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# Impact of rainfall pattern on the occurrence of flash floods in Hungary

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with 12 figures and 3 tables

**Summary.** Despite the country's lowland character, flash floods have frequently been reported from the hilly and low mountain catchments of Hungary (e.g.: Vass 1997; Horváth 2005; Szlávik & Kling 2007). To avoid flash-flood damage, development of a flash flood guidance (FFG) system was suggested by the concerned authorities.

To generate a rapid screening based nationwide flash flood hazard mapping as part of the FFG system, in the present study we considered and included both passive environmental factors (PFB model), and randomly occurring active environmental factors (precipitation). Currently, we determined the (i) spatial and (ii) the temporal patterns and behavior of rainfall events in Hungary and prepared a hazard map that is based on both passive and active environmental factors (APFB model).

Extreme rainfall pattern was analyzed both in time and space using data provided by the National Oceanic and Atmospheric Administration (NOAA) and the Hungarian Meteorological Services (HMS). The hazard map was then validated using HEC-HMS simulations and calculated threshold discharge values.

The spatial pattern of extreme events indicates a strong orographic effect. The frequency of extreme precipitation is always higher on the watersheds of the PFB model with highest hazard, than in both the zone of the PFB model with the lowest hazard and the national average. Consequently, the vulnerability of the passive factor-based most endangered areas will be further enhanced by the higher frequency of extreme events.

Temporal changes are ambiguous based on the long term observed data of extreme rainfall. Model indicated increase of extreme rainfall events is not clearly shown based on the employed HMS and NOAA data. However, a fluctuating cyclic pattern is clearly identifiable. The majority of the observed years was characterized with a lower-than-average number of extreme events. However, these long periods are interrupted with short spells (usually lasting a year or two) when the number of extreme events significantly exceeded the mean value.

The temporal frequency of flash flood events is lower than expected based on model validation processes. This discrepancy is likely to be explained by (i) the duration difference between the simulated rainfall period and the observed rainfall period, (ii) the overestimation of total runoff by the runoff model, (iii) the fact not all flash flood-generated damages were reported to the insurance companies and (iv) the inappropriate calculation of the discharge threshold values.

## 1 *Introduction*

Due to the geographical settings of western and northern Hungary, flash floods are frequent phenomenon and have been reported several times over the past decades (Horváth 1999; Koris & Winter 2000; Ely et al. 2001; Hizsák 2005; Szlávik 2003,). As the Carpathian Basin is surrounded by subalpine and alpine mountains in three directions, drainage to low elevation areas naturally trigger floods when extreme atmospheric events occur. They are usually localized events; however, they may cause widespread and considerable economic losses (Lóczy & Juhász 1996; Gyenizse et al. 2005). To minimize the magnitude of such

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economic and social impacts, a sophisticated and efficient prevention and warning system need to be developed. To appropriately operate a flash flood warning system of this type the areas possibly affected by flash flood needs to be precisely located.

In our previous study (Pirkhoffer et al., submitted), partially based on the results of Davis (2001) and Szlávik et al. (2002), we delineated the flash flood affected watersheds of Hungary, and classified them according to their flood susceptibility (Fig. 1). However, this approach cannot be considered as an entirely satisfactory hazard map, as only passive environmental factors are included here, i.e. those that do not behave randomly both in space and time. Passive factors, in a given watershed, change slowly over time or may only show seasonal patterns (e.g. seasonal change of canopy cover in hardwood forests). Precipitation, however, occurs randomly, and both intensity and cumulative rainfall are variable both in time and space. Thus, it is not ignored during the process of rapid screening type vulnerability mapping. In spite of the consequences of global climate change, i.e. the aridification of Hungary's climate (Bihari et al. 2008), we think precipitation is a crucial component of the hazard map.

While the contributing effectiveness of passive factors can be quantified with a relative easiness, modeling of rainfall occurrence and precipitation is more challenging (Bálint & Szlávik 2001). However, when the cumulative effect of passive factors may indicate extreme vulnerability in a given watershed, a higher-than-average (peak-over-threshold) rainfall event likely triggers flash flood there.

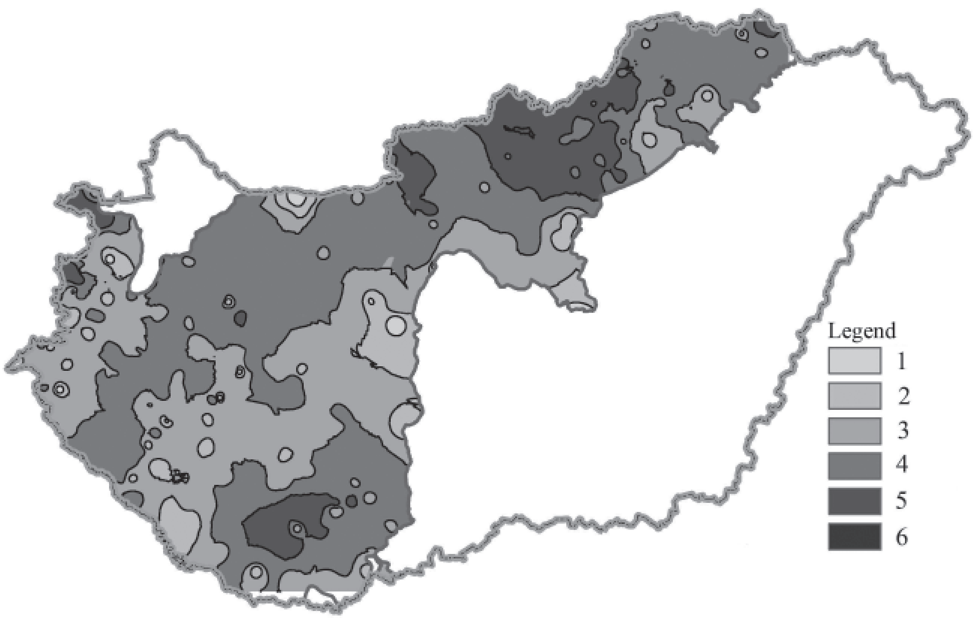


Fig. 1. Interpolated (among the outflow points) flash flood hazard map of Hungary (OFPI5). Watersheds below 5 $km^2$ area are neglected. The darker the color, the higher the flash flood hazard is in the area (1 is the least and 6 is the most hazardous area).

