FLASH FLOODS AS NATURAL HAZARDS IN HUNGARY, WITH SPECIAL FOCUS ON SW HUNGARY

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ABSTRACT. – Flash floods as natural hazards in Hungary, with special focus on SW Hungary. Flash floods are increasingly frequent natural hazards in Hungary. Record precipitation values in Hungary in May and June, 2010, underline the importance of the modeling of the extension of inundations and the prediction of flood events. This paper summarizes the concept of flash floods from hydrological and meteorological approaches and, shows an example for the application of rapid screening, GIS and numerical modeling in Southern Transdanubia.

Key words: flash flood, modeling, rapid screening, prediction system, GIS

Introduction

Due to the climate change of the recent days, frequency of extreme, hard-to-forecast weather phenomena and their consequences gradually increases. Such phenomena generate significant losses in areas of strong relief and may also cause injuries and deaths. According to a report of the European Environment Agency, flash floods rank as number one on the list of the most frequent natural disasters in Europe (EEA, 2005).

Flood related disasters and their consequences have appeared with an increasing frequency in the Hungarian media as well. Over the period of May and June, 2010, hitherto quasi-unknown stream names (e.g. Hábi Canal, Bükkösd Stream and Baranya Canal) appeared in the media in Hungary. Floods caused significant economic losses in Csikóstőttős and Sásd, Baranya County, SW Hungary (Fig. 1). Locally, cumulative precipitation exceeded 300 mm between May 2 and June 16, 2010, while cumulative daily precipitation and intensity values broke the previous records at several locations. As a result stream stages have also exceeded the previous records at many stream gages. Consequently, flood prevention needs to be also extended to the previously neglected small mountainous catchments that cover about 30 per cent of the entire land area of Hungary, while the cumulative length of streams total more than 20,000 km (KALICZKA, 1998). Novel flood assessment and prevention programs, such as the presently planned and constructed nationwide ÁKIR (Flood Risk Information System) program, a model and software based flood prediction system, need to devote a considerable attention to flash flood affected stream reaches and watersheds (PÁSZTHORY & SZIGETI, 2009).

Objectives

The present review paper provides an overview of the general characteristics of flash floods, and describes the potential risks associated with devastating floods of this type through selected Hungarian instances. A proposed flood risk assessment map and numeric flood forecasting systems would likely mitigate flood-triggered (economic and life) losses and would aid insurance companies to appropriately delineate the areas of various coverage categories.

Materials and methods

Numeric modeling of flash flood requires a different approach from that of large riverine floods. Analyses require a more complex approach while several environmental factors need to be considered and regularly monitored. The first comprehensive, but least detailed type of approach is the so-called rapid screening type analysis that employs ARC GIS and SGA GIS softwares. This type of analysis requires various input datasets, e.g.: soil databases, land use, geologic and topography.

In case studies and pilot catchments we used the 50 m and 10 m spatial resolution topographic maps. With field survey, using TOPCON HiPER Pro RTK GNSS high-precision GPS an SOKKIA geodetic instruments, the spatial resolution of the generated DEM was locally (usually in the immediate vicinity of water courses) increased to 1 m.

Radar images and various meteorological data was obtained from the Hungarian Meteorological services, while hydrological data (e.g.: stage and discharge) was received from VITUKI Rt. (Water Resources Research Centre), DDKÖVIZIG (South-Transdanubian Environmental Protection and Water Management Directorate) and the MECSEKÉRC Rt., a sister company of the former uranium mining company.

Surface runoff was simulated using HEC-HMS *(HEC Hydrologic Modeling System,* developed by the *Hydrologic Engineering Center, Davis, CA, United States),* while inundation mapping was done with HEC-RAS, HEC-GeoRAS and ArcGIS 9.1. The HEC-HMS is designed to simulate the precipitation-runoff processes of dendritic watershed systems. It is designed to be applicable in a wide range of geographic areas for solving the widest possible range of problems. This includes large river basin water supply and flood hydrology, and small urban or natural watershed runoff (*US Army Corps of Engineers*, 2005)

To obtain field measured data we monitored soil moisture (using Time Domain Reflectrometry technique), canopy cover and precipitation at 14 monitoring station in a 1.7 km^2 pilot catchment. Runoff output data was then compared with observed flow.

General characteristics of flash floods

Flash floods are naturally not novel phenomena, however the frequency of their occurrence indicates an increasing tendency. Similarly, they are not as intensively studied as conventional large riverine floods, however in certain countries (e.g.: United States and United Kingdom) extensive literature is available on flash flood research (e.g.: GRUNTFEST, 1977, 1987; CARPENTER *et al.*, 1999; SCHMITTNER & GIRESSE 1996; GEORGAKAKOS, 1987). Storm driven floods or flash flood may also trigger debris flow when the amount of transported sediment is considerable compared to the volume of the water (Iverson, 1997). The particle size of the transported sediment varies greatly ranging from clay size particles to large blocks. Debris flow moves relatively rapidly, usually between a velocity of 0.5 to 20 m s^{-1}, however often confined to a relatively narrow area.

Meteorologically flash floods are best described by the term "too much water in too little time" (GRUNDFEST, E. & RIPPS, A., 2000). This expression refers to the large amount of precipitation that falls on a relatively small catchment in a relatively short time. The hydrological approach is somewhat more sophisticated in this case: it also considers topography and other aforementioned environmental factors as boundary conditions for flash flood generation.

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

Similar rainfall event triggers urban floods (e.g.: STEVAUX & LATRUBESSE, 2010), however in this case the environmental factors are completely different from the previous cases, thus the adequate literature distinguish them as a stand-alone category. In this case the high proportion of impervious surfaces and the limited capacity of drainage system may be responsible for flooding. For urban floods, the observed events in Pécs, Szekszárd and Komló over the period of May and June, 2010 are the finest examples in Hungary (Fig. 2 and 3).

