Trends in extreme precipitation events (SW Hungary) based on a high-density monitoring network

Gabriella SCHMELLER[1], Gábor NAGY[2], Noémi SARKADI[1], Anikó CSÉPLŐ[1], Ervin PIRKHOFFER[1], István GERESDI[1], Richárd BALOGH[1], Levente RONCZYK[1] and Szabolcs CZIGÁNY[1]

Abstract

Climate change is commonly associated with extreme weather phenomena. Extreme weather patterns may bring prolonged drought periods, more intense runoff and increased severity of floods. Rainfall distribution is extremely erratic both in space and time, particularly in areas of rugged topography and heterogeneous land use. Therefore, locating major rainfall events and predicting their hydrological consequences is challenging. Hence, our study aimed at exploring the spatial and temporal patterns of daily rainfall totals of R ≥ 20 mm, R ≥ 30 mm and R ≥ 40 mm (extreme precipitation events, EPE) in Pécs (SW Hungary) by a hydrometeorological network (PHN) of 10 weather stations and the gridded database of the Hungarian Meteorological Service (OMSZ). Our results revealed that (a) OMSZ datasets indicated increasing frequencies of EPEs for the period of 1971–2020 in Pécs, (b) the OMSZ dataset generally underestimated EPE frequencies, particularly for R ≥ 40 mm EPEs, for the period of 2013 to 2020, and (c) PHN indicated a slight orographic effect, demonstrating spatial differences of EPEs between the two datasets both annually and seasonally for 2013–2020. Our results pointed out the adequacy of interpolated datasets for mesoscale detection of EPE distribution. However, topographically representative monitoring networks provide more detailed microscale data for the hydrological management of urban areas. Data from dense rain-gauge networks may complement interpolated datasets, facilitating complex environmental management actions and precautionary measures, particularly during weather-related calamities.

Keywords: rainfall pattern, extreme precipitation events, monitoring, rainfall frequency, Pécs

Received March 2022, accepted September 2022.

Introduction

Climate change is not only associated with higher temperatures but also involves the changes of the temporal and spatial pattern of precipitation and particularly the dynamics of severe weather phenomena, including extreme precipitation events (EPE) (Lovino, M. *et al*. 2014; Grazzini, F. *et al*. 2019; Jakab, G. *et al*. 2019; Balatonyi, L. *et al*. 2022). EPEs, defined as daily precipitation totals higher than 20 mm by the Hungarian Meteorological Services (OMSZ), are commonly associated with low pressure systems of either Atlantic or Mediterranean origin (Maheras, P. *et al*. 2018).

Orographic and topographic barriers, as well as large inland water bodies often influence precipitation regimes and patterns (Roe, G.H. *et al*. 2003; Roe, G.H. 2005; Pavelsky, T.M. *et al*. 2012; Veals, P.G. *et al*. 2018; Napoli, A. *et al*. 2019; Schnek, T. *et al*. 2021). The dynamics as well as the microphysical and thermodynamical properties of convective clouds, combined with the

[1] Institute of Geography and Earth Sciences, Faculty of Sciences, University of Pécs. Ifjúság u. 6. H-7622 Pécs, Hungary. Corresponding author's e-mail: sarkadin@gamma.ttk.pte.hu

[2] South Transdanubian Water Management Directorate. Köztársaság tér 7. H-7623 Pécs, Hungary. E-mail: gabor.nagy.84@gmail.com

physical attributes of the surface (e.g., elevation, land use and aspect) distinctly influence the spatial distribution of rainfall totals and intensity (Kunz, M. and Kottmeier, C. 2006; Malby, A.R. *et al*. 2007; Houze, R.A. 2012; Scaff, L. *et al*. 2017; Geresdi, I. *et al*. 2017, 2020; Kirshbaum, D. *et al*. 2018).

Knowledge on the spatial pattern of precipitation is critical in terms of many practical applications (Minder, J.R. *et al.* 2008; Houze, R.A. 2014). A strong correlation between erosion rate, morphological evolution and the spatial distribution of precipitation was revealed in the Olympic Mountains (State of Washington, US). The geographical pattern of precipitation is particularly important when the hydrological consequences of extreme rainfall events are considered, e.g., in the case of intense runoff and flash floods (Pirkhoffer, E. *et al.* 2009; Czigány, Sz. *et al.* 2010a; Hanel, M. *et al.* 2012; Karlsson, I.B. *et al.* 2016; Kis, A. *et al.* 2020), soil erosion (Pásztor, L. *et al.* 2016) and mass movements (Kovács, I.P. *et al.* 2015, 2019a, b; Józsa, E. *et al.* 2019). Varied topography, combined with the dense stream networks and the large areas of silty loam, relatively low-coherence soils of South Transdanubia of Hungary, necessitates knowledge on rainfall patterns in this region with high erosion rates (Waltner, I. *et al.* 2020).

Due to its topography, Hungary is only moderately affected by surplus orographic precipitation. Only the northern mountains, the Bakony, the Sopron and the Kőszeg Mountains as well as the Mecsek Hills in the south are affected by thunderstorms and EPEs of partly orographic origin (Kovács, A. and Kovács, P. 2007; Kovács, E. *et al*. 2018; Lakatos, M. *et al.* 2020). Southern Transdanubia is especially prone to extreme precipitation and its vulnerability is large because of multiple aspects (Kovács, I.P. *et al.* 2015). Where rugged topography is associated with a high percentage of impervious surfaces, like in the urban area of Pécs and on the southern slopes of the Mecsek Hills, appropriate water management is crucial (Ronczyk, L. *et al.* 2012).