A peculiar property of vulnerability maps is their temporal variability as some environmental factors do change both temporally and spatially. In the current study, special attention was paid to rainfall events exceeding the 40 mm and 50 mm thresholds. The former threshold was selected from the viewpoint of insurance covers, as insurance companies consider damage as "elemental" when cumulative rainfall from a single event exceeds 40 mm. To verify both the formerly published PFB model and the presently discussed APFB map we used a database that includes reports on flood-trigerred damages submitted to insurance companies since 1990.

Topography plays an important role in rainfall pattern and may further increases flash flood hazard on complex terrains (e.g.: Buzzi et al. 1998; Federico et al. 2003; Sotillo et al. 2003; Kobold & Pogačnik 2008). Flood prediction for small low-mountain watershed characterized by complex topography and short time of concentration, thus forecast cannot rely solely on observed precipitation (Diomede et al. 2008). Prediction and warning system need to be aided by radar observations, rainfall models, rapid screening of the most flash flood impacted areas and generation of appropriate hazard maps (Georgakakos 1986; Cobby et al. 2009; Fang et al. 2008). To generate an adequate hazard map, rainfall pattern and frequency of extreme precipitation events need to be incorporated. Furthermore, to determine the peaks-over-threshold cumulative rainfall amounts for the outflow point of a given watershed, actual maximum rainfall values need be determined, or at least estimated.

The objective of the present paper is to determine the (i) spatial and (ii) the temporal patterns and behavior of rainfall events in Hungary and to prepare a hazard map that is based on both passive and active environmental factors (APFB model). This approach may reclassify and restructure the vulnerability map that is based on solely passive environmental factors (PFB model). This new approach may also recalculate the area of the individual vulnerability classes and shifts and redraws their boundaries. As an additional goal of the present paper we validated the HEC-HMS threshold values for selected watersheds in northern Hungary.

## 2 *Materials and methods*

As the generation of the PFB model was discussed in detail in our former paper (Pirkhoffer et al., submitted), here we only present a brief summary of this passive factor based hazard map.

Passive data were classified into three major categories: (a) topography, (b) soil properties and land use data, and (c) hydrological data. Topography was obtained from the 50-meter resolution digital elevation model of Hungary, soil data was obtained from the AGROTOPO soil database, generated by the Hungarian Research Institute for Soil Sciences and Agrochemistry (e.g.: Várallyay et al. 1979; Várallyay et al. 1980a; Várallyay et al. 1980b; Várallyay 1985). We obtained land cover data from the CLC 2000 (Corine Land Cover) 1:100 000 resolution database. To determine the hydrological parameters that contribute to flash flood generation (e.g. channel length, time of concentration and storage coefficient), we employed the stream network database of Hungary created in accordance with the European Union Hydrological framework. Data was then processed in ArcView/ArcGIS 9.1 software environment.

The generation of the APFB model, depicted in the present paper, includes the spatio-temporally variable precipitation data for the potentially flash flood affected (PFFA) areas of Hungary. PFFA area was deselected based on topography (Czigány et al. 2009).

Rainfall data were obtained from two sources: (a) from the National Oceanic and Atmospheric Administration (NOAA) and (b) for the Hungarian Meteorological Service (HMS). Precipitation data including cumulative rainfall events exceeding 40 mm daily was obtained from the HMS within the framework of the Jedlik Ányos joint grant (Grant No.: NKFP3-00022/2005). This database included data from 492 rain gages when the intra-settlement relocation of rain gage is ignored. Considering short-distance relocation of the rain gages, we obtain a total of 1004 rain gages. These rain gages are approximately evenly distributed in the entire land area of Hungary. However, the spatial density of precipitation data did not allow us to interpolate rainfall data appropriately. To overcome this difficulty, we only accounted for the exact location of the observed precipitation data, i.e. we did not extrapolate data beyond the location of the rain gage.

Data observation period, however, was variable for the >40 mm precipitation data. The longest measurement period (and actually the majority of the observation) spanned the interval between 1952 and 2007 (Fig. 2), while the shortest covered the period from 2006 to 2007. Thus, for objective purposes, in the map generation we used the annual number of events (annual frequency) during the APFB map generation.

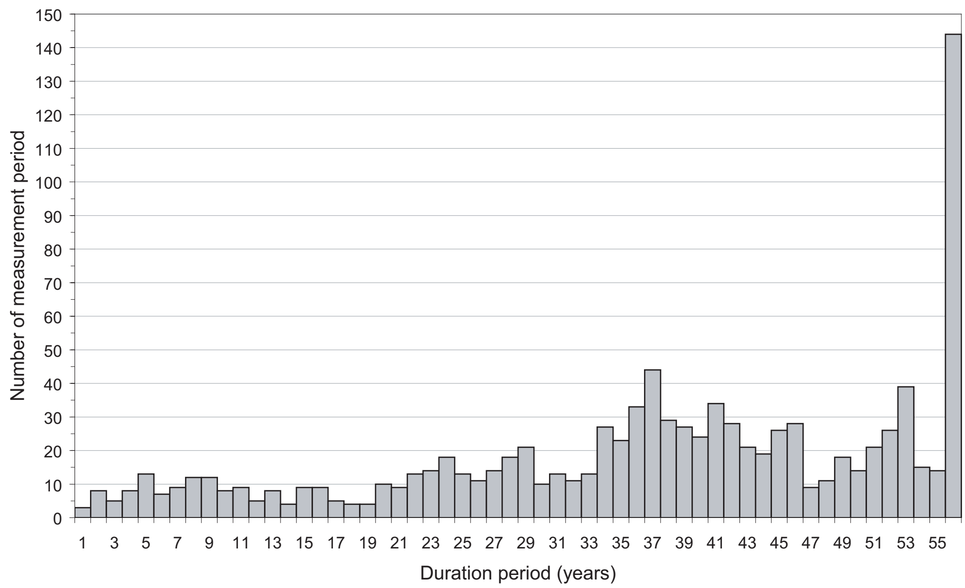


Fig. 2. Histogram of the frequency of the observation duration for the >40 mm threshold HMS data (including short-distance relocation of the rain gages).

The >50 mm threshold database included data for the observation period between 2000 and 2007. As in this case measurement periods were identical for each meteorological station, we did not draw a frequency map for the >50 mm events.

Both datasets were then analyzed and mapped in ArcGIS 9.2 and were used for the generation of the APFB hazard map.

To study the temporal changes of extreme rainfall data, 100-year (1901–2000) of daily data sets were obtained from the HMS for Budapest, Szeged and Debrecen. The shorter-duration (1973–2008) publicly available NOAA data (accessible at http://gis.ncdc.noaa.gov/website/ims-cdo/gsod/viewer.htm) for 15 locations were also used to determine the temporal variability of rainfall pattern (Fig. 3). Our reason for using NOAA data was their higher spatial resolution compared to the long-term HMS data available for the public.