Figure 2. Urban flood inundation in the town of Komló

Figure 3. Urban flood inundation along the Meszes Stream in Pécs

It is obvious, that conventional large riverine floods and flash floods not only differ in their general characteristics but also in the way they appearances are predicted. The first and perhaps most notable difference lies in their time of concentration and the duration of flood peaks. Time fo concentration in the case of flash floods is up to 6 hours, according to definition of the National Oceanic and Atmospheric Administration (Fig. 4). This extremely short lead time makes warning and prevention extremely challenging and difficult. Due to the rapid process, we only obtain a vague overview of any flash flood events in unexplored and ungauged watersheds. Here, our knowledge is limited to field surveys, and in many cases only the falling limb of the hydrograph is observed, and flood reconstruction is only available by assessing of the event aftermaths.

The general characteristics of the flood-triggering precipitation also largely differ between the two flood types. Flash floods are generally associated with intense and convective rainfall events which is often further enhanced in intensity by orographic effects (HORVÁTH, 2005). Large riverine floods, on the other hand, are often preceded by multiple-day rainfall events that extends to large (several 100s or 1,000s km^2) areas and to several watersheds. However, despite their precipitation characteristics, flash floods are not exclusively associated with the summer season (at least under humid continental climate), but rain-on-snow events also often generate flash flood events in SW Hungary PIRKHOFFER E. et al., 2009a, 2009b; CZIGÁNY et al., 2010).

From forecast viewpoint, the area of the simulated watersheds also considerably differs between the two flood types. For flash flood modeling and forecast, usually an area of 10 to 200 km^2 is selected: in other words about an order or two magnitude less than in the case of large riverine floods. Secondly, in the

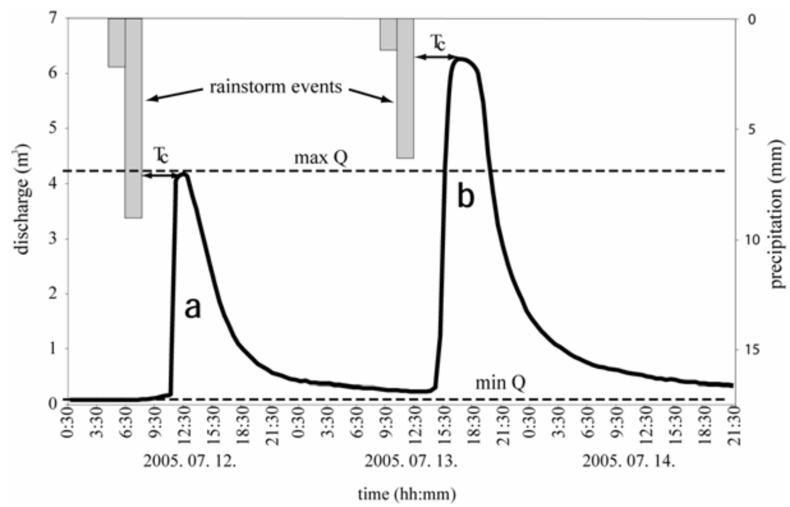

Figure 4. Hydrograph of a typical flash flood (a) and of a flood event with saturated soils (b)

case of flash floods peak flow may exceed baseflow several hundred times, and peak discharge only last for a few hours. Moreover, as flash floods are usually triggered in the upper narrow reach of the stream, stage increase is even more pronounced than flow changes. Fig. 4 shows a typical example for a rapidly rising, but slowly mitigating hydrograph, where time of concentration (T_c) is extremely short. The second flow peak, due to higher soil moisture contents, is triggered by a relatively low cumulative precipitation.

Time of residence in the individual reservoirs (e.g.: canopy storage or surface storage) of the hydrologic cycle is usually much shorter for flash floods than for conventional large riverine floods. Rainfall intensity largely exceeds infiltration rate, thus excess runoff will rapidly be collected to intermittent and periodic streams flowing in surface gullies that soon reach permanent river beds where rapid increase of water will be observed (Fig. 4.). The complexity of numeric modeling is further exacerbated by the plethora of environmental factors that need be considered during the simulation process. Based on the available data on documented flash floods, settlements and residential areas of highest risk are located at the boundaries of areas of high and adjacent low relief and where abrupt narrowing (bottleneck) of river valleys are found. 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.

Flash flood disasters in Hungary

The most significant flash flood events in Hungary have been described by the authors of the present paper formerly (PIRKHOFFER et al., 2009b). There are a relatively few flash flood events have been documented and reported in Hungary (Gyneizse & Vass, 1998; Fábián et al., 2009). The reason for this low level of documentation is the lack of appropriate monitoring systems in the flash flood affected watersheds (Vass, 1997).

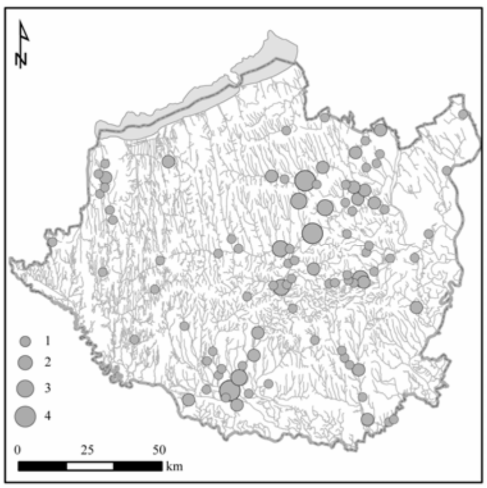

Figure 5. Local inundation damage in Southern Transdanubia based on insurance data (after VARANNAI, A. 2005)

A major concern with the development of a well-established flash flood warning system in Hungary is the lack of measured data and adequate monitoring system in the flash flood affected watersheds. Thus, the number of documented flash flood event is very low in Hungary. The best approach to estimate the approximate number of flash flood events is Hungary is through reports submitted to insurance companies. Here we present the reported insurance claims where damage is likely to be associated with flash floods for the period of 1980 to 2005 (Varannai, 2005) (Fig 5).

