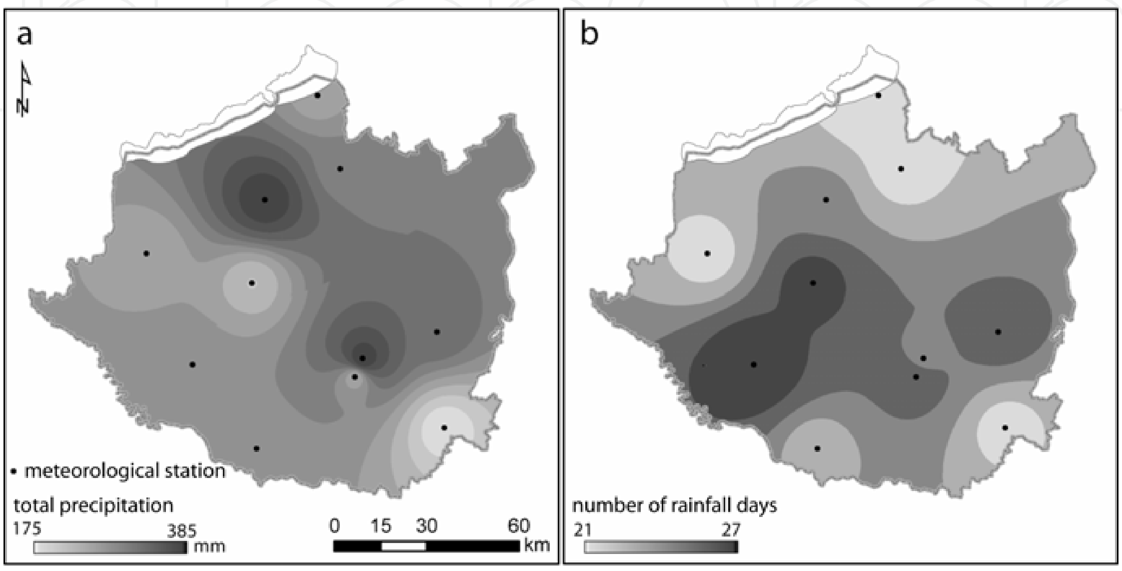


Fig. 6. Total cumulative rainfall (a) and number of rainy days (b) in Southern Transdanubia between 1 May and 16 June 2010 (data provided by the Hungarian Meteorological Service)

Table 2 clearly illustrates the extreme precipitation characteristics of the mentioned 47-day period. At many rain gauges in the study area precipitation reached or even exceeded 50% of the mean annual rainfall. The long-term average May precipitation in Pécs is 84 mm, while the cumulative precipitation in May 2010 was nearly threefold higher. The return time of such precipitation is estimated at 400 years.

The extremity of rainfall is also clearly reflected in the actual intensity values. For short periods, intensity values reached 30 mm h^{-1}, while 10-minute intensity was 51.6 mm h^{-1} at the Keszthely main meteorological station. For small mountainous catchments it is essential to know the areal extent of the rainfall zone. Due to the scarcity of rain gauges, we have to rely on radar images. Convective cells are around 5 to 10 km across, thus radar images of adequate (at present 2 by 2 km) resolution are extremely helpful in the estimation of the areal extent of precipitation for modelling purposes. Heavy rainfall characterized the settlements of Sásd and Csikóstőttős on 15 May 2010 (Fig. 7) and maximum rainfall and intensity were observed basically in the same area on the following day (16 May 2010).

On 15 May 86 mm of rain fell on the upper catchments of the Baranya Canal, where T_c is shortest within the catchment, with similar flood stages. As a consequence, rapidly rising flood stages were just slightly off from the previous records (Fig. 8). South of the divide, in the mountainous Bükkösd Stream catchment, the rainfall was much more prolonged and high water stages persisted longer at the Szentlőrinc stream gauge than at the gauges upstream (Fig. 9).

Meteorological station	Total precipitation in the study period (mm)	Annual mean precipitation, 1941–1970 (mm)	Total precipitation in % of the mean of 1941–1970	Annual mean cumulative precipitation, 1961–1990 (mm)	Total precipitation in % of the mean of 1961–1990
Bátaapáti	308.0	741	41.57	593.0	51.94
Fonyód	278.3	730	38.12	561.2	49.59
Homokszentgyörgy	175.1	773	22.65	648.2	27.01
Iklódbördőce	285.6	…	…	688.0	41.51
Iregszemcse	226.7	640	35.42	617.0	36.74
Kaposvár	225.8	746	30.27	578.6	39.02
Keszthely	385.5	664	58.06	526.9	73.16
Kisbárapáti	185.1	688	26.9	559.3	33.09
Nagykanizsa	251.0	743	33.78	726.0	34.57
Nemeskisfalud	273.2	...	…	648.8	42.11
Pécs. Ifjúság u. 6.	331.6	741	44.75	…	…
Pécs Pogány	253.6	666	38.08	620.0	40.90
Pécs, Árpádtető	385.0	839	45.9	729.6	52.77
Sármellék	204.2	…	…	585.3	34.89
Mohács, Sátorhely	177.3	631	28.10	588.0	30.15
Sellye	274.5	725	37.86	695.6	39.46
Siófok	257.9	615	41.93	577.0	44.70

Table 2. Cumulative rainfall amounts of selected settlements in Southwest-Hungary between May 1 and June 16, 2010, compared to the long-term annual average