Peak-over-threshold precipitation values were calculated for 11 watersheds using HEC-HMS runoff model for two flood levels (33-year and 100-year return period). The selected watersheds are located in northern Hungary, and in vulnerability zones 5 and 6 (Fig. 4) and parts of the drainage basins of the Hangony, Hódos, Morgó, Török, Malomvölgyi and Dobroda Streams. The studied catchments have an average land area of 161.1 km$^2$, with minimum and maximum areas of 38.0 km$^2$ and 292.3.km$^2$, respectively. The threshold values were determined on the basis of an actual 3-hour convective rainfall event, for 20 scenarios (Fig. 5). Threshold discharge values were either measured or calculated and provided to us by the VITUKI (Vízügyi Tudományos Kutató Intézet, National Hydrological Research Institute). When no measured discharge was available, the following relationship was used to calculate specific threshold discharge, $q$:

$$\lg(q_{i\%}) = m \times \lg(T_a) + b \qquad \text{Eq. 1}$$

where $q_{i\%}$ is the specific surface runoff at a return period of $100/i$, $T_a$ is the land area of the given watershed in km$^2$, $m$ and $b$ are the empirically determined runoff correction factors for a given runoff region (e.g.: SW Hungary)

$$Q_{i\%} = a_{i\%} \times q_{5\%} \times T_a \qquad \text{Eq. 2}$$

where $a_{i\%}$ is the likelihood of rainfall intensity for a return period.

Scenarios varied according to soil moisture content, soil temperature, snow cover and canopy cover and were organized to a flow chart model. Results of two scenarios are presented in this paper, namely (i) for frozen soil with snow cover and (ii) for the summer season with 25 % soil moisture content and no >10 mm precipitation in the preceding 72 hours. The flow chart will form the basis of the proposed flash flood guidance and warning system for the hilly and low-mountain areas of Hungary. To verify the occurrence of flash flood events in the selected watersheds we obtained public insurance reports from the Hungarian Central Statistical Office (KSH).

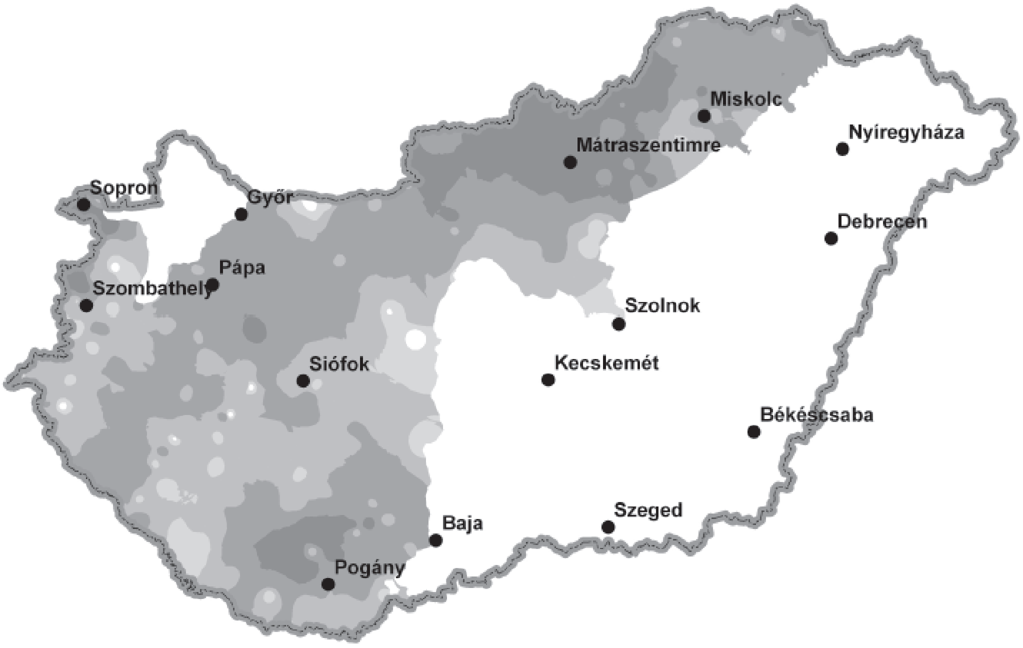


Fig. 3. Locations of the employed meteorological stations from which NOAA-accessible data (1973–2008) were obtained.

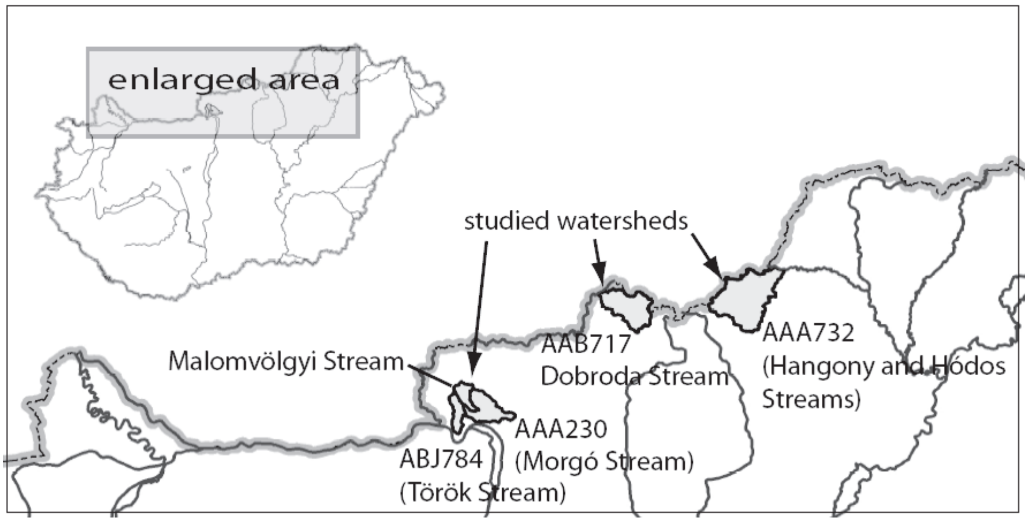


Fig. 4. Location of the studied watershed used for the determination of rainfall thresholds.