One of the most disastrous flash flood events in Hungary occurred on May and June, 2010. Flood swept through Pécs-Meszes destroying several houses and partly the road pavement (Fig. 3). Sixty-five people were evacuated in Csikóstőttős in May, a 1 m high flood swept away a children's camp in Szekszárd, where firemen assisted to evacuate the campers.

According to the estimation of the insurance companies, the May and June flood events caused about a 100 billion forint (360 million Euros) economic loss, at least 3,100 residential homes were damaged and the agricultural loss totals about 30 billion HUF (110 million Euros).

Hydrographic basics of flash flood modeling

To study and potentially predict flash floods, we need be aware of the hydrographic and hydrodynamic characteristics of the area of concern.
The cumulative strength of water courses in SW Hungary (South Transdanubian region) totals about 10,000 km, from which 8,000 km is found in hilly and mountainous areas.

The most important water courses found in hilly and mountainous areas include the Kapos, Koppány, Baranya Canal, Pécs Stream, Bükkösd Stream, Völgység Stream that are all fed by numerous small streams (Fig. 6). Over the past few years several flood mitigation pools were constructed in order to avoid or mitigate losses caused by heavy convective rainfall.

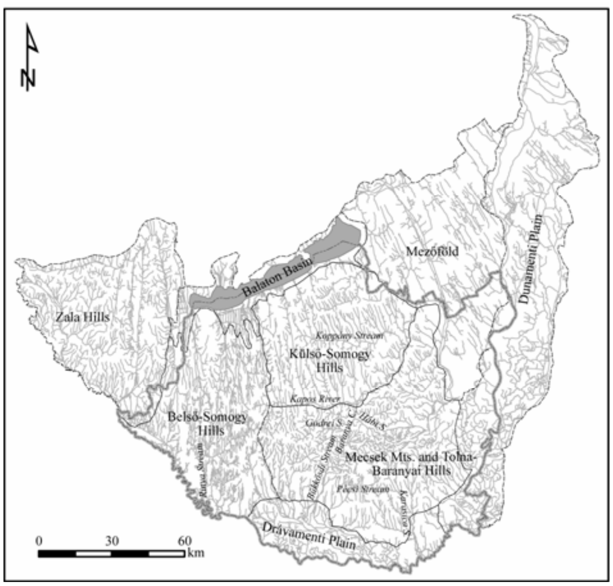

Figure 6. Drainage network of Southern Transdanubia

Correlation between rainfall and flood levels

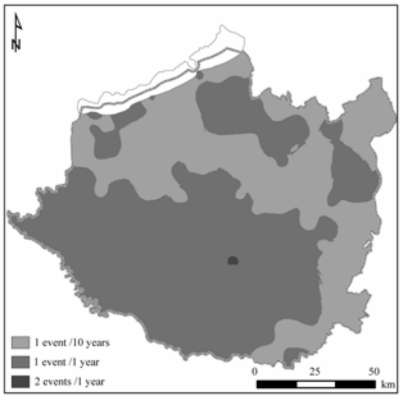

Figure 7. Probability of occurrence of more than 30 mm daily precipitation

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 behavior of rainfall during the period of May and June, 2010 in SW Hungary.

Insurance covers damages in Hungary when rainfall events exceed a daily cumulative daily precipitation of 30 mm, if it is confirmed by the Hungarian Meteorological Services (VARANNAI, 2005). Fig. 7 clearly shows that at least one event exceeding 30 mm is documented in each year in the entire area of SW Hungary. The actual number of events of this type is shown in Table 1.

Table 1. Selected rainfall properties of the studied area between May 1 and June16, 2010

Name of the 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

A persistent waving low-pressure system dominated in the central and western part of the Mediterranean and Central and Eastern Europe on in mid-May and stayed in this region for three to four days. Similarly, the Carpathian basin was affected by wet air masses generating extensive, long term and relatively high-intensity precipitation on May 14 to 17, while the second part of May was characterized with local, however extremely high intensity rain showers and downpours.

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

Name of the meteorological station	Cumulative precipitation during the studied period (mm)	Annual mean cumulative precipitation between 1941–1970 (mm)	Percentage of the cumulative precipitation of the studied period compared to the mean of 1941-1970 period (%)	Annual mean cumu lative precipitation between 1961–1990 (mm)	Percentage of the cumulative precipitation of the studied period compared to the mean of 1961-1990 period (%)
Bátaapáti	308.0	741	41.57	593.0[3]	51.94
Fonyód	278.3	730	38.12	561.2[4]	49.59
Homokszentgyörgy	175.1	773	22.65	648.2[4]	27.01
Iklódbördőce	285.6	…	…	688.0[4]	41.51
Iregszemcse	226.7	640	35.42	617.0	36.74
Kaposvár	225.8	746	30.27	578.6[4]	39.02
Keszthely	385.5	664	58.06	526.9[4]	73.16
Kisbárapáti	185.1	688[1]	26.9	559.3[4]	33.09
Nagykanizsa	251.0	743	33.78	726.0	34.57
Nemeskisfalud	273.2	...	…	648.8[4]	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[2]	45.9	729.6[4]	52.77
Sármellék	204.2	…	…	585.3[5]	34.89
Sátorhely/Mohács	177.3	631	28.10	588.0	30.15
Sellye	274.5	725	37.86	695.6[4]	39.46
Siófok	257.9	615	41.93	577.0	44.70