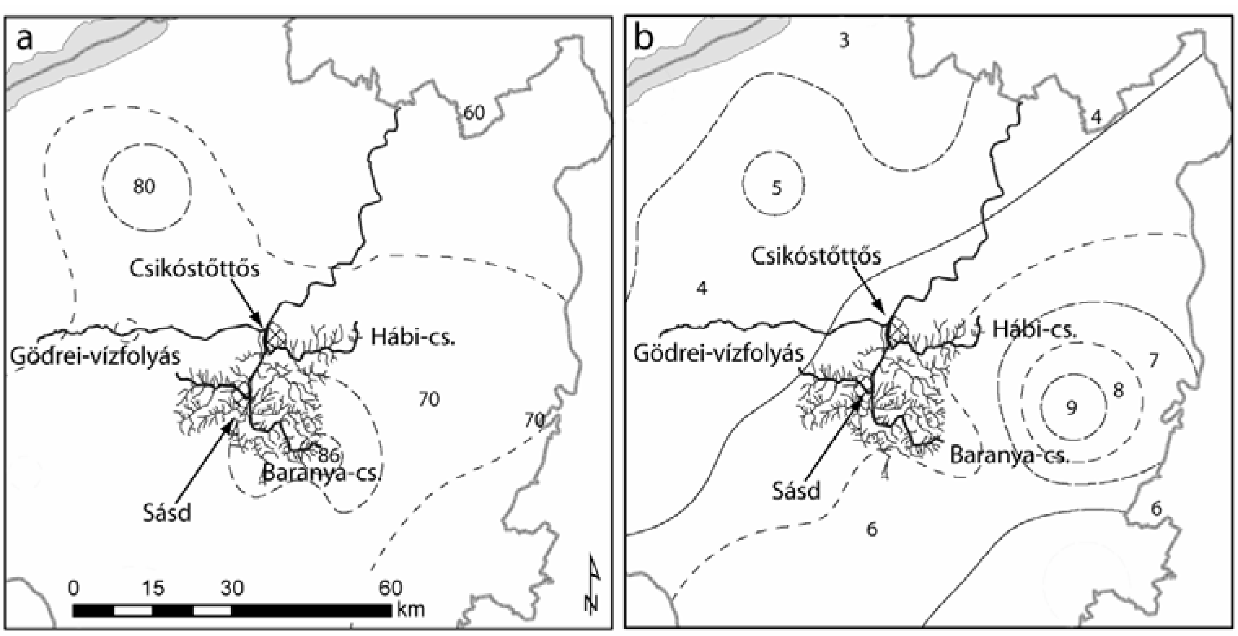


Fig. 7. Total rainfall (mm) (a) and maximum daily rainfall intensities (mm h^{-1}) (b) triggering floods on 16 May in Sásd and Csikóstőttős

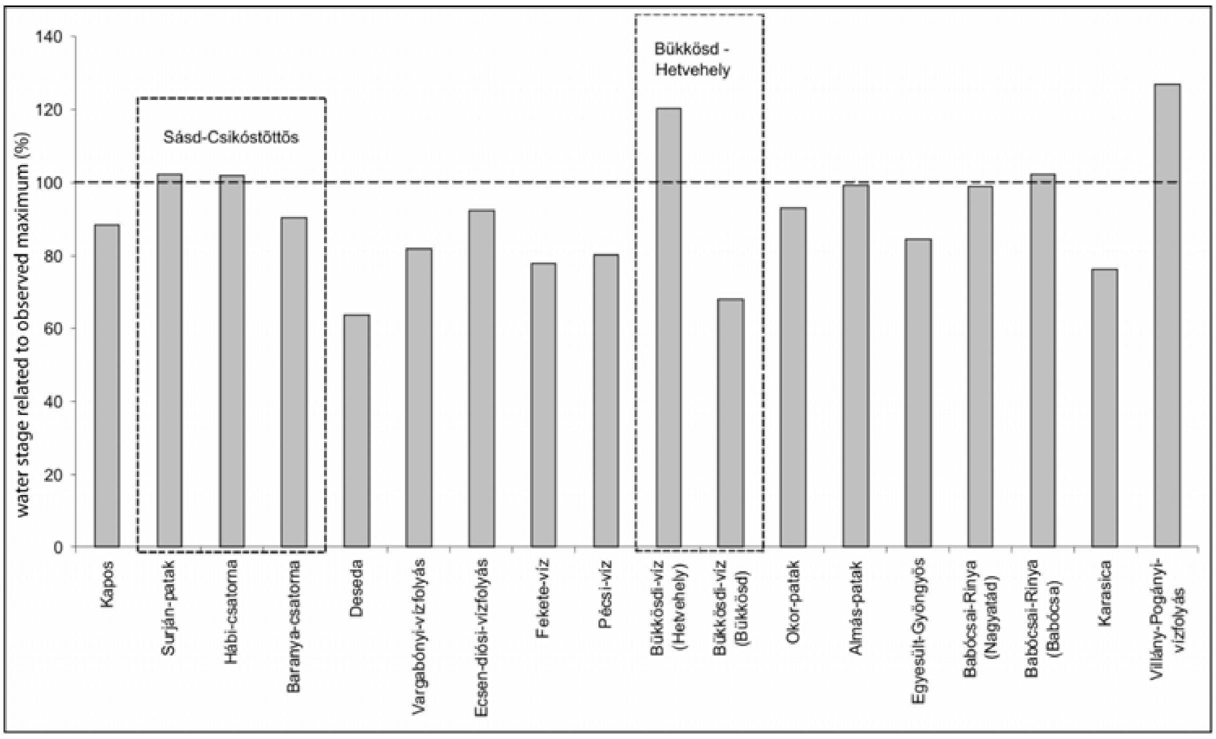


Fig. 8. Stages of selected Southern Transdanubian watercourses between 15 and 18 May 2010, in percentage of the highest stage observed to date. Crucial settlements are marked