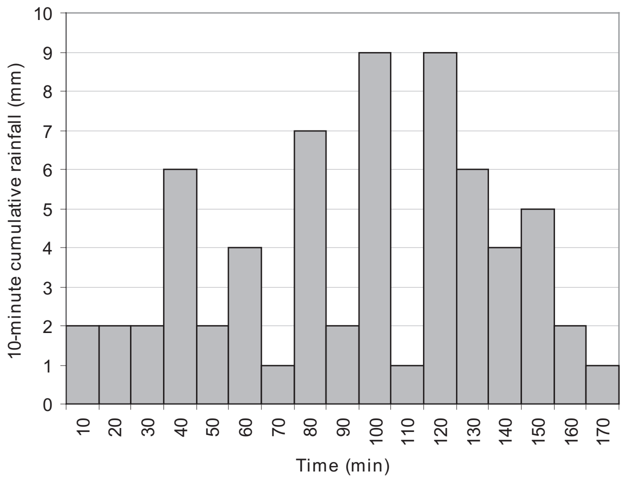


Fig. 5. Temporal distribution of the template convective rainfall event used for the determination of threshold precipitation and the peak-over-threshold flood levels.

## 3 *Results*

### 3.1 *Spatial distribution of extreme rainfall events*

The total number and the annual frequency of >40 mm rainfall events are shown on Figs. 6 and 7. Based on the rainfall data provided by the HMS, the total number of >40 mm rainfall events for the periods of observation and for the 492 rain gages totaled 15,370. The average frequency of >40 mm rainfall events is 0.4375 events per rain gage annually, equaling a return time of 2.286 years for the entire land area of Hungary.

The frequency distribution of the >40 mm rainfall events considerably differed from the total number of events for >40 mm rainfalls (Fig. 7). Topographic impacts, especially in the case of the Mecsek, Bakony, Börzsöny, Mátra and Bükk Mountains, are considerably more pronounced than in the case of the spatial distribution of total event number.

However, both frequency and total number of occurrence were higher for zones 5 and 6 of the PFB model than both the national average. In total, 2,240 >40 mm event was observed in the most flash flood-susceptible zones of 5 and 6 (as zone 6 only covers a small area, it was not treated separately). The combined area of zones 5 and 6 covers 14.00 per cent of all PFFA areas, while 20.22 per cent of all events happened in these two susceptibility zones. Zones 5 and 6 include 7.08 per cent of the entire land area of Hungary, while almost twice as many, i.e. 14.00 per cent of all events occurred in these zones. The average frequency in zones 5 and 6 for the 40 mm events is 0.4844 events annually for each rain gage in zones 5 and 6. This frequency is higher than both the averages for zone 4 (0.4766) and for the PFFA areas (0.4759).

The total number of observed >40 mm events in hazard zone No. 4 amounts to 5293 events. Here frequency is just slightly higher than the average of the PFFA areas. This obser-


Fig. 6. Total number of >40 mm rainfall events in Hungary. Background indicates the PFFA areas classified according to their flood hazard.


Fig. 7. Frequency of >40 mm rainfall events in Hungary (large circles indicate larger number of >50 mm events at the actual measurement location).

vation is also reflected when event percentage (compared to the total number of events) and area ratio is compared. Zone 4 covers 46.74 per cent of the PFFA areas, while 47.78 per cent of all PFFA events occurred in zone 4. Event frequency in zone 4 is well above the national average of 0.4375 event annually per rain gage.

The total number of >50 mm events is significantly less than that of the >40 mm events (1110 events for entire Hungary). Here again, increased number of events is observable along the highest terrains of Hungary: 187 events were observed in zones 5 and 6 in the PFB areas (17.00 per cent of the total number observed in Hungary). This ratio is higher than implied based on the land area ratio of 7.08 per cent. Similarly, the percentage of >50 mm events in zones 5 and 6, compared to the national total, is higher than that of the >40 mm events. Similar variation is observable when the ratio of zone 5 and 6 events is compared to that of the PFFA areas. However, in zone 4, the percentage of >50 mm events is lower than in the case of the >40 mm events (Table 2).

The effect of topography is more pronouncedly shown in the case of >50 mm than for >40 mm events when displayed in ArcGIS environment (Fig. 8). Frequency in hazard zones of 5 and 6 reached 0.3710 events annually per rain gage, compared to 0.2837 and 0.2820 for vulnerability zone 4 and entire Hungary, respectively (Table 2). Interestingly, in the case of the >50 mm events, the PFFA area average is higher than that of the zone 4 average (0.2837 vs 0.2991, see Table 2). The national average is only slightly lower than that of the zone 4 average (0.2837 and 0.2820, respectively).

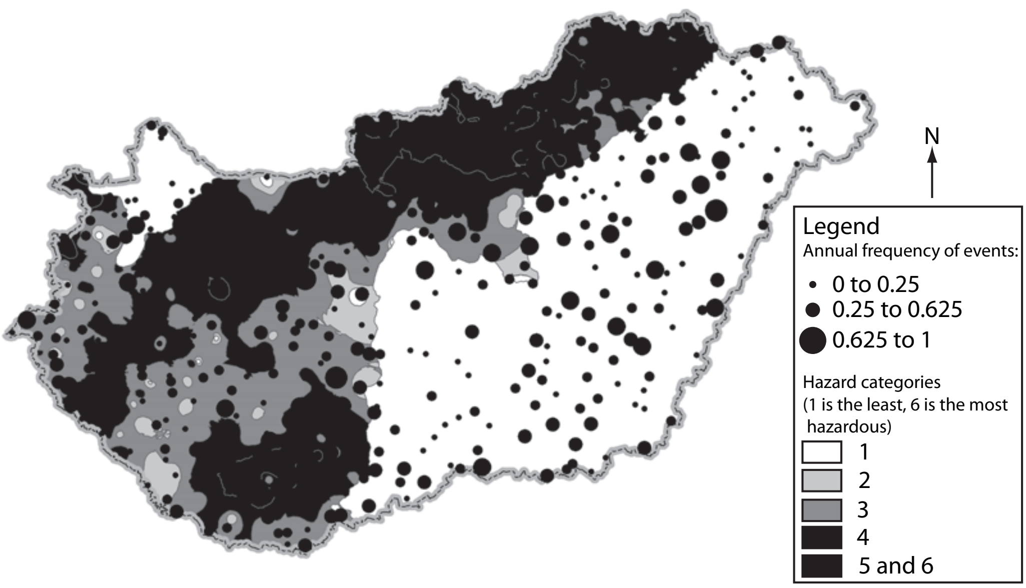


Fig. 8. Total number of >50 mm rainfall events in Hungary (large dots indicate larger number of >50 mm events at the actual measurement location). Background indicates the PFFA areas classified according to their flood hazard.