The intensity and frequency of observed EPEs have markedly changed over the past decades not only globally but also in the Carpathian Basin. Observed data revealed increasing frequency of EPEs for the period of 1946 to 2001 while annual precipitation totals decreased over this time (Bartholy, J. and Pongrácz, R. 2007) and also since 1901 (Kocsis, T. and Anda, A. 2017). Similarly, Berényi, A. *et al.* (2021) found that during the period of 1951–2019 the frequency and the intensity of the extreme precipitation events has been increased, such as the extreme weather events. In accordance with the latter trend, but based on climate model simulations, drying of the climate of Hungary, particularly for summer, was simulated for the 21st century with large uncertainties in rainfall pattern and seasonal distribution (Pieczka, I. *et al.* 2011; Kovács, A. and Jakab, A. 2021). Bartholy, J. and Pongrácz, R. (2007) demonstrated the change of the seasonal pattern of precipitation. According to Bötkös, T. (2006), who also used OMSZ dataset for Pécs, from 1951 to 2005, no marked changes were observed in the frequency of EPEs in Pécs-Pogány but he found slightly increasing annual totals with a decreasing annual number of rainy days with < 10 mm daily totals. The return periods of EPEs demonstrated a decreasing trend in Pécs-Pogány, SW Hungary by Lakatos, M. and Hoffmann, L. (2019). Climate simulations projected diminishing return periods of EPEs by a factor of 1.2 to 2.0 by the end of the 21st century for Hungary (Pongrácz, R. *et al.* 2014; Breuer, H. *et al.* 2017). Cheval, S. *et al.* (2017) predicted steady aridification for SE Europe and specifically for the Carpathian (Pannonian) Basin over the period of 1961 to 2050. For the better understanding of urban hydrodynamics, and the management of surplus water, or in contrast, the shortage of soil moisture, smart city concepts and dense hydrometeorological monitoring networks may prove adequate solutions. Spatially dense rain-gauge networks do not only provide high-resolution data on the elements of the hydrological cycle but may also be useful for the verification of numeric models (e.g., Sarkadi, N. *et al.* 2016) and, thus, may increase the accuracy of weather forecasts and improve nowcasting.

Hence, our study aimed at providing additional pieces of information on the spatial and temporal patterns of EPEs in Pécs. Our findings fill in a significant research gap, as in absence of a dense ground rain-gauge network, no spatial precipitation data of high resolution had been available for Pécs until 2012. Our specific objectives were threefold: (i) mapping of EPEs for the period of 2013 to 2020 and (ii) to validate the OMSZ interpolated data with the ground measured rainfall data; (iii) to analyse the temporal variability of the frequencies of EPEs compared to corresponding OMSZ data for the period of 1971 to 2020.

Materials and methods

Study site

The city of Pécs covers an area of 167 km^2 and is located on the southern slopes of the Mecsek Hills, the Pécs Basin and the northern margin of the Baranya Hills. The highest point within the administrative border of the city is the Tubes Hill (612 m), while the lowest point is in the Pécs Basin (Megyeri út, 103 m). The Mecsek Hills is a low-mountain range that spans for about 45 km in an ENE-WSW direction and has a width of about 10 km (Lovász, Gy. 1977) *(Figure 1).*

The study area lies in the south-eastern Transdanubian Hills macroregion (Dövényi, Z. 2010). The region is located in the temperate climatic zone, fully humid with hot summers and Mediterranean and arid continental influences (Lovász, Gy. 1977; Péczely, Gy. 1981). The long-term average annual temperature is 11.5 °C (1991–2020 in Pécs-Pogány) with markedly higher values in the past few years (12.66 °C at the Ifjúság Street campus of University of Pécs for the period of 2009 to 2021). The mean temperature of the coldest month (January) is -0.39 °C, while the warmest month is July with a mean temperature of 22.06 °C for 1991–2020 at Pécs-Pogány. The average annual precipitation total is around 680 mm in the region. The 30-year average value is 672 mm in Pécs (1991 to 2020 data, source: Hungarian Meteorological Services). Based on the 1991 to 2020 meteorological data in average January was the driest month (31 mm), while the highest 30-year averaged precipitation was recorded in June (83 mm). According to Ács, F. *et al.* (2015) the climate of the Transdanubian Hills region can be characterized with the combination of four climatic types: moderately cool/cool and moderately dry/moderately moist in the period of 1901–1930. These climatic zones shifted toward the moderately cool/moderately dry category over the period of 1971–2000 (Ács, F. *et al.* 2015). However, Breuer, H. *et al.* (2017) demonstrated that the change of the climatic classification of this region was mainly manifested in drying with minimal or no alterations in categorical changes related to temperature.