Even though the May 15 and 16 flash floods are typical from a hydrologic viewpoint, they were not typical regarding the general characteristics of the precipitation as typical convective cells were not observed in this period. The reason for flash flood occurrence here is the pre-saturation of soils in the upper and steep portions of the watersheds of the Baranya and Hábi Canals and the Bükkösd Stream in the first part of May. Due to the nearly water saturated soil conditions, soil behaved as an impervious surface triggering extreme surface runoff. Soil moisture content only slightly decreased in the following two wee thus the second storm with less cumulative rainfall again triggered flash floods on May 31 and June 1. Over the period of May 1 to

June 16 the cumulative number of rainy days reached at least 21 at all rain gages operated by the Hungarian Meteorological Services in SW Hungary (Table 1. and Fig 8b). Groundwater tables in the observation wells of the area indicated a mean elevation increase of 1 to 1.2 meters in the entire region (DDKÖVIZIG, 2010).

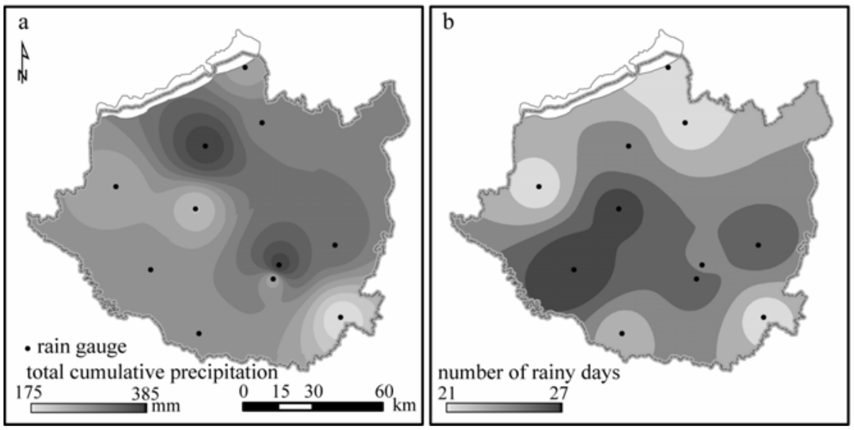

Figure 8. Total cumulative rainfall (a) and number of rainy days (b) in Southern Transdanubia between May 1 and June 16, 2010 (data provided by the Hungarian Meteorological Services)

Table 2. clearly illustrates the extreme precipitation characteristics of the above mentioned 47-day period. At many rain gages in the studied area precipitation reached or even exceeded 50% of the mean annual rainfall.

The long term monthly average precipitation in May in Pécs is 84 mm; the cumulative precipitation in May, 2010 was nearly threefold higher. The estimated return time of such precipitation is 400 years (Bötkös T., personal communication).

The extreme rainfall behavior is also well reflected in the actual intensity values observed in the studied area. For short periods, intensity values reached 30 mm h^{-1}, while for a 10-minute period in Keszthely at the HMS-operated rain gage, intensity reached 51.6 mm h^{-1}.

In the case of small mountainous watersheds is essential to know the areal extent of the rainfall zone. Due to the scarcity of actual rain gages, observations need to be aided with radar images. The average diameter of convective cells is around 5 to 10 km, thus radar images (presently 2 by 2 km in Hungary) of adequate resolution are necessary for optimal estimation of the areal extent of precipitation for modeling purposes.

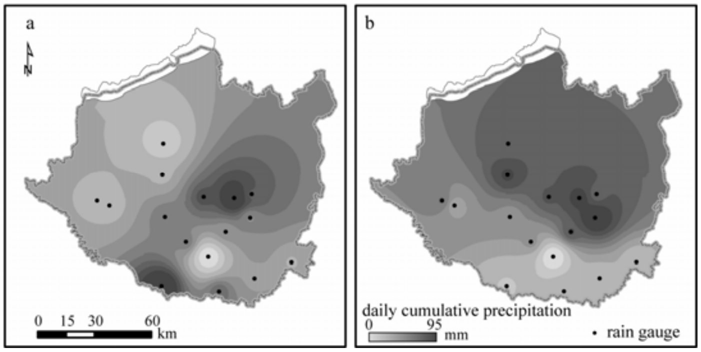

Figure 9. Cumulative daily rainfall in Southern Transdanubia on 15 (a) and 16 (b), May, 2010 (data provided by DDKÖVIZIG)

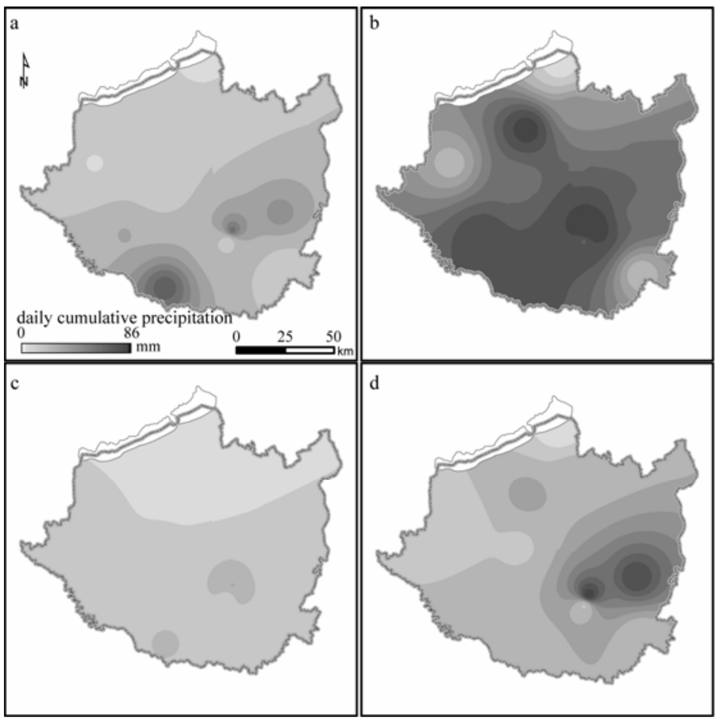

Figure 10. Cumulative daily rainfall in Southern Transdanubia on (a) May 15, (b) May 16, (c) May 31 and (d) June 1, 2010 (data provided by the Hungarian Meteorological Services)