Table 1. Statistical summary of observed >40 mm rainfall events.

| | Total number of events | Percentage of total number compared to PFFA area | Percentage of number of events compared to the total number of events in Hungary (%) | Event/ year for each rain gage | Area compared to PFFA (%) | Area compared to Hungary (%) |
|---|---|---|---|---|---|---|
| Vulnerability zones 5 and 6 | 2,240 | 20.22 | 14.00 | 0.4844 | 14.00 | 7.08 |
| Vulnerability zone 4 | 5,293 | 47.78 | 33.64 | 0.4776 | 46.74 | 24 |
| PFFA areas | 11,078 | 100 | 70.43 | 0.4759 | 100.00 | 52.77 |
| Entire Hungary | 15,730 | N/A | 100 | 0.4375 | N/A | 100.00 |

Table 2. Statistical summary of observed >50 mm rainfall events.

| | Total number of events | Percentage of total number compared to PFFA area | Percentage of number of events compared to the total number of events in Hungary (%) | Event/ year for each rain gage | Area compared to PFFA | Area compared to Hungary |
|---|---|---|---|---|---|---|
| Vulnerability zones 5 and 6 | 187 | 23.97 | 17.00 | 0.3710 | 14.00 | 7.08 |
| Vulnerability zone 4 | 345 | 44.23 | 31.08 | 0.2837 | 46.74 | 24 |
| PFFA areas | 780 | 100 | 70.27 | 0.2991 | 100.00 | 52.77 |
| Entire Hungary | 1,110 | N/A | 100 | 0.2820 | N/A | 100.00 |

### 3.2 *Temporal distribution of extreme rainfall events*

According to the climate models, climate change is likely to be characterized by the increased frequency of extreme events, including precipitation. Based on the NOAA quasi-long-term datasets, the temporal frequency of >20 mm and >30 mm rainfall events indicates both decreasing and increasing tendencies, depending on the location of the meteorological station. However, the reliability of the NOAA data is variable and need to be handled with extreme caution. Compared to the HMS data, great variations are detectable between the two datasets. Pronounced and large differences are observable in the measurement period between 1991 and 1994 for high daily rainfall values. The NOAA dataset includes a large number of extreme rainfall events; for example, a daily rainfall of 321 mm was reported for

Kékestető, while the highest ever measured daily precipitation was 203 mm in Hungary and the highest estimated being 260 mm (Szilágyi 1953). We did not study the temporal changes of the frequency of >40 mm rainfall events, as the reliability of the NOAA data is extremely low in that precipitation range.

Based on the 100-year HMS data, the frequency of >20, >30 mm and >40 mm data increases in Debrecen, while it decreases in Budapest (with the exception of >40 mm data) and Szeged (Fig. 9). However, there is no steady increasing tendency of extreme rainfall. The majority of the years of observation have a lower than average number of extreme events. In other words, in the majority of the years, a lower than average number of extreme rainfall were observed. However, these low-frequency years are then interrupted with short (usually a year-long) high-frequency years (Fig. 9).

When the number of above-average and below-average years is plotted for each meteorological station, the previous pattern is further confirmed. With two exceptions (Pogány and Debrecen, >20 mm data), the number of below-average years is always higher than that of the above-average years for both the >20 mm and the >30 mm events (Fig. 10).

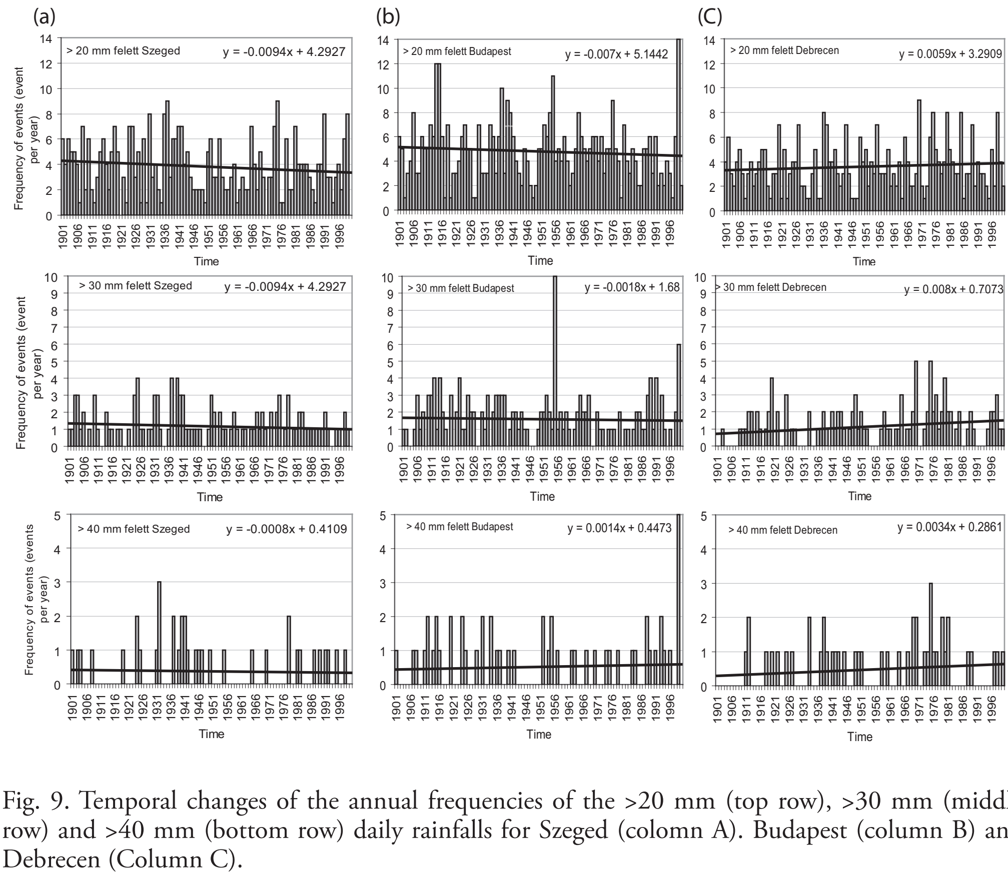


Fig. 9. Temporal changes of the annual frequencies of the >20 mm (top row), >30 mm (middle row) and >40 mm (bottom row) daily rainfalls for Szeged (colomn A). Budapest (column B) and Debrecen (Column C).