The hydrometeorological monitoring network

In the current paper precipitation data from the 10 stations of the Pécs Hydrometeorological Network (hereafter: PHN) were analysed. Eight stations of the PHN were manufactured by Boreas Ltd. (Érd, Hungary) using BES-06 automated rain gauges of 0.1 mm resolution[3]. The network of the Boreas stations has been jointly operated by the Tettye Forrásház Ltd. (Water Supplying and Water Management Company of Pécs) and the Institute of Geography and Earth Sciences of the University of Pécs since 2012. The weather station at the Ifjúság Street Campus of the University of Pécs, operated by the national weather network of the Hungarian Meteorological Services, is equipped with a Lambrecht 15188 rain gauge (Lambrecht GmbH, Göttingen, Germany) as well as with a manual Hellmann rain gauge. The latter provided data for this study. The 10th station of the manual Hellmann rain gauge used in the analysis is

[3] www.boreas.hu

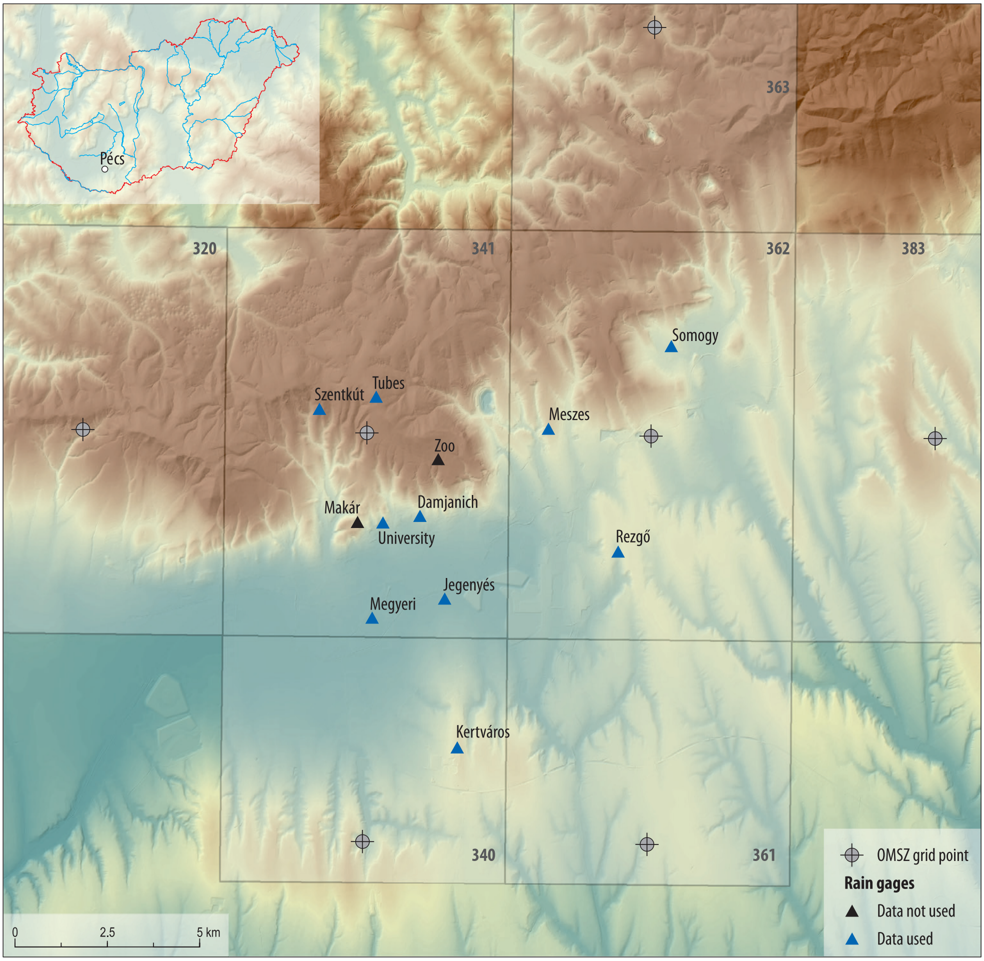

Fig. 1. Location of the study area and the PHN stations (black and blue triangles). The crossed circles show the OMSZ grid data points. The transparent squares indicate the area which we assumed to be representative for the OMSZ grid data points.

located in Jegenyés, central Pécs. It was used to double-check the manually and automatically measured rainfall data and its data were also used in the analyses. Missing data were either replaced by PHN daily mean precipitation (usually non-precipitating days) or, if found substantial, the station or period was omitted from the calculations (see *Appendix* for incorrect or missing data periods).

Due to the rugged topography and higher frequency of flash floods (Czigány, Sz. *et al.* 2013) more rain gauges were installed in the northern side of the city. A secondary aspect of the installation was the maintenance of appropriate operation (safety and access to power supply network) of the instruments whereas, thirdly, stations were installed according to the distribution of the sewage-sheds of the Tettye Forrásház Ltd. A fourth aspect of the Boreas rain gauge distribution was to detect the impact of topography on rainfall distribution within the administrative borders of Pécs.