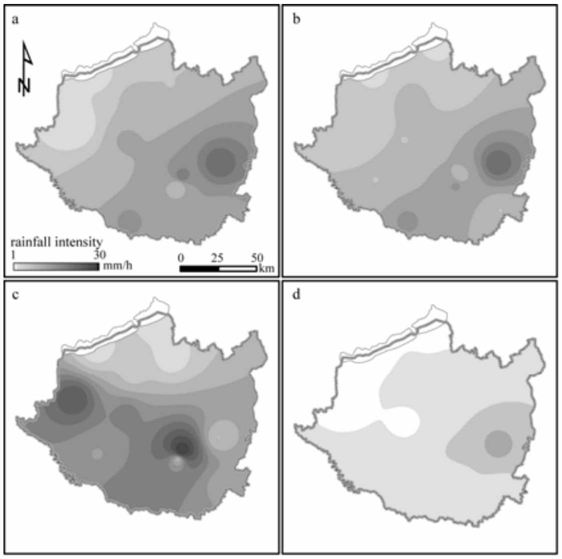

Figure 11. Daily rainfall intensities in Southern Transdanubia on (a) May 15, (b) May 16, (c) May 31 and (d) June 1, 2010 (data provided by the Hungarian Meteorological Services)

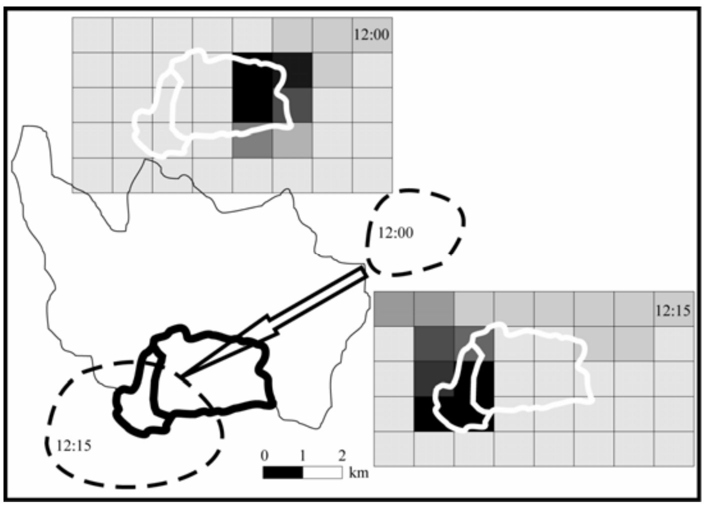

Figure 12. Application of radar images for estimation of cumulative rainfall in ultra-small catchments (for further explanation see the text)

Heavy rainfall characterized the settlements of Sásd and Csikóstőttős on May 15, 2010 (Fig. 13) and maximum cumulative rainfall and intensity values were observed basically in the same area on the following day (May 16, 2010, Figs. 9 and

10). Eighty-six millimeters of rain fell on May 15 to the upper catchments of the Baranya Canal, where time of concentration is shortest within the catchment. As a consequence flood stages were just slightly off from the previous records (Fig. 14). South of the divide, in the watershed of the Bükkösd Stream the rainfall event was much longer, thus the persistent high flood levels were also longer at the Szentlőrinc stream gage than at the gages further upstream (Fig. 15).

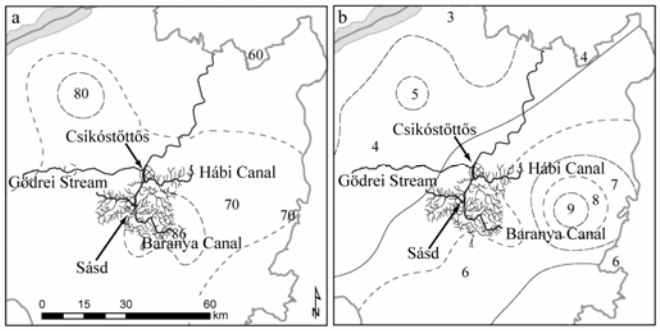

Figure 13. Total cumulative rainfall (mm) (Fig. a) and maximum daily rainfall intensities (mm/h) (Fig. b) triggering floods on May 16 in Sásd and Csikóstőttős

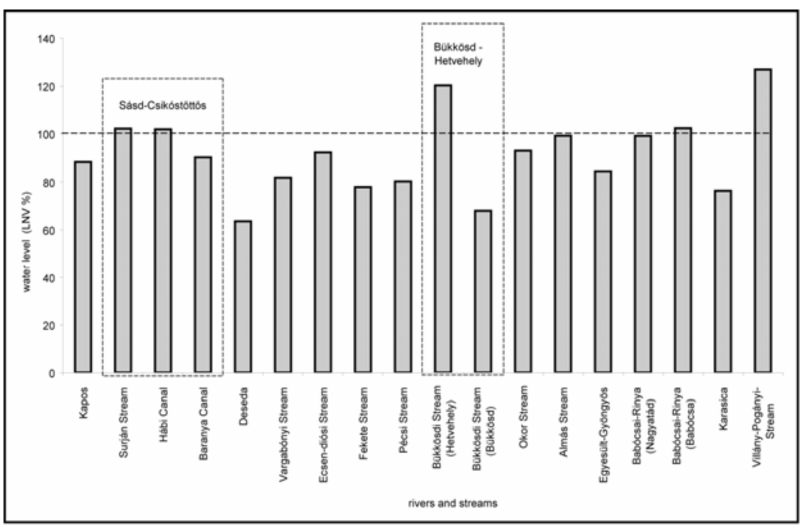

Figure 14. Stages of selected Southern Transdanubian water-courses between May 15 and 18, 2010, in percentage compared to the highest stage to date