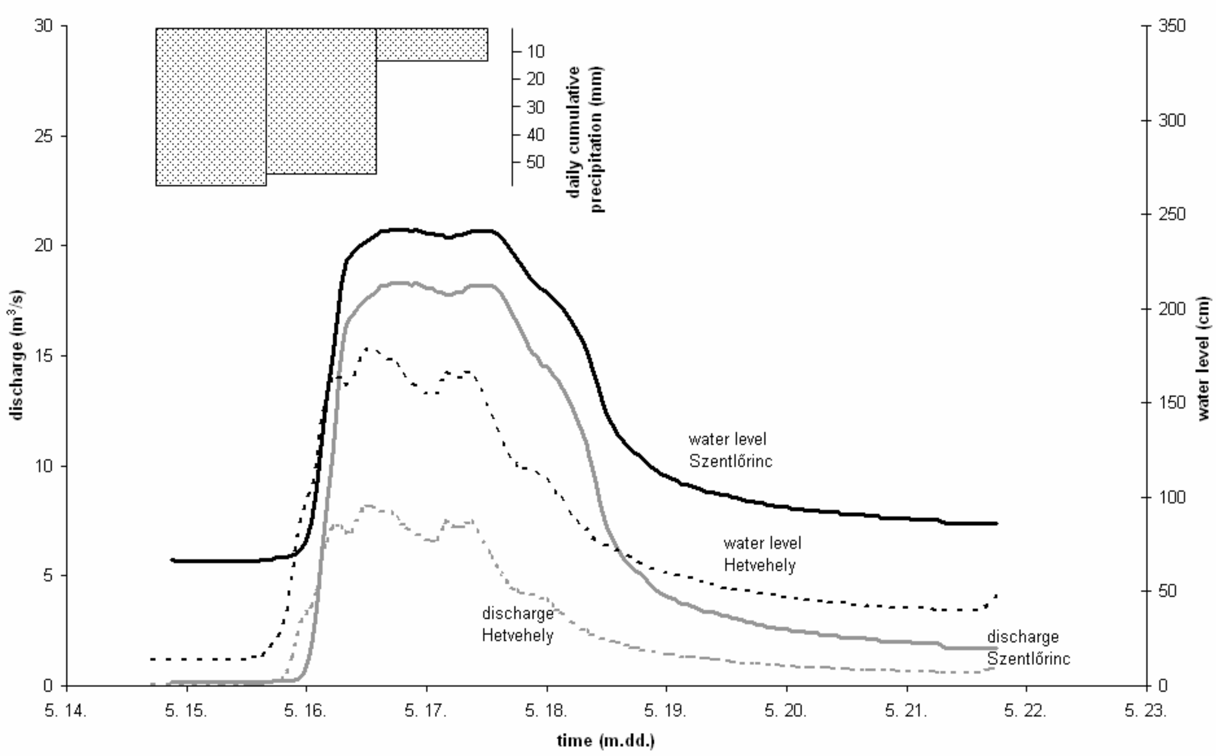


Fig. 9. Discharge and water level curves of the Bükkösd Stream at the Szentlőrinc and Hetvehely stream gauges, showing cumulative rainfall amounts from 15 to 22 May 2010 (data from Institute of Hydrology, Research Institute for Environmental Protection and Water Management [VITUKI])

3.4.2 Results of risk mapping and hydrological modelling

Altogether 210 catchments were delineated in the study area. Their average size is 42 km², the smallest is 2 km², while the largest is 300 km² in area. Figure 10 shows the catchments delineated using the above described method. Considering the combined effect of hydrology and precipitation pattern in Southern Transdanubia, there is a risk of flash flood with a return period of maximum 10 years in almost all mountains and hills of the region.

The categories shown on the output risk map indicate a relatively good correspondence with observed locations of flooding and inundations during the May, 2010 events and the map seems reliable for risk assessment purposes (Fig. 10).