Temporal changes in the frequency of extreme rainfall events

Gridded climatological rainfall data of 0.1° resolution was downloaded from the website of the OMSZ[4]. The precipitation data for each grid point were calculated by the OMSZ by homogenizing and interpolating measured data using the MASH (Multiple Analysis of Series for Homogenization) and MISH (Meteorological Interpolation based on Surface Homogenized Data Basis) method (Szentimrey, T. and Bihari, Z. 2007). We assumed that the OMSZ grid point values are representative for the grid box depicted in *Figure 1.* Although, this can result some biases on spatial investigations due to for instance the under-represented terrain conditions. PHN data of the rain gauges located within the boundaries of the specific OMSZ grid were compared to the gridded rainfall data *(Table 1).* Seven grids cover the entire administrative area of the City of Pécs. However, rain gauges of the PHN are only found in three grid points, numbered 340, 341 and 362 in the OMSZ database (see *Figure 1*, and *Table 1*). Due to their spatial influence, grid points 320, 361, 363 and 383, partially covering the city of Pécs, were also considered in our calculations.

Table 1. Distribution of PHN rain gages according to the OMSZ grids

Grid name	Name of PHN rain gages within the given HMS grid
NW grid (gp 341)	Szentkút, Tubes, Zoo, University, Makár, Damjanich, Jegenyés, Megyeri út
NE grid (gp 362)	Somogy, Meszes, Rezgő út
SW grid (gp 340)	Kertváros (Garden City)

Temporal changes of the annual frequency of the OMSZ EPEs were also determined for all OMSZ grid points for the period of 1971–2020. Linear trends were calculated for each of these grid points.

[4] https://odp.met.hu

PHN's EPE frequencies of mm daily rainfalls were also compared with the corresponding OMSZ grid point data for the period of 2013–2020 dataset. We also analysed the type of precipitation activity that generated the EPEs of the PHN. Climatological data of precipitation type were obtained from the Hungarian Meteorological Service. The following categories are defined in the OMSZ dataset: drizzle, rain, sleet (freezing rain), shower, snow, snow shower, hail, thunderstorm, snowstorm, thunderstorm with hail, thunder.

Spatial distribution of annual and seasonal OMSZ and PHN data for extreme precipitation events

Due to the relatively low number of weather stations available (10) to determine the spatial distribution of PHN precipitation events for the period of 2013 to 2020, Thiessen polygons were generated in ArcGIS 10.4 software environment. The general pattern of the gridded OMSZ data (Ch. 2.4) and the Thiessen polygons of the PHN data set were compared for the comparative spatial analysis of the two datasets.

The same spatial interpolation with Thiessen polygons was performed for the $R \geq 20$ mm events for winter (December to January), spring (March to May), summer (June to August) and fall (September to November) and for the $R \geq 40$ mm frequencies for summer and fall. Spring and winter had negligibly low frequencies hence their data are not shown.

Results

Temporal changes of the OMSZ data

The annual number of OMSZ-registered EPEs only slightly increased over the period of 1971 to 2020 with a mean slope of 0.0237, i.e., 2.37 EPE events per 100 years (*Table 2*, *Figures 2*, *3* and *4*). The $R \geq 20$ mm EPEs of grid 340 demonstrated the highest increase with a slope of 0.04274 (4.274 events per 100 years).

Table 2. Slopes of the changes of the annual frequencies of EPE for OMSZ grids 340, 341 and 362 for the period of 1971 to 2020

Daily precipitation, mm	340	341	362	Mean
R ≥ 20	0.04274	0.02468	0.04010	*0.03580*
R ≥ 30	0.02699	0.02555	0.02463	*0.02570*
R ≥ 40	0.01176	0.00797	0.00922	*0.00960*

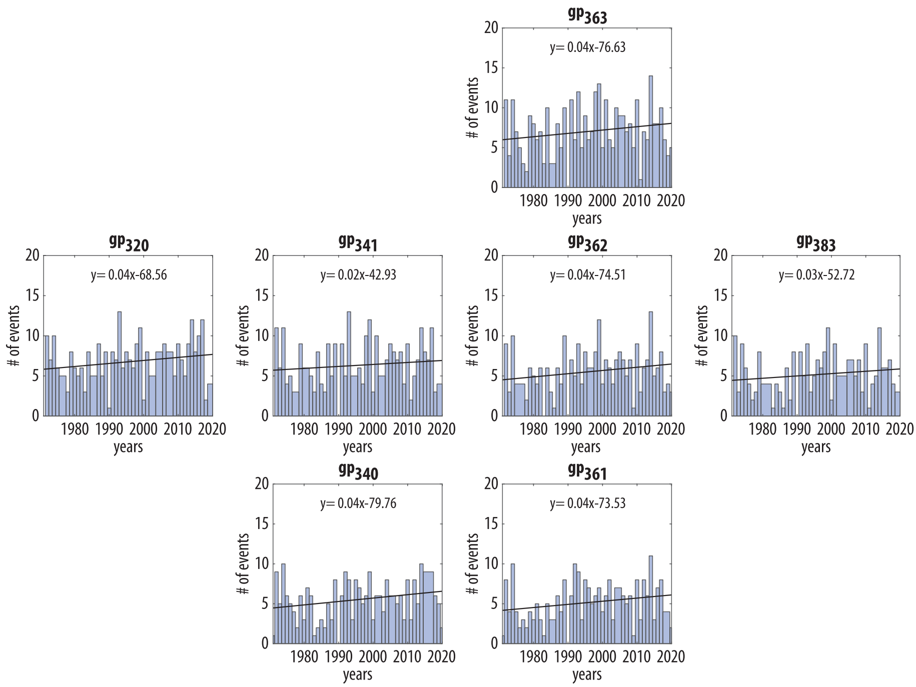

Fig. 2. Temporal changes in the annual number of the R ≥ 20 mm OMSZ's EPE observed daily precipitation totals for the period of 1971 to 2020 at all OMSZ grid points (gp).