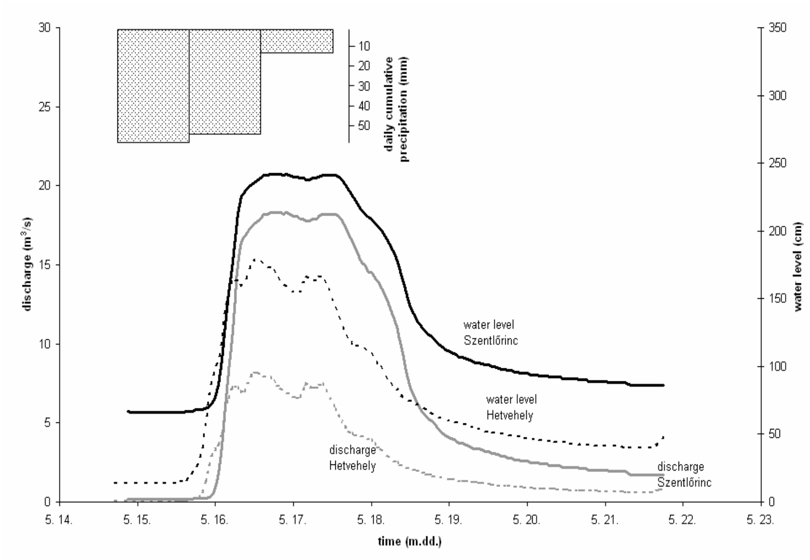

Figure 15. Flow and stage chart of the Bükkösd Stream at the Szentlőrinc and Hetvehely stream gauges, showing cumulative rainfall amounts

Rapid screening type models

Watershed delineation tools for potential flood risk greatly differ in their way of approach. They are based on spatial statistics, GIS methods or complex hydrologic and numeric models. Naturally, models are simplified versions of real events, there not necessary accurate, but their accuracy may be increased with filed observations and verifications.

The so-called rapid screening type models are employed to delineate the actual area of natural disasters or classify them according to their actual risk level (COBBY et al., 2009; CZIGÁNY et al., 2008; PIRKHOFFER, et al., 2008). This type of maps provide a general overview for both experts, decision-makers and civilians for prevention and potential loss mitigation decisions. The first step of our research included the delineation, from a topographic and hydrologic viewpoint, of those watersheds of Hungary which are potentially affected by flash floods (Fig. 16.).

Risk assessment has to be carried out for individual watersheds, as watershed characteristics influence flood level, stream behavior, while the impacts of floods are most pronounced along the water course and at the outflow point of the watershed. All watersheds were assigned with an unique ID number and an outflow point with same ID number where each outflow point is a settlement or a residential area.

An arbitrary watershed, i.e. where the outflow point is located within a settlement is not a physically based natural delineation of watershed boundaries, but real economic loss is obviously occurs at residential areas thus we believe that watershed delineation from this viewpoint is appropriate. Based on the aforementioned delineation method we identified 210 watersheds in the studied area of SW Hungary. The average watershed size in this delineation scheme is 42 km^2, the smallest studied watershed has a surface area of 2 km^2, while the largest one is 300 km^2.

Figure 16. The studied catchments and their outflow points

For flood risk assessment in mountainous and hilly areas two basic methods are available: the first one is based on passive factors those that do not change significantly with time, the second method is extended with the active factors i.e. those change significantly with time (precipitation, canopy cover and soil moisture content). Passive environmental factors are determined with relatively high accuracy; however spatially and temporally correct data on active factors are hard to obtain (BÁLINT & SZLÁVIK, 2001). Vulnerability is determined by the complex, superimposed impact of passive factors when appropriate weighing is employed. Considering the combined effect of hydrology and precipitation pattern of the South Transdanubian area, there is a risk of flash flood with a return period of maximum 10 years in almost all mountainous and hilly areas of SW Hungary.

To generate the vulnerability model, data were derived from 50-meter resolution raster databases. However, this resolution does not necessarily mean the identification of 50-meter units. This pixel size was employed to ease data processing from the digital elevation model. Due to the average resolution of the input databases, the approximate resolution of the vulnerability map is 1:100,000 to 1:250,000. Considering that scaling used in geoinformatics is not entirely analogous with that used in conventional cartography, an approximate scale range as a resolution was provided for the vulnerability map.

The environmental factors incorporated in the vulnerability map are classified into three categories (topographic, land cover, and hydrological parameters). Factors included in the first group (topographic parameters) are derived from the digital elevation model. Factors belonging the second group were derived from land cover parameters (Corine Land Cover 2000) and soil databases (AGROTOPO Hungarian soil database). The third groups of environmental factors were derived from the river network database of Hungary.

From the viewpoint of flash flood vulnerability, three topographical properties were chosen to be incorporated in the final vulnerability model. Firstly, the average slope was applied on a watershed basis. Secondly, the slope range that is spanned between the most gentle to the steepest slope was used within a given watershed. Thirdly we calculated valley density in a unit of km per km^2.