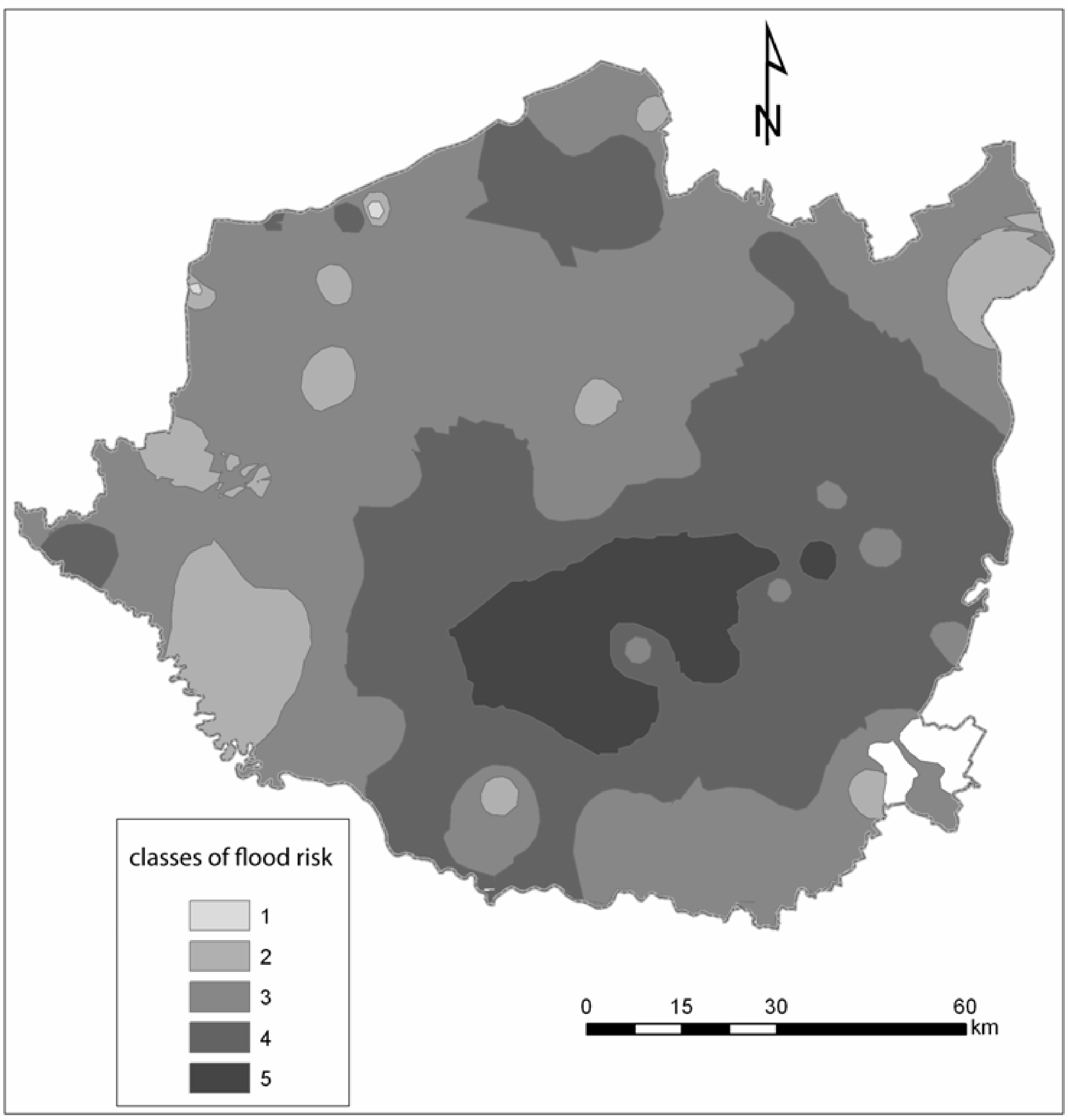


Fig. 10. A flood risk map of Southern Transdanubia prepared using the rapid screening technique. 1 = lowest risk; 2 = highest risk

The basically static approach of GIS-based modelling (focusing on passive factors of inundation risk) is supplemented by hydrodynamic modelling, which expresses basic physical and hydrological relationships with mathematical equations (Maddox et al. 1979). Runoff is represented in critical flow or stage value, which is further analyzed with a flood transformation model. If appropriate data of sufficient spatial resolution are available, the HEC software environment is also suitable for the estimation of the extention of potentially inundated areas. Thus, it can also fulfil a verification function.

Firstly, the HEC-HMS model determines the actual discharge responding to critical rainfall for the catchment under study. However, the output data verification will only be feasible if stream gauge data are available for the catchment. If the simulation is carried out on an unexplored catchment, total runoff (flow) has to be estimated by empirically based equations (Koris, 2002).

Threshold precipitation values, i.e. those that trigger floods with a given return period are determined for various flood levels. In our investigations, based on observed rainfall, a 400-year return period (during which probably a series of undocumented flash flood events occurred) had to be taken into consideration. In this case, in addition to the actual rainfall values, we have to acquire comprehensive knowledge on the entire hydrological cycle, including information on elements like the hydraulic conductivity and infiltration rate of soils, canopy and surface storage. The numerical models also involve topographical analyses, but they are focused on the study of cross-sections. Valley cross-sections are established at predetermined spacing and analyzed along the whole length of the watercourse (Fig. 11). The actual width of the cross-section is designed with regard to the critical flood level above the valley floor or the mean long-term water stage. River flow or stage values are then determined for each cross-section (Fig. 11).

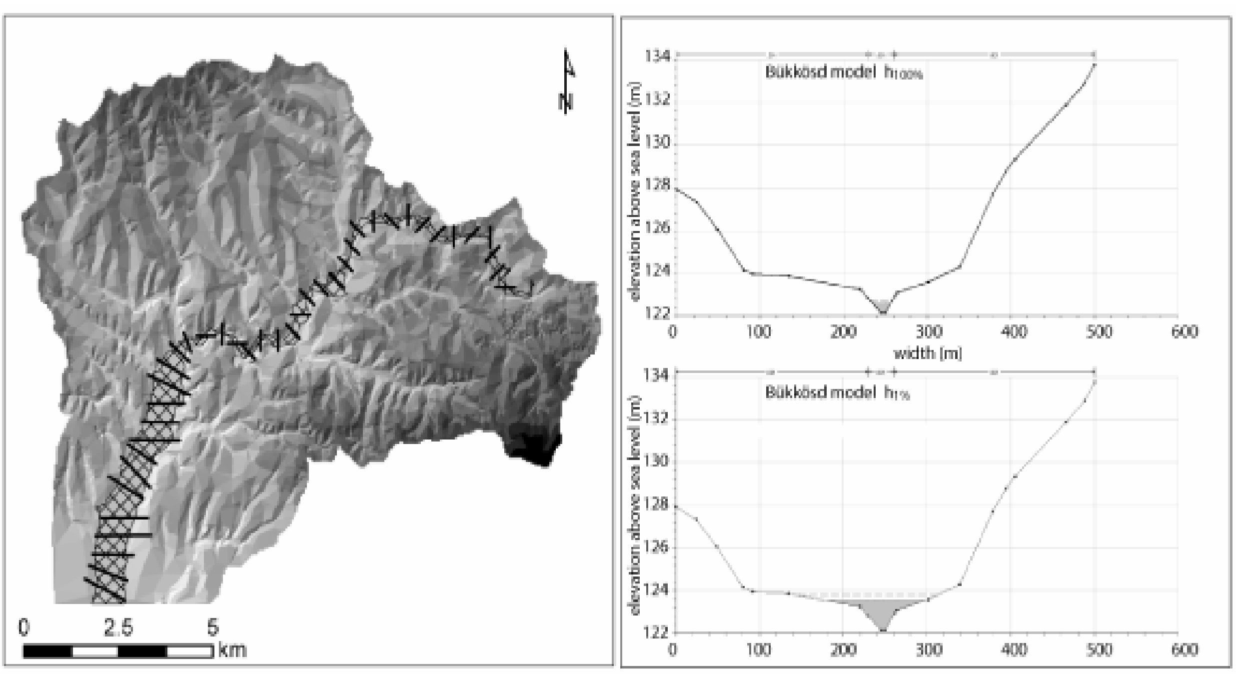


Fig. 11. Cross-sections across the Bükkösd Stream valley (left) and water levels at a sample cross-section for floods of a given probability computed by the HEC-RAS model (right)

Today numerical models are widely applied tools to simulate the areal extent of inundations and flooding along a watercourse (i.e during riverine floods) (Gaume et al., 2004). They are also suitable for flood simulation in urban environments, where the proportion of permeable surfaces are limited and impervious paved surfaces are widespread (e.g. Xia et al., 2011). Numerical modelling is particularly suitable for the analyses of risk scenarios, such as dam breaching, and also capable of the exact localization and parameterization of the elements of the channel and drainage systems (e.g. bridges, levees and culverts) and even appropriate for the 3D representation of these structures.