In general, the lowest increase was observed for the R ≥ 40 mm EPEs with a mean slope of 0.0096 (0.96 events per 100 years).

In terms of grid point location, the values of grid points 340 (SW grid) and 362 (NE grid) indicated similar increase with slopes of 2.72 and 2.47 events per 100 years, respectively, while grid point 341 showed markedly lower slope (1.94 events per 100 years) for the same period.

Spatial comparison of the PHN and the OMSZ data for the period of 2013 to 2020

Marked differences were revealed in the frequencies of the EPEs between OMSZ and PHN datasets. Typically, the annual number of extreme events recorded by the PHN network was slightly higher than the annual numbers based on the OMSZ gridded dataset at most stations (*Figures 5, 6* and *7*). When

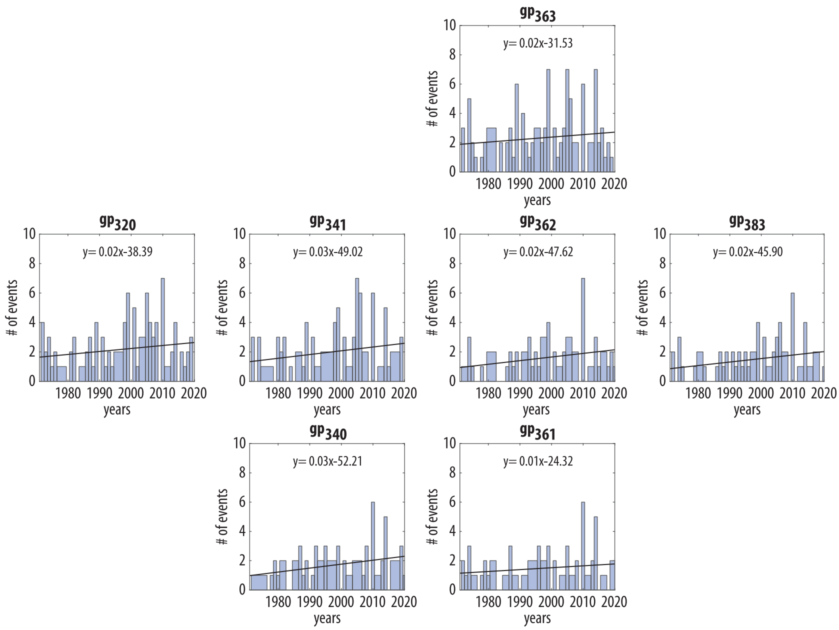

Fig. 3. Temporal changes in the annual number of the R ≥ 30 mm OMSZ's EPE observed daily precipitation totals for the period of 1971 to 2020 at all OMSZ grid points (gp).

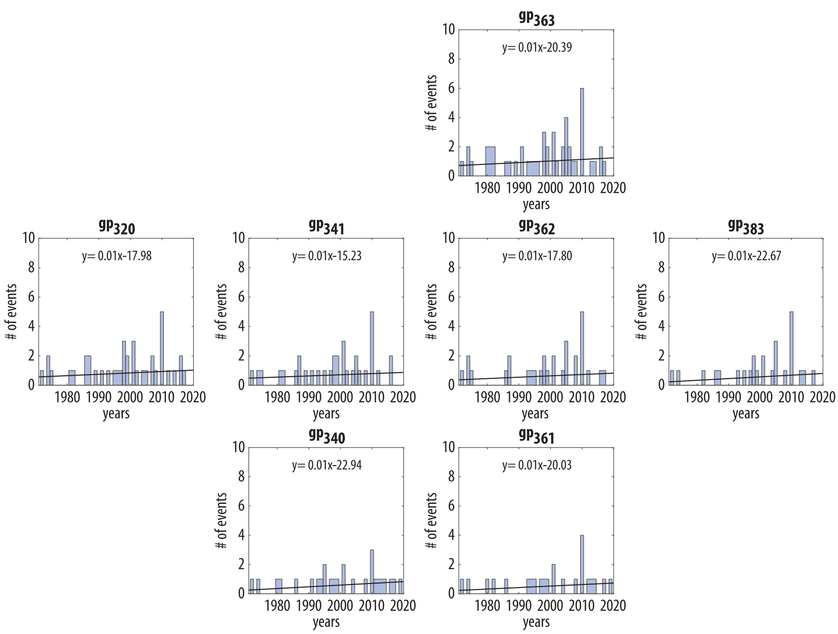

Fig. 4. Temporal changes in the annual number of the R ≥ 40 mm OMSZ's EPE observed daily precipitation totals for the period of 1971 to 2020 at all OMSZ grid points (gp).