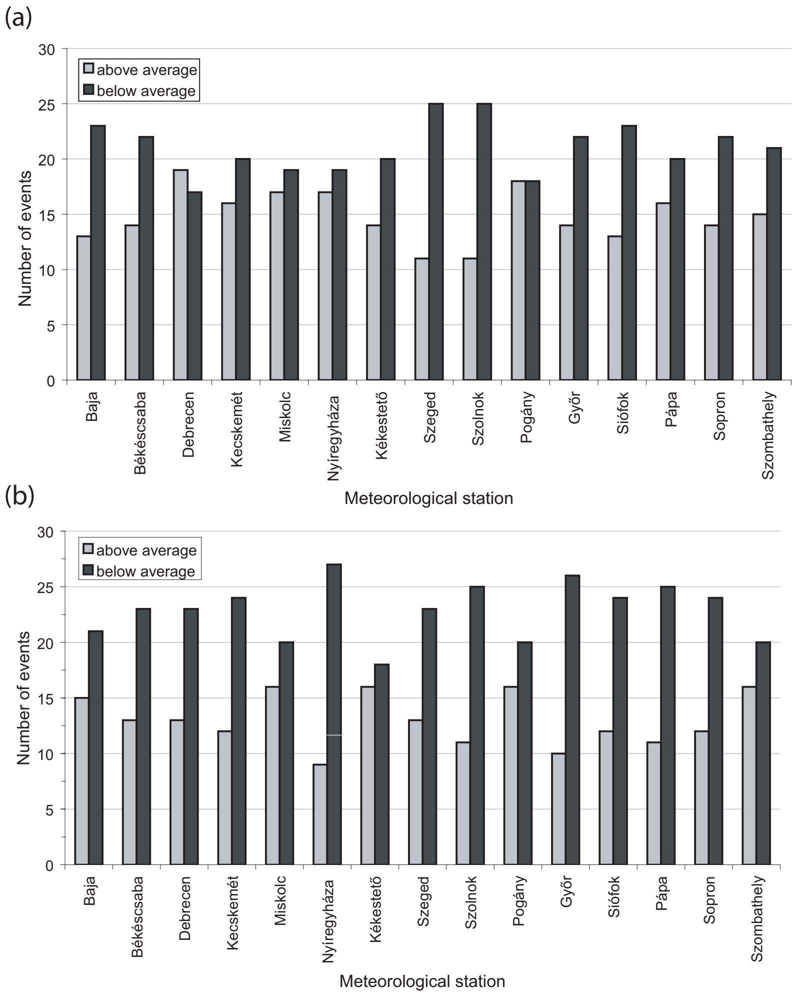


Fig. 10. Ratio of the number of annual rainfall events characterized by lower-than-average and higher-than-average number of extreme rainfall events of >20 mm (a) and >30 mm (b).

### 4.3 *Impact of rainfall distribution on flood levels in selected watersheds*

Threshold precipitation values, above which flood is declared at the outflow points of the individual watersheds, ranged between 8.8 and 58,0 mm for a three-hour period for all studied watersheds, depending on the actual scenario. Lowest threshold precipitation values were determined for frozen soils with snow cover. Although not typical, yet rain-on-snow events may also trigger flash-flood events in mountainous catchments (Pirkhoffer et al. 2007; Pirkhoffer et al. 2008). For the summer scenarios when canopy cover is significant for interception and convective precipitaton typically occurs, threshold precipitation ranges between 13 and 58 mm (Table 3).

Table 3. Threshold precipitation values for the selected 11 watersheds, based on two scenarios and with 100-year and 33-year return period. Maximum precipitations were observed over the period of 2000–2007.

| **watershed ID** | **area ($km^2$)** | **max. precipitation (mm)** | **1 % snow scenario (mm)** | **3 % snow scenario (mm)** | **1% summer scenario (mm)** | **3% summer scenario (mm)** |
|---|---|---|---|---|---|---|
| AAA230_0000-0017_M-2 | 138.4 | 54.1 | 12.8 | 9.6 | 31.0 | 28.0 |
| ABJ784_0000-0010_S-2 | 42.2 | 51.9 | 36.0 | 25.6 | 58.0 | 47.0 |
| ABI664_0005-0010_M-1 | 38.0 | 50.5 | 24.8 | 18.4 | 40.0 | 31.5 |
| AAB717_0008-0020_M-2 | 87.5 | 62.0 | 15.6 | 11.6 | 31.5 | 27.0 |
| AAB717_0000-0008_S-3 | 116.7 | 62.0 | 12.4 | 9.9 | 24.0 | 20.5 |
| AAB717_0000-0008_S-1 | 140.8 | 62.0 | 12.0 | 9.6 | 23.5 | 20.0 |
| AAB717_0000-0008_S-2 | 147.5 | 62.0 | 12.4 | 9.9 | 24.0 | 20.5 |
| AAA732_0000-0010_S-5 | 219.4 | 80.6 | 11.2 | 9.2 | 11.2 | 9.2 |
| AAA732_0000-0010_S-4 | 263.2 | 80.6 | 10.8 | 8.8 | 10.8 | 8.8 |
| AAA732_0000-0010_S-1 | 285.7 | 80.6 | 11.2 | 9.2 | 11.2 | 9.2 |
| AAA732_0000-0010_S-3 | 292.3 | 80.6 | 11.6 | 9.6 | 11.6 | 9.6 |

Our findings show that mean soil moisture content ranges between 30.77 per cent and 67.49 per cent for a measurement period of September 5$^{th}$, 2008 to December 5$^{th}$, 2008 on a low-mountain watershed of 6.7 $km^2$ area in SW Hungary (Czigány et al., submitted). During this period, the lowest value was observed in the beginning of the measurement period, while highest soil moisture content was found in December, with a good correspondence of the temperature regime of the period. When considering the typical soil saturation value, we primarily consider the 50 per cent soil saturation scenario (25 per cent soil moisture content). With one exception (ABJ784_0000-0010_S-2, summer scenario, 100-year return period), observed maximum daily rainfall values exceeded the calculated thresholds.

Threshold precipitation values were then compared with the maximum observed daily rainfall values for the period of 2000–2007. In 43 cases out of the total 44 scenario-based threshold precipitation values simulated rainfall values were less than the observed maximum rainfall value. Despite our expectations, among the three studied watersheds, flash flood events were only reported to insurance companies from the watershed of the Hangony and Hódos Streams and the watershed of the Dobroda Stream over 2000–2007 (Fig. 11). Despite the large number of peak-above-threshold precipitation values, reports on damage generated by flash flood were submitted only from Ózd (2003), Domaháza (2003), Litke (2005) and Sajónémeti (2005). Flash floods were reported from other settlements located in the 11 studied watersheds prior to 2000, i.e. before the observation period of the rainfall data (2000–2007). Two flash-flood events were reported from Kismaros (1995 and 1999), while one event was reported from Litke (1995), Verőce (1999) and Zebegény (1999).