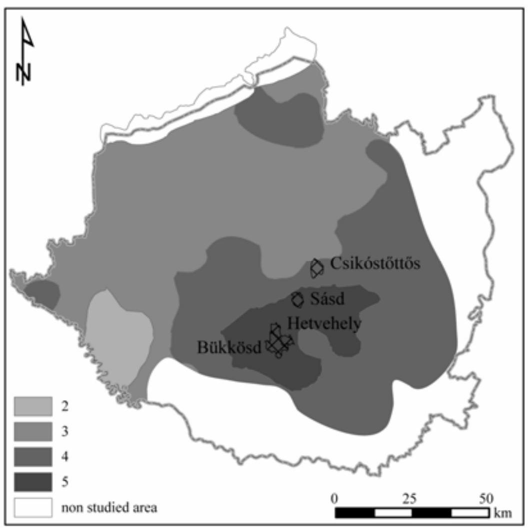

Figure 17. A rapid screening-type flood hazard map of Southern Transdanubia

To include land use and soil parameters in our vulnerability model, four parameters of this type were considered. These parameters may influence surface runoff, infiltration and interception in the watershed. Topsoil thickness, soil physical properties, proportion of barren surfaces compared to vegetation-covered surfaces and the area of limestone covered areas were included in the generation of the flood risk map.

To determine the hydrological parameters as contributing factors to flash flood generation we employed the stream network database of Hungary created in accordance with European Union Hydrological framework. The vulnerability impact of watercourses was approached in two ways. First the number of stream confluences per unit area (1 km^2) were determined. Confluences (number of tributary rivers) are prone to enhance the magnitude of flash floods as it was proven during the Mátrakeresztes flash flood event on April 18, 2005 (HORVÁTH, 2005).

The obtained categories on the output vulnerability map show 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. 17).

GIS based inundation maps

These types of models indicate transitional models between the rapid screening type models and the numeric analyses. However floodings in this case are not associated with a given rainfall event; they are rather hypothetical and indicate flooding extent at a certain elevation above the valley floor or the mean stream stage (Fig. 19d).

GIS models are primarily based on topography, as all parameters, including runoff, time of concentration and hydrography are derived from topography. Stream bed widths vary greatly in areas of high relief, ranging from 0.5 to several dozen meters. When the spatial resolution of the topographic map exceeds stream width, the stream bed as a physical entity will not be represented in the final output map. In this case, a theoretical centerline is represents the stream itself (*valley inundation model*, Fig. 18 a). However in this case we need to delineate valley floor, with the aid of visual interpretation, wherever possible, including bottlenecks and broader alluvial plains (Fig. 19 c).

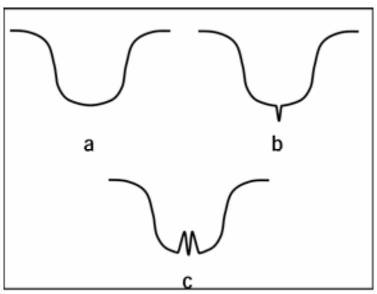

Figure 18. Basic situations for the simulation of valley and channel in GIS and numerical modelling: valley model (a), valley-channel model (b), channel model with levees (c), channel model with incision between levees (e.g.: railway embankment)

In a GIS based model, surface runoff need to be determined from a DEM (Digital elevation model) of 5 to 10 m spatial resolution (Fig 19 b). However, errors tend to be relatively considerable in this case between the calculated and the actual (observed) water courses: in certain cases spatial differences my even reach 100 m. The so-called impervious surface (IS) models that ignore infiltration and the effect of canopy, derive runoff direction and volume exclusively form topographic models. However, to obtain an appropriate picture of runoff behavior, the impact of soils and land use essentially need to be considered. Fig. 19b clearly show the differences light colors indicate runoff according to IS models, darker colors indicate runoff when the impact of soils and land use is included in the calculations.

Fig. 19 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.

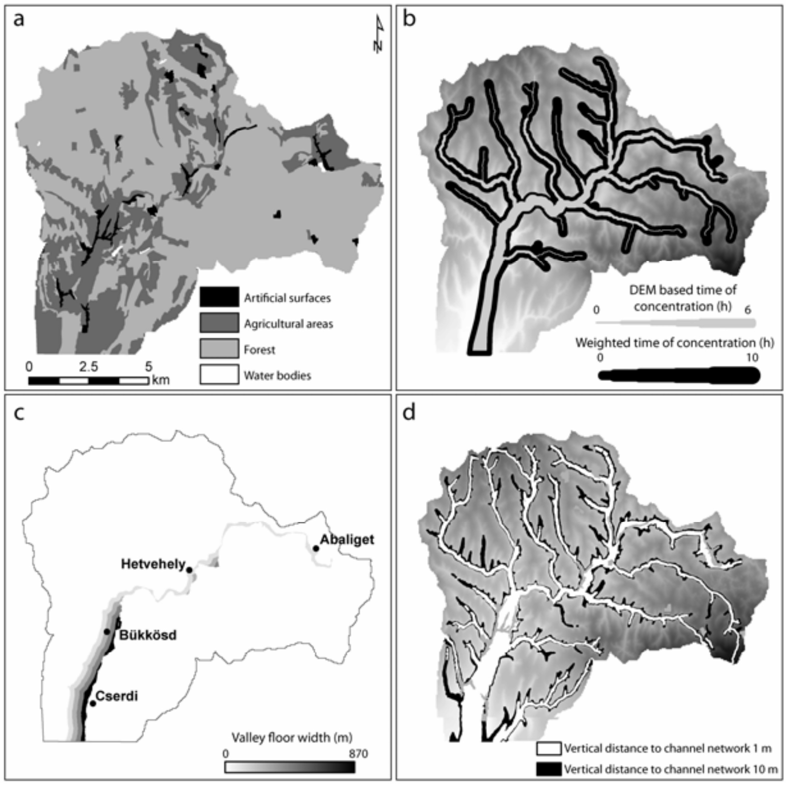

Figure 19. Parameters for the construction of GIS inundation maps

Inundation maps based on numeric, hydrologic-hydrodynamic models

This model includes the basic physical and hydrological relationships of a given watercourse and is expressed with basic well-known mathematical equations. Runoff is represented in critical flow or stage value which is further analyzed with a flood transformation model. If appropriate data with sufficient spatial resolution is available, the HEC software environment is suitable to calculate the areal extent of flooded areas. Firstly, the HEC-HMS model determines the actual discharge value to a given critical rainfall value for the studied watershed (Fig. 20). However, the output data verification will only be feasible if stream gage data is available for the studied watershed. If the simulation is carried out on an unexplored watershed, total runoff (flow) need to be estimated by empirically base equations (Koris, 2002).