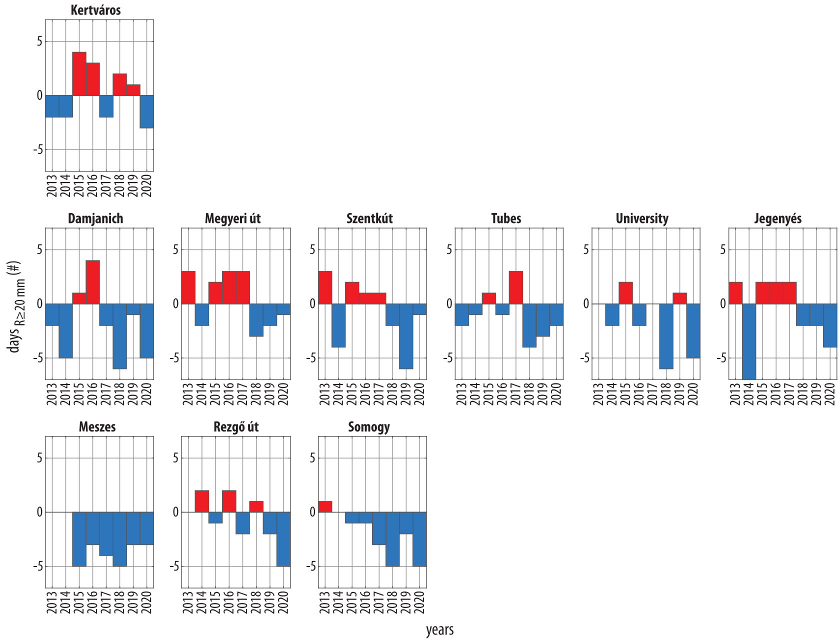

Fig. 5. Difference between the annual number of events of R ≥ 20 mm EPEs compared to the OMSZ dataset (baseline) at each PHN station for the period of 2013 to 2020. Calculation basis: OMSZ – PHN, hence blue columns show higher PHN frequencies, red colours higher OMSZ frequencies; top: grid point 340, centre: grid point 341, bottom: grid point 362).

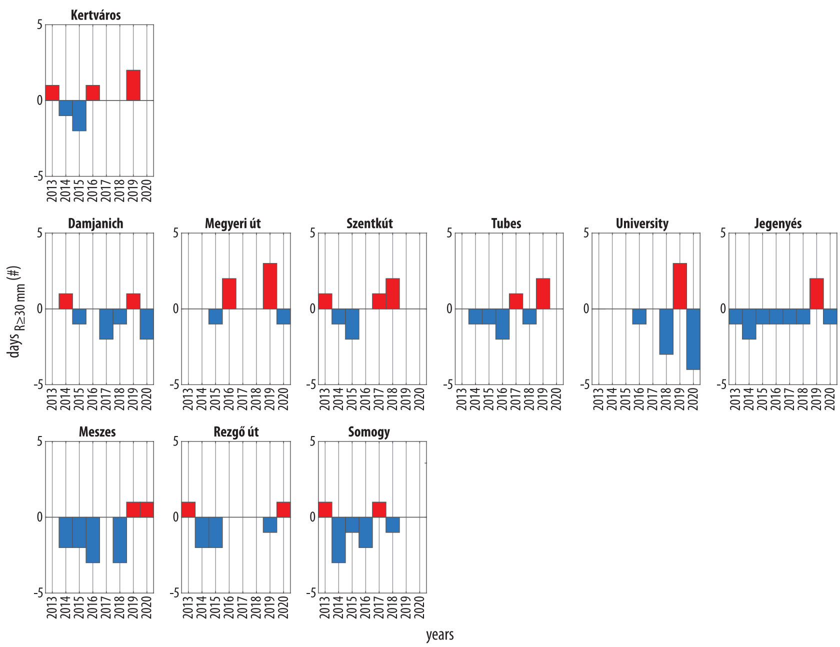

Fig. 6. Difference between the annual number of events of R ≥ 30 mm EPEs compared to the OMSZ dataset (baseline) at each PHN station for the period of 2013 to 2020. For further explanations see *Fig. 5.*

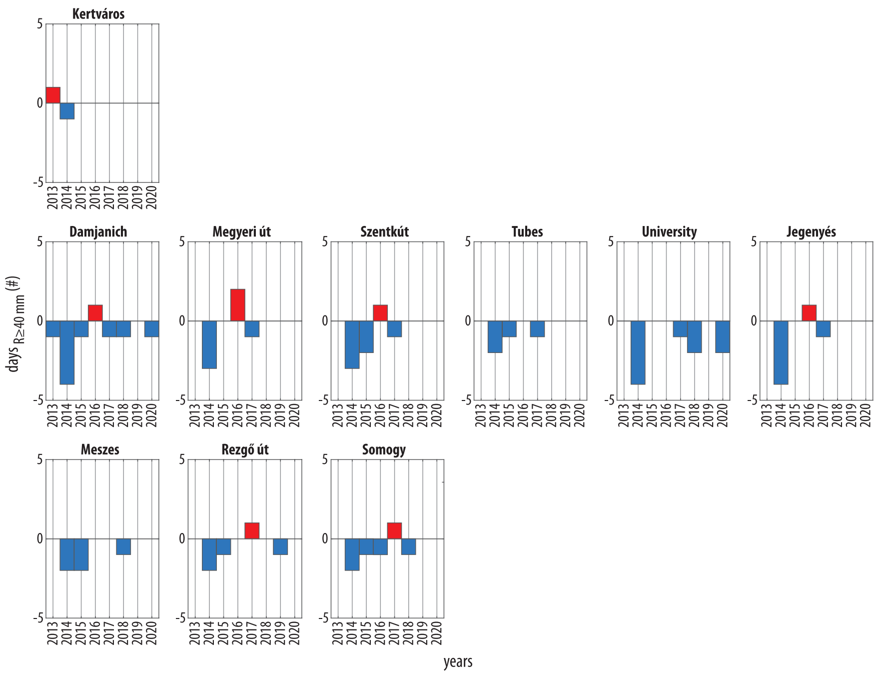

Fig. 7. Difference between the annual number of events of R ≥ 40 mm EPEs compared to the OMSZ dataset (baseline) at each PHN station for the period of 2013 to 2020. For further explanations see *Fig. 5.*

the total number of events was considered, marked differences were found among the three EPE categories.