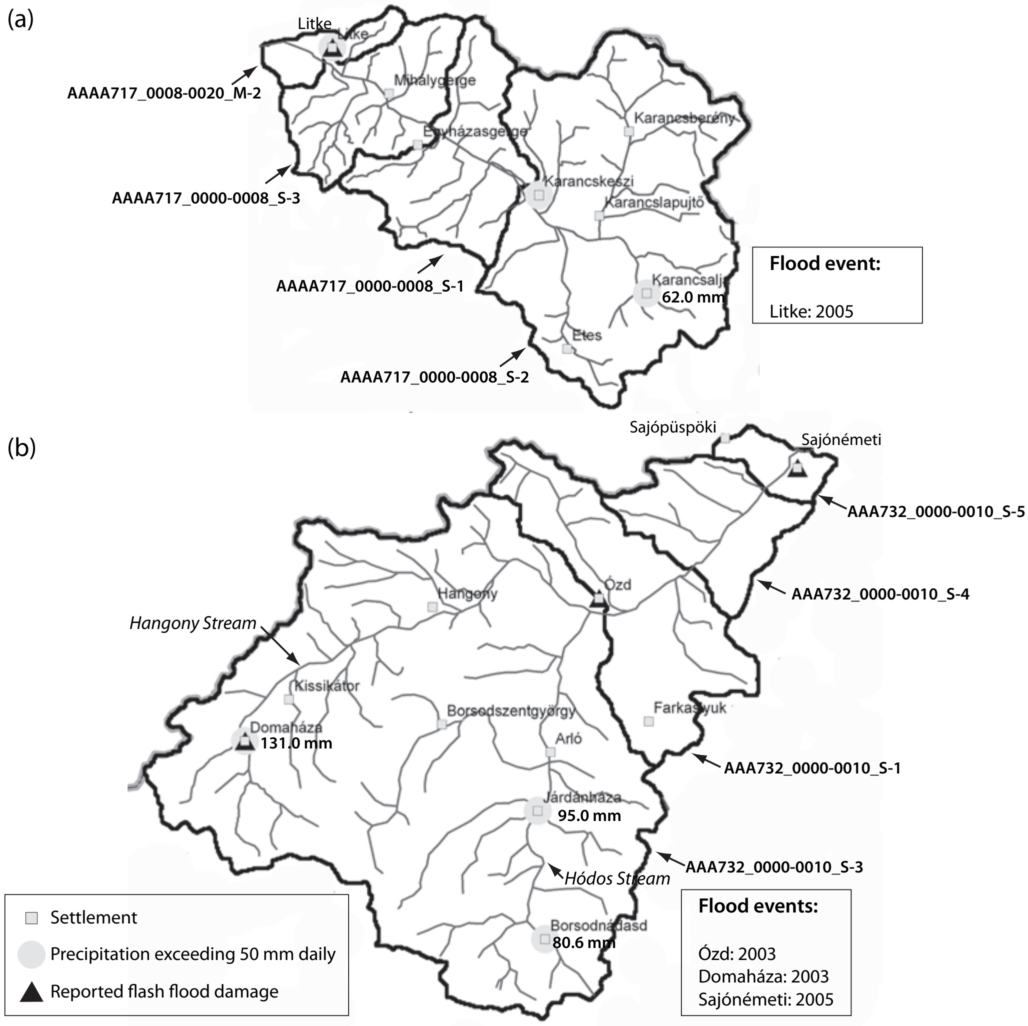


Fig. 11. Settlements affected by extreme rainfall and flash flood in the watersheds of the (a) Dobroda Stream and the (b) Hangony and Hódos Streams over the period of 2000–2007.

Largest cumulative daily rainfall values (Domaháza: 131.0 mm, Járdánháza: 95.0 mm and Borsodnádasd: 80.6 mm) were observed in the headwaters of the Hangony and Hódos Streams. However, only a single report was submitted from the headwaters (Domaháza), while several report arrived from Ózd and Sajónémeti, downstream from the confluence of the Hangony and Hódos Streams.

The largest cumulative daily rainfall of 62.0 mm was observed in Karancsalja for the observation period of 2000–2007 in the watershed of the Dobroda Stream (Fig. 11). This rainfall was reported from the headwaters, while the reported flood events (Litke) are located

20 km downstream from the rain gage. No observed flash floods were reported from the third studied watershed (drainage basin of the Morgó Stream) during the study period.

The low number of flash flood events associated with extreme rainfall events is explained by the following factors: (a) the duration of the rainfall event used in the runoff simulations was three hours, while for the observed data daily rainfall was available, (b) the model underestimated the cumulative amount of the peak-over-threshold rainfall, i.e. overestimated total runoff from a given watershed, (c) not all flash-flood events were reported to the insurance companies and (d) potential errors in the calculation of the stream discharge threshold values.

## 5 *Conclusions*

### 5.1 *Spatial variability of rainfall*

In the field of flood prediction for small low-mountain watersheds characterized by complex hilly topography and short time of concentration, forecast cannot solely rely on observed precipitation (Diomede et al. 2008). To overcome this problem, precipitation models and radar prediction is required to increase forecast accuracy (Fang et al. 2008). However, convective precipitation has a large spatial variability. Such spatial variability of extreme rainfalls (over 40 and 50 mm per event) clearly reflects the complex terrain and the orographic effects in Hungary. The higher than average number of extreme rainfall events, as well as their frequency further enhances the flash flood hazard of the hilly and low-mountain areas of Hungary. Based on satisfactory rainfall data, occurrence of extreme rainfall is highly expectable in the most flash flood susceptible PFFA areas. This phenomenon will further exacerbate the likelihood of flash flood occurrence in the most vulnerable zones delineated in our previous study (Pirkhoffer et al., submitted). Both total number and frequency of extreme rainfall were higher in zones 5 and 6 compared to the PFFA areas and the entire land area of Hungary.

### 5.2 *Temporal variability of precipitation*

The effect of climate change and temporal variation on rainfall pattern are challenging to identify. Based on regional climate models, the frequency of heavy precipitation is likely to increase in severity (Kysely & Beranova 2009). However, prediction uncertainties are rather large. Uncertainties are further exacerbated by the limited availability of reliable long-term measurement data. For instance, NOAA data may be employed with significant limitations and reservations as the NOAA datasets considerably deviates from the HMS data.