4. Potential prediction models

The prediction of flood occurrence is the ultimate goal of modelling. Prediction models are classified into two categories: real-time direct forecasting (similar to weather forecasting – e.g. Doswell III, 1996, 1998) and flowchart-type modelling or scenario building (similar to climate change prediction). The models of the first type of forecasting do not seem useful in flash flood prediction in our case since no appropriate monitoring system exists in the study area. Applying the second approach scenarios or flowcharts can be designed for the most endangered catchments in the region (e.g. Alkema, 2003). Flowchart-type modelling takes advantage of the results of the aforementioned rapid screening analysis and risk assessment. The most probable environmental change scenarios are generated with preselected boundary conditions. The boundary conditions incorporated in the model include soil moisture content, relief, surface storage, canopy cover, cumulative rainfall and rainfall intensity. To validate the suitability of this model type we need to verify it with hindcast modelling, i.e. we perform simulation backward in time to see whether it reconstructs the observed event.

For a flowchart analysis data on preceding rainfall events have to be collected to see whether the previous rainfall event was followed by flood warning. Precipitation data originates from meteorological data usually with a 3-hour lead time. These rainfall prediction schemes determine whether a heavy convective, or a prolonged and relatively low-intensity rainfall is expected. All the scenarios in a flow chart model contain a unique code. An analytical software investigates the resemblance of the present scenario to all the predetermined scenarios and finally selects the most adequate output scenario. Finally, it supports the decision of authorities on issuing a flood warning or not.

5. Conclusions

Being an increasingly dangerous environmental hazard, flash floods are intensively investigated worldwide. Information on floods in remote areas is accumulating. Probably related to climate change, flash floods are also becoming a common phenomenon in the mountainous and hilly region of Southern Transdanubia. At least 433 settlements are located and 700,000 inhabitants live in areas potentially affected by flash floods – although the return period of severe inundations is likely to exceed 100 years for most localities. Unfortunately, new developments often ignore this potential hazards and during prolonged dry periods agricultural cultivation frequently extends over floodplains. However, a flood of long return time may cause economic losses of millions of Euros. The investigations in Southwest-Hungary helped to identify areas where, despite the available long-term statistics, settlements, residential areas and farmlands are potentially affected by flooding and serious damage from floods can be predicted. The choice of methodological approaches to the topic is rapidly broadening. The combination of rapid screening methods, GIS-based risk assessment with numerical hydrological modelling and the flowchart analysis of probable scenarios opens new vistas in this research field.

6. Acknowledgements

This research was supported by the Baross Gábor Program (Grant No. REG_DD_KFI_09/PTE_TM09), the Hungarian Science Fundation (OTKA, Grant No. T 68903) and the Bolyai János Scholarship. The authors are grateful for the data and support provided by the Hungarian Meteorological Service, the South-Transdanubian Water Management Directorate (DDKÖVIZIG), the VITUKI Rt. and the Mecsekérc Zrt. The authors are especially indebted to Ákos Horváth, Gábor Horváth, András Varannai, Gergely Resitcky and Roland Vendégh for their contribution to the present work.

7. References

AG BoM (2010). *Facts on Flash Floods in NSW*. Australian Government, Bureau of Meteorology, Melbourne, Victoria, Australia Available from http://www.bom.gov.au/nsw/sevwx/flashfact.shtml Accessed on 10.02.2011

Alkema, D. (2003). Flood risk assessment for EIA (environmental impact assessment): an example of a motorway near Trento, Italy. *Studi Trentini di Scienze Naturali*, Vol.78, pp. 147-153, ISSN 2035-7699

Allan, R.J. (1993). Historical fluctuations in ENSO and teleconnection structure since 1879: Near-global patterns. *Quaternary Australasia,* Vol.11, No.1, 17–27, ISSN 0811-0433

Bálint, G. & Szlávik, L. (2001). Hegy- és dombvidéki kisvízfolyások szélsőséges árvizeinek vizsgálata (Investigation of extreme floods on streams in mountains and hills), *International Conference "Water and Nater Conservation in the Danube–Tisza River Basin",* pp. 341–353, Debrecen, Hungary, 19–21 September 2001, Hungarian Hydrological Society, Budapest (in Hungarian)

Bettess, R. (2005). *Flooding in Boscastle and North Cornwall, August 2004: Phase 2 Studies Report*, HR Wallingford Report EX5160 Available from http://www.hrwallingford.co.uk/downloads/publications/EX5160_Boscastle_floodings.pdf Accessed on 06.06.2011

Borga, M.; Boscolo, P.; Zanon, F. & Sangati, M. (2007). Hydrometeorological analysis of the August 29, 2003 flash flood in the eastern Italian Alps. *Journal of Hydrometeorology*, Vol.8, No.5, pp. 1049–1067, ISSN 1525-755X

Brandes, H. (2000). The Venezuela flash floods and debris flows of 15-16 December 1999. *Landslide News*, Japan Landslide Society, Vol.13, No.1, pp. 5-7, ISSN 0919-5629

Bull, L.J. & Kirkby, M.J. (Eds.). (2002). *Dryland Rivers: Processes and Management in Mediterranean Climates*, John Wiley and Sons, ISBN 0-471-49123-3, Chichester, UK

Burroughs, W.J. (Ed.). 2003. *Climate into the 21st century*, World Meteorological Organization, Cambridge University Press, ISBN 9780521792028, Geneva, Switzerland – Cambridge, UK