Due to their higher number, the largest differences were observed for the R ≥ 20 mm EPEs. However, the relative differences were higher for the annual frequency of R ≥ 40 mm events than for the other two EPE frequencies. Nonetheless, the difference for the R ≥ 20 mm events was not distinctive and showed a rather equivocal pattern. The highest discrepancy of the R ≥ 20 mm events was found for the Damjanich station, while for the R ≥ 30 mm and the R ≥ 40 mm events the University station showed the greatest differences.

OMSZ frequencies were typically, but non-uniformly lower than the PHN frequencies at the studied grid points (see *Figures 5, 6* and *7*). At grid point 340, the number of R ≥ 20 mm events in PHN station, Kertváros (Garden City) were higher than the OMSZ dataset. In the years of 2013, 2014, 2017, 2018 and 2020, but were lower in the years of 2015, 2016 and 2018. The number of R ≥ 20 mm events of the PHN stations was higher than the OMSZ dataset in the year of 2013 at Damjanich and Tubes; in the year of 2014 at Damjanich, Jegenyés, Megyeri út and Szentkút; in the years of 2018 and 2019 all PHN stations registered higher number of events compared to the OMSZ data and in the year of 2020 at Damjanich, Jegenyés, Szentkút and Tubes. In the years of 2015, 2016 and 2017 all PHN stations registered a lower or equal number of events as the OMSZ.

At grid point 362, the number of R ≥ 20 mm events of the PHN stations was higher than the OMSZ dataset in 2015 at Meszes; in the year of 2017 at all stations; in the year of 2018 at Meszes and Somogy; in the years of 2019 and 2020 at all stations. In the years of 2013, 2014 and 2016 all PHN stations registered a lower or equal number of events compared to the OMSZ.

Opposed to the R ≥ 20 mm and R ≥ 30 mm events, significantly higher PHN frequencies were observed for the R ≥ 40 mm EPEs at all stations *(Figure 8)*.

Therefore, when the PHN data were included in the temporal analysis, the increase of the frequency EPEs was even more pronounced than solely based on the OMSZ interpolated dataset.

Non-convective precipitation (rain, snow or sleet) and thunderstorms were found to be responsible for EPEs in Pécs over the studied period, assuming that the precipitation type of the Pécs-Pogány OMSZ station is representative for all PHN precipitation events. In some cases, however, the Pécs-Pogány station did not report any precipitation, whereas rainfall was detected by the PHN. These cases are represented by the category called 'not specified' in *Figure 8*. Non-specified events were classified as convective cases based on the observed amount and intensity of precipitation for analysation of occurrence of frequency in different categories. The frequency of non-convective rainfall events were a few percent higher than that of the convective cases. A slight gradient with decreasing differences from north (62–38%) to south (50–50%) is observable in the studied area. Minor differences were detected in an east-west direction with a slightly increasing gradient from west to east.