Former studies indicated that the annual total cumulative precipitation decreases for the majority of stations in Hungary, while the total number of days during which precipitation occurs decreases even more significantly. Both observations imply that average daily rainfall amounts, at least over the period of observation, are increasing (Horváth 2005).

In general, we conclude that the temporal frequency of extreme rainfall events is highly variable. However, certain fluctuating and cyclic patterns are clearly observable in the long-term data. The majority of the years of the observation period have lower than average frequency of extreme events. These longer periods are then intersected by periods that are characterized with a large number of extreme events.

Although at the same time, regional climate model-based predictions indicate the likelihood of increasing frequency of extreme events for the future (Horváth 2005). This contradiction may be explained by the period of observations. An increasing tendency of extreme events is observable, for instance, in the late 1990s. When this period is incorporated into the prediction models, the forecasted increasing tendency of extreme events is not unexpected.

The partially employed NOAA data may be used with significant limitations and reservations as the NOAA datasets, at least in certain periods, considerably deviate from the HMS data. When the cumulative NOAA-based frequency of extreme events is plotted, a steady increase of the number of events is shown, i.e. year-by-year changes of the number of extreme rainfall events are insignificant. This steadiness is reflected in correlation coefficients of larger than 0.9. These steady increases are intermittently interrupted by step-like abrupt changes (Fig. 12). These abrupt changes are indicative of those years, when a large number of extreme events were recorded. This step-like pattern is then followed by longer, less steep periods when the average number of extreme events are lower than average.

### 5.3 *Impact of rainfall distribution on flood levels in selected watersheds*

Based on the minimum threshold values, calculated by the employed runoff model, 10 out of the 11 watersheds are potentially affected by flash floods over an eight-year long period. Despite this relatively large expected temporal frequency of flash flood events, only four flash flood were reported for the period of 2000–2007 on the studied 11 watersheds. This lower-than-expected number of flash-flood events is probably the result of the difference between the simulation rainfall and the observed rainfall duration (3 hours and 24 hours, respectively), the overestimation of the total runoff by the applied model and the lack of public reports to insurance companies. Further source of potential errors is the inappropriate calculation of the 1 per cent and 3 per cent threshold discharge values. Thus, for the proposed flash-flood guidance system, obtained peak-over-threshold precipitation values need to be handled with extreme caution.

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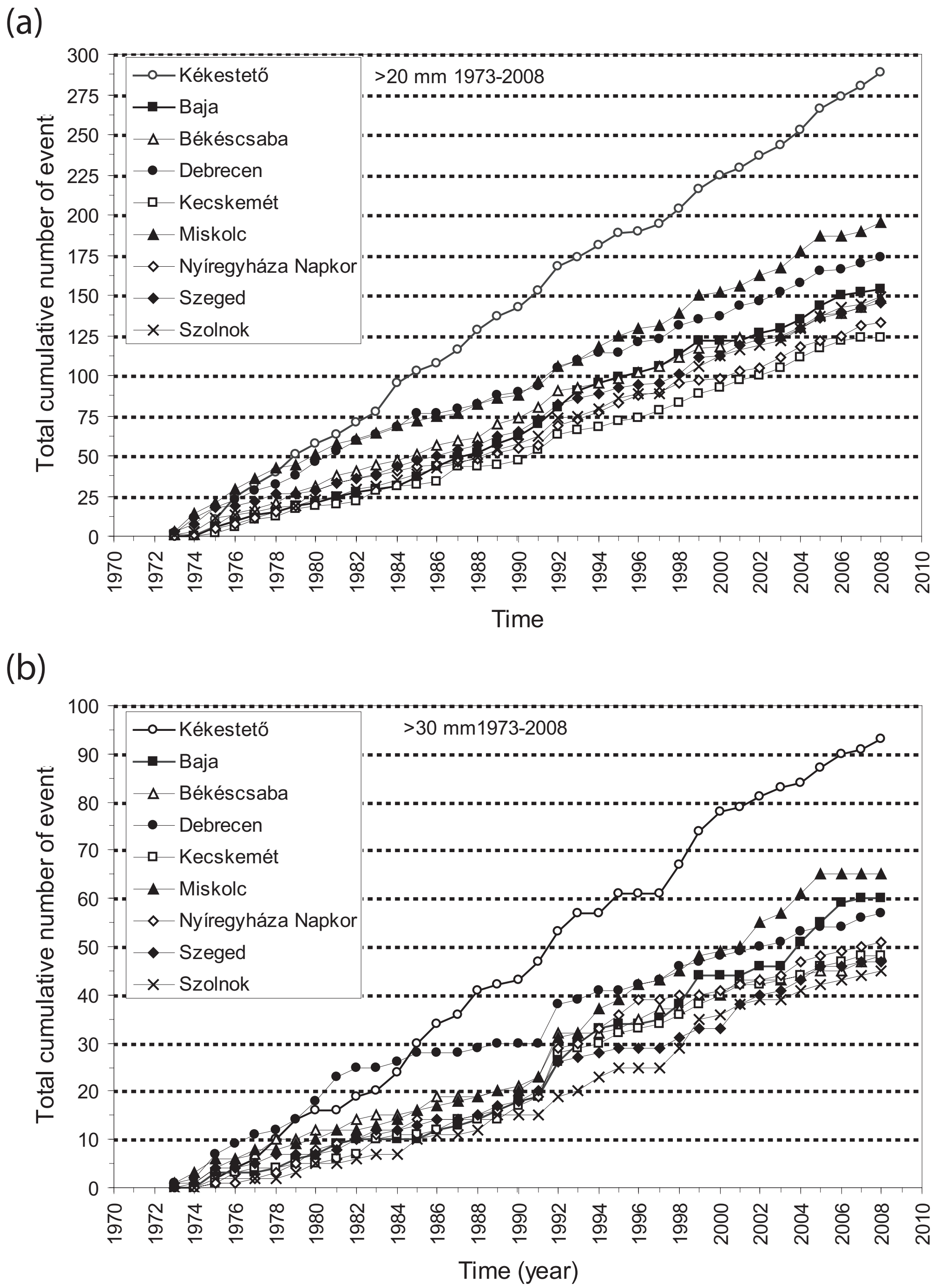


Fig. 12. Cumulative diagram of the total extreme events of >20 mm (top) and >30 mm (bottom) for selected meteorological stations of Hungary.

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