Caracena, F.; Maddox, R. A.; Hoxit, L. R. & Chappell, C. F. (1979). Mesoanalysis of the Big Thompson storm. *Monthly Weather Review,* Vol.107, No.1, pp. 1–17, ISSN 0027-0644

Carpenter, T.M.; Sperfslage, J.A.; Georgakakos; K.P., Sweeney, T. & Fread, D.L. (1999). National threshold runoff estimation utilizing GIS is support of operational flash flood warning systems. *Journal of Hydrology,* Vol.224, No.1, pp. 21–44, ISSN 0022-1694

Cobby, D.; Falconer, R.; Forbes, P.; Smyth, P. & Widgery, N. (2009). Potential warning services for groundwater and pluvial flooding, In: *Flood Risk Management: Research and Practice*, Samuels, P., Huntington, S., Allsop, W. & Harrop, J., (Eds.), pp. 1273–1280, Taylor & Francis Group, ISBN 978-0-415-48507-4, London, UK

Cohen, H. & Laronne, J.B. (2005). High rates of sediment transport by flashfloods in the Southern Judean Desert, Israel. *Hydrological Processes*, Vol.19, No.8, pp. 1687–1702. doi: 10. 1002/hyp.5630, online ISSN 1099-1085

Collier, C. (2007). Flash flood forecasting: what are the limits of predictability? *Quarterly Journal of the Royal Meteorological Society,* Vol.133, No.622A, pp. 3–23, doi: 10.1002/qj.29, online ISSN: 1477-870X

Costa, J.E. (1983). Paleohydraulic reconstruction of flash-flood peaks from boulder deposits in the Colorado Front Range. *Geological Society of America Bulletin*, Vol.94, No.8, pp. 986–1004, doi: 10.1130/0016-7606(1983)94<986:PROFPF> 2.0.CO;2, ISSN 0016-7606

Czigány, S.; Pirkhoffer, E. & Geresdi, I. (2008). Environmental impacts of flash floods in Hungary, In: *Flood Risk Management: Research and Practice*, Samuels, P., Huntington, S., Allsop, W. & Harrop, J., (Eds.), pp. 1439–1447, Taylor & Francis Group, ISBN 978-0-415-48507-4, London, UK

Czigány, Sz.; Pirkhoffer, E. & Geresdi, I. (2010). Impact of extreme rainfall and soil moisture on flash flood generation. *Időjárás,* Vol.114, No.1, pp. 79–100, ISSN 0324-6329

Czigány, Sz.; Pirkhoffer, E.; Nagyváradi, L.; Hegedűs, P. & Geresdi, I. (2011a). Rapid screening of flash flood-affected watersheds in Hungary. *Zeistschrift für Geomorphololgie*, Vol.55, Supplementary Issue 1, pp. 1-13, ISSN 0372-8854

Czigány, Sz.; Pirkhoffer, E.; Fábián, Sz. Á. & Ilisics, N. (2011b). Flash floods as natural hazards in Hungary, with special focus on SW Hungary. *Riscuri şi catastrofe, Cluj-Napoca, Romania,* Casa cartii de stiinta. Vol.8, No.1, pp. 117–130, ISSN 1584-5273

Davis, R.S. (2001). Flash flood forecast and detection methods. *Meteorological Monographs,* American Meteorological Society, Vol.28, pp. 481–526, doi: 10.1175/0065-9401-28.50.481, ISSN 0065-9401

Davies, W.; Bailey, J. & Kelly, D. (1972). West Virginia's Buffalo Creek Flood: A Study of the Hydrology and Engineering Geology. *US Department of the Interior, Geological Survey Circular* No.667, pp. 1-32, ISSN 0364-6017

DDKÖVIZIG (2010). *Az esőzések miatt kialakult helyzet Dél-Dunántúlon (The situation caused by heavy rainfall in Southern Transdanubia).* Available from http://www.ddkovizig.hu/magyar/hirek/az_esozesek_miatt_kialakult_helyzet_del-dunantulon (in Hungarian) Accessed on 01.06.2010

De Roo, A.P.J.; Wesseling, C.G. & Van Deursen, W.P.A. (2000). Physically based river basin modelling within a GIS: The LISFLOOD model. *Hydrological Processes*, Vol.14, No. 11-12, pp. 1981–1992, online ISSN 1099-1085

Doswell III, C. A.; Brooks, H. E. & Maddox R. A. (1996). Flash flood forecasting: An ingredients-based methodology. *Weather Forecasting,* Vol.11, No.4, pp. 560–581, ISSN 0882-8156

Doswell III, C. A.; Brooks, H. E.; Romero, R. & Alonso, S. (1998). A diagnostic study of three heavy precipitation episodes in the western Mediterranean region. *Weather Forecasting,* Vol.13, No.1., 102–124, ISSN 0882-8156

EEA (2005). *Climate Change and Floods in Europe*. Report of the European Environmental Agency. Copenhagen, Denmark Available from http://www.eea.europa.eu/hu/publications/briefing _2005_1 Accessed on 01.06.2010

Fábián, Sz. Á.; Görcs, N. L.; Kovács, I. P.; Radvánszky, B. & Varga, G. (2009). Reconstruction of a flash flood event in a small catchment: Nagykónyi, Hungary. *Zeitschrift für Geomorphologie*, Vol.53, No.2, pp. 215–222, ISSN 0372-8854

Gaume, E.; Livet, M.; Desbordes, M. & Villeneuve, J.P. (2004) Hydrological analysis of the river Aude, France, flash flood on 12 and 13 November 1999. *Journal of Hydrology,* Vol. 286, No.1, pp. 135–154, ISSN 0022-1694