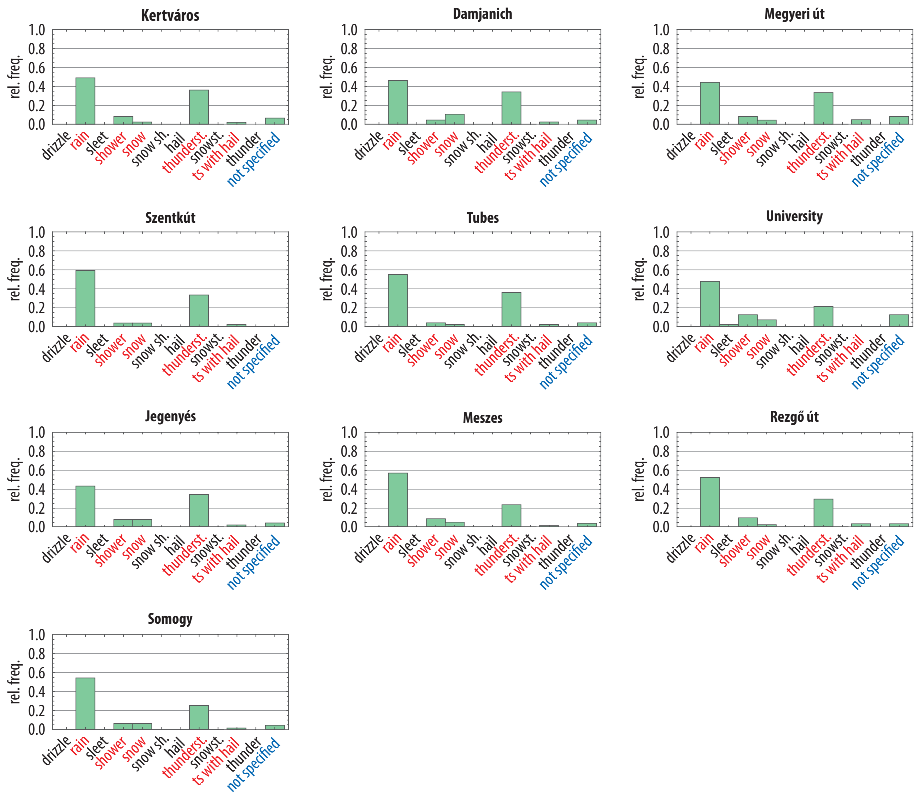

Fig. 8. Relative frequencies of the type of extreme precipitation events (R ≥ 20 mm) at different locations, for the period of 2013-2020. Red fonts highlight the events that occurred at the stations based on the reported type of precipitation at OMSZ Pécs-Pogány station. Blue fonts highlight non-specified events (the occurrence of EPE at PHN station, but OMSZ data did not report precipitation on the same day).

Spatial pattern of annual mean extreme rainfall events

The spatial distribution of the R ≥ 20 mm EPEs markedly differed between the two datasets *(Figure 9)*. Firstly, as it was already claimed in chapter 3.2, in general, the PHN dataset indicated higher mean annual frequencies of EPEs than the OMSZ data for the period of 2013 to 2020. Secondly, contrast to the higher frequencies in the western and northern part of the city and the OMSZ dataset, the PHN dataset indicated the highest frequencies in the north-central part of Pécs along a SW-NE axis with an annual frequency of 8 to 9 events (see *Figure 9*, A and B). This frequency decreased to a minimum of 6.5 events yearly in the Pécs Basin (lowest

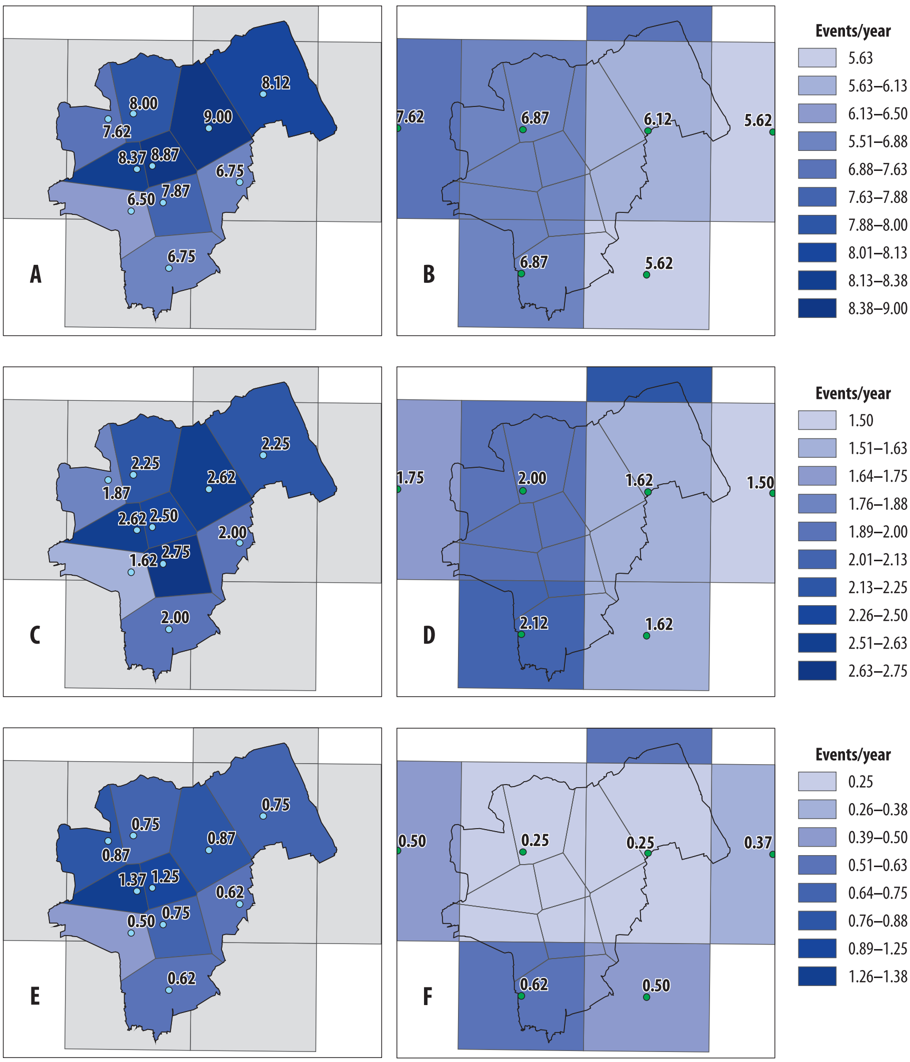

Fig. 9. Spatial distribution of the annual mean frequencies of the R ≥ 20 mm (A), R ≥ 30 mm (C), and R ≥ 40 mm (E) EPEs of the PHN stations and the corresponding values of the OMSZ grids (B, D and F) over the period of 2013 to 2020 in Pécs.

part of the city) and the southern outskirts. The PHN data revealed ever higher annual frequencies of the events with increasing elevation on the southern slopes of the Mecsek Hills; however, this pattern was