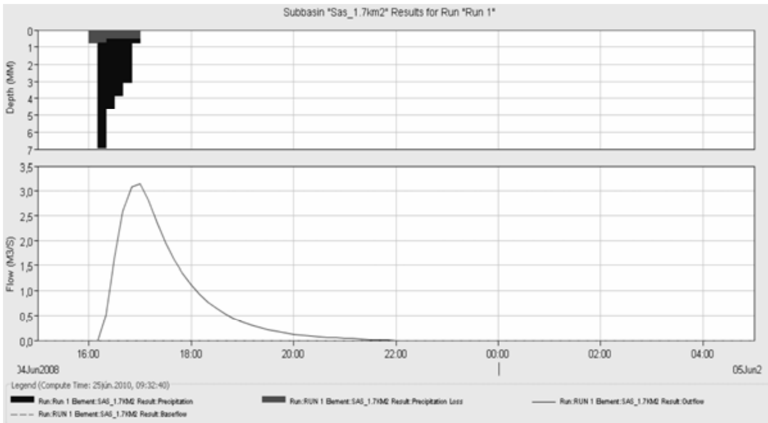

Figure 20. Rainfall-runoff curve from the HEC-HMS model

Threshold precipitation values, i.e. those that trigger floods with a given return period need be determined for various flood levels, in cases, based on the aforementioned instances, even for 400-year return periods when undocumented flash floods occurred. In this case, in addition to the actual rainfall values we need to have suitable knowledge on other elements of the hydrologic cycle.

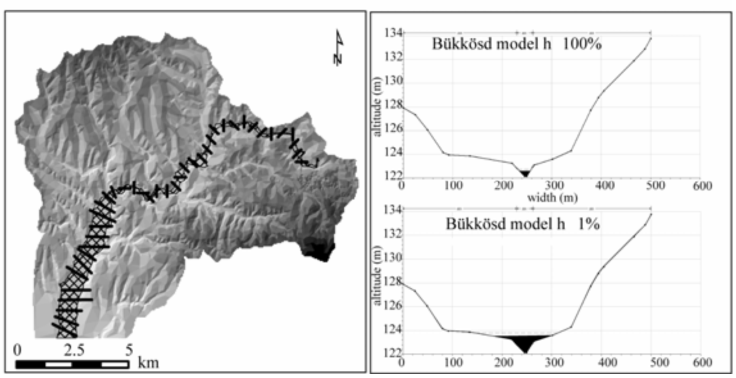

Figure 21. Establishing cross-sections across a river valley (a) and water levels for floods for a given probability computed by the HEC-RAS model

Those elements include e.g.: hydraulic conductivity and infiltration rate of soils, canopy and surface storage. In numeric models, topographical analyses are focused on cross section analyses. With a given spacing, valley cross sections are calculated and analyzed along the water course (Fig. 21).

The actual width of the cross section is determined according to the critical flood level above the valley floor or the mean long term water stage (Fig. 19 c and d). Flow or stage values are then determined for each cross section (Fig. 21).

Numeric models are the best tools to simulate the areal extent of inundations and flooding along a water course. They are also suitable for simulation in urban environments where the proportion of permeable surfaces are limited and impervious paved surfaces dominate the surface. Numeric models are proper tools for simulation and analyses of risk scenarios, such as dam breaching, Numeric models are also capable for 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 artifacts.

Potential prediction models

Prediction models are classified into two categories. The first one is similar to meteorological models and is a real time direct forecast. However, this type of forecasting system does not appear realistic in the ST area due to the lack of appropriate monitoring systems. The second approach includes preprocessed scenarios, i.e. is a typical flowchart type model. The flow chart type model was generated in the ST area for the most hazardous watersheds selected according to the aforementioned rapid screening type vulnerability analysis. For the selected watersheds we carry out GIS and numeric analysis based simulations at various environmental scenarios. Typical scenarios are generated at preselected boundary conditions. Boundary conditions 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 modeling, i.e. we carry out temporally backward simulation beginning that reconstructs an observed event.

In a flow chart analysis we also collect data on preceding rainfall events and 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 predictions schemes determine whether heavy convective, or long term 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, while ultimately deciding whether it is necessary to issue flood warnings.

Summary

Flash flood became increasingly common phenomena in the ST area in SW Hungary characterized with rugged topography. At least 433 settlements are located and 700,000 residents live in potentially flash flood affected regions, as flood return period likely to be exceeding 100 years at many locations. New developments ignore the flood-generated potential hazards, while agricultural area cultivated and tilled once again in alluvial plains. However, a flood of long return time may cause economic losses that worth several millions Euros.

The present study points out the existence of areas where, despite the available long-term statistics, floods damages are expected. The so-called rapid screening type statistics delineate areas of highest risk, numeric models, on the other hand, determine the extent of inundated areas as well as flood water depths and determine which settlements, residential areas and farmlands are potentially affected by flooding.

ACKNOWLEDGEMENTS

This research was supported by the Baross Gábor Program (Grant No. REG_DD_KFI_09/PTE_TM09) and the Bolyai János Scholarship. The authors are grateful for the data and support provided by the Hungarian Meteorological Service, 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 help and contribution to the present work.

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