Gaume, E.; Bain, V.; Bernardara, P.; Newinger, O.; Barbuc, M.; Bateman, A.; Blaškovičova, L.; Bloschl, G.; Borga, M.; Dumitrescu, A.; Daliakopoulos, I.; Garcia, J.; Irimescu, A.; Kohnova, S.; Koutroulis, A.; Marchi, L.; Matreata, S.; Medina, V.; Preciso, E.; Sempere-Torres, D.; Stancalie, G.; Szolgay, J.; Tsanis, I.; Velascom, D. & Viglione, A. (2009). A compilation of data on European flash floods. *Journal of Hydrology*. Vol. 367, No.1, pp. 70–78, ISSN 0022-1694

Georgakakos, K. P. (1987). Real-time flash flood prediction. *Journal of Geophysical Research,* Vol.92, No.D8, pp. 9615–9629, ISSN 0148-0227

Georgakakos, K. P. (2006). Analytical results for operational flash flood guidance. *Journal of Hydrology*, Vol.317, No.1-2, pp. 81–103, doi: 10.1016/j.jhydrol.2005.05.009, ISSN 0022-1694

Golding, B. (2005). Meteorology of the Boscastle flood. *National Hydrology Seminar 2005*, Galway, 15 November 2005, Irish National Committee, International Hydrological Programme Available from http://www.opw.ie/hydrology/data/speeches/c_gold~1.pdf

Graf, W. L. (2002). *Fluvial Processes in Dryland Rivers*, Reprint of 1st edition (1988), Blackburn Press, ISBN 978-1930665514, Caldwell, New Jersey, USA

Grundfest, E. (1977). What people did during the Big Thompson Flood. *Working Paper No. 32*, Natural Hazards Research and Applications Information Center, Boulder, Colorado, USA

Grundfest, E. (1987). What we have learned since the Big Thompson Flood. *Proceedings of the Tenth Anniversary Conference*, 17–19 July 1986, Special Publication No. 16. Natural Hazards Research and Applications Information Center, Boulder, Colorado, USA Available from http://www.uccs.edu/~geogenvs/flood/ Accessed on 10.05.2011

Grundfest, E. & Ripps, A. (2000). Flash floods, In: *Floods. Vol. 1,* Parker, D. J. (Ed.), pp. 377–390, Routledge, ISBN 978-0415172387, London and New York,

Gutiérrez, F.; Gutiérrez, M. & Sancho, C. (1998). Geomorphological and sedimentological analysis of a catastrophic flash flood in the Arás drainage basin (Central Pyrenees, Spain). *Geomorphology*, Vol.22, No. 3-4, pp. 265-283, ISSN 0169-555X

Gyenizse, P. & Vass, P. (1998). A természeti környezet szerepe a Nyugat-Mecsek településeinek kialakulásában és fejlődésében (The role of the physical environment in the development of settlement in the Western Mecsek Mountains). *Földrajzi Értesítő*, Vol.47, No.1–2, pp. 131-148, ISSN 0054-1503

Horváth, Á. (2005). A 2005. április 18-i mátrakeresztesi árvíz meteorológiai háttere (Background to the 18 April 2005 flood at Mátrakeresztes, North-Hungary). *Légkör*, Vol.50, No.1, pp. 6–10, ISSN 0133-3666 (in Hungarian with English summary)

Iverson, R. M. (1997). The physics of debris flows. *Reviews of Geophysics*, Vol.35. No.3, pp. 245–296, ISSN 8755-1209

Kaliczka, L. (1998). *Hegy és dombvidéki vízrendezés (Water management in mountains and hills),* Manuscript lecture notes. Eötvös József Technical College, Baja (in Hungarian) Available from:
http://levelezo.atw.hu/Jegyzet/hegydombvizrend.pdf Accessed on 03.05.2011

Kodama, K. & Barnes, G. M. (1997). Heavy rain events over the south-facing slopes of Hawaii: Attendant conditions. *Weather Forecasting,* Vol.12, pp. 347–367, ISSN 0882-8156

Koris, K (2002). A hazai hegy- és dombvidéki kisvízgyűjtők árvízhozamainak meghatározása (Determining flood discharges on small cathcment in the mountains and hills of Hungary). *Vízügyi Közlemények*, Vol.84, No.1, pp. 64–77, ISSN 0042-7616 (in Hungarian)

Koris, K. & Winter, J. (2000). Az 1999. évi nyári rendkívüli árvizek a Mátra és a Bükk déli vízgyűjtőjén (Extreme summer floods in the southern catchments of the Mátra and Bükk Mountains, North-Hungary, in 1999). *Vízügyi Közlemények*, Vol.82, N.2, pp. 199–219, ISSN 0042-7616 (in Hungarian)

Laing, A. G. (2004). Cases of heavy precipitation and flash floods in the Caribbean during El Niño winters. *Journal of Hydrometeorology*, Vol.5, (August 2004), pp. 577–594, doi: 10.1175/1525-7541(2004)005<0577:COHPAF>2.0.CO;2, ISSN 1525-7541

Lóczy, D. & Juhász, Á. (1996). Hungary, In: *Geomorphological hazards of Europe*, Embleton, C. and Embleton, Ch., (Ed.), 243-262, Elsevier, ISBN 0-444-88824-1, Amsterdam, The Netherlands

Lóczy, D. (2010). Flood hazard in Hungary: a re-assessment. *Central European Journal of Geosciences,* Vol.2, No.4, pp. 537–547, doi: 10.2478/v10085-010-0029-0, ISSN 18961517

Maarten, R.; Erlich, M.; Versini, P.-A.; Gaume, E.; Lumbroso, D.; Asselman, N.; Hooijer, A. & de Bruijn, K. (2007). *Review of flood event management Decision Support Systems*. FLOODsite Project Report T19-07-01 Available from:
http://floodsite.net/html/cd_task17-19/docs/reports/T19/Task19_report_M19_1 review_v1_4.pdf Accessed on 03.06.2011

Maddox, R. A.; Chappell, C. F. & Hoxit, L. R. (1979). Synoptic and mesoalpha-scale aspects of flash flood events. *Bulletin of American Meteorological Society,* Vol.60, pp. 115–123, ISSN 1520-0477

NOAA, National Weather Service (1992). *Puerto Rico flash floods, January 5–6, 1992*. Natural Disaster Survey Report, Silver Spring, Maryland, USA, 92 pp.

Norbiato, D.; Borga, M.; Degli Esposti, S.; 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* Vol.362, Nos. 3–4, pp. 274–290, doi:10.1016/j.jhydrol.2008.08.023, ISSN 0022-1694

Pászthory, R. & Szigeti, F. (2009). Árvízi Kockázati Információs Rendszer (Flood Risk Information System), *Conference paper at the Conference of the Hungarian Hydrological Society*, Baja (in Hungarian) Available from: http://www.hidrologia.hu/mht/index.php Accessed on 01.06.2010

Paudel, M. (2010). *An examination of distributed hydrologic modeling methods as compared with traditional lumped parameter approaches*. PhD Dissertation, Brigham University, Provo, Utah, USA Available from: http://contentdm.lib.byu.edu/ETD/image/etd3708.pdf Accessed on 06.07.2011

Pirkhoffer, E.; Czigány, S. & Geresdi, I. (2009a). Impact of rainfall pattern on the occurrence of flash floods in Hungary. *Zeitschrift für Geomorphologie*, Vol.53, No.2, pp. 139–157, ISSN 0372-8854

Pirkhoffer, E.; Czigány, Sz.; Geresdi, I. & Lovász, Gy. (2009b). Environmental hazards in small watersheds: flash floods – impact of soil moisture and canopy cover on flash flood generation. *Riscuri şi catastrofe, Cluj-Napoca,* Casa cartii de stiinta, pp. 117–130, ISSN 1584-5273

Pontrelli, M. D.; Bryan, G. & Fritsch, J. M. (1999). The Madison County, Virginia, flash flood of 27 June 1995. *Weather Forecasting,* Vol.14, No.4, pp. 384–404, ISSN 0882-8156

Reid, I. (2004). Flash flood, In: *Encyclopedia of Geomorphology Vol.1.*, Goudie, A.S., (editor-in-chief), Routledge, pp. 376–378, ISBN 0-415-32737-7, London, UK

Reid, I.; Laronne, J.B.; Powell, D.M. & Garcia, C. (1994). Flash floods in desert rivers: studying the unexpected. *EOS, Transactions, American Geophysical Union*, Vol.75, No.39, p. 452, doi: 10.1029/94EO01076 ISSN 0096-3941

Schmittner, K.E. & Giresse, P. (1996). Modelling and application of the geomorphic and environmental controls on flash flood flow. *Geomorphology*, Vol.16, No.4, pp. 337–347, doi:10.1016/0169-555X(96)00002-5, ISSN 0169-555X

Stevaux, J.C. & Latrubesse, E. (2010). Urban Floods in Brazil, In: *Geomorphology of Natural Hazards and Human Exacerbated Disasters in Latin America*, E. Latrubesse, (Ed.), pp. 245-266, Elsevier, ISBN 9780444531179, Amsterdam, The Netherlands

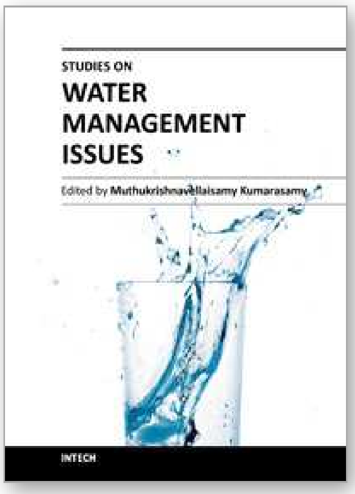
US Army Corps of Engineers (2005). *Hydrologic Modeling System HEC-HMS*. User's Manual, Version 3.0.0. USACE Hydrologic Engineering Center, Davis, California, USA

Vass, P. (1997). Árvizek a Bükkösdi-patak felső szakaszán (Floods in the headwaters of the Bükkösd Stream), In: *Földrajzi tanulmányok a pécsi doktoriskolából I.,* Tésits, R. & Tóth, J. (Eds.), pp. 261–285, Bornus Nyomda, Pécs, Hungary (in Hungarian, English summary)

Weston, K. J. & Roy, M. G. (1994). The directional-dependence of the enhancement of rainfall over complex orography. *Meteorological Applications,* Vol.1, No.3, pp. 267–275, doi: 10.1002/met.5060010308, ISSN 1469-8080

Wieczorek, G. F.; Larsen, M. C.; Eaton, L. S.; Morgan, B. A. & Blair, J. L. (2001). Debris-flow and flooding hazards associated with the December 1999 storm in coastal

Venezuela and strategies for mitigation. *U. S. Geological Survey Open File Report 01-0144*, Available from:
http://pubs.usgs.gov/of/2001/ofr-01-0144 Accessed on 02.04.2011
Xia, J.Q.; Falconer, R.A.; Lin, B.J. & Tan, G.M. (2011). Modelling flash flood risk in urban areas. Water Management, Vol.164, No.6, pp. 267–282, doi: 10.1680/wama.2011.164.6.267, ISSN 1741-7589



Studies on Water Management Issues

Edited by Dr. Muthukrishnavellaisamy Kumarasamy

ISBN 978-953-307-961-5
Hard cover, 274 pages
Publisher InTech
Published online 18, January, 2012
Published in print edition January, 2012

This book shares knowledge gained through water management related research. It describes a broad range of approaches and technologies, of which have been developed and used by researchers for managing water resource problems. This multidisciplinary book covers water management issues under surface water management, groundwater management, water quality management, and water resource planning management subtopics. The main objective of this book is to enable a better understanding of these perspectives relating to water management practices. This book is expected to be useful to researchers, policy-makers, and non-governmental organizations working on water related projects in countries worldwide.

InTech Europe
University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
Fax: +385 (51) 686 166
www.intechopen.com

InTech China
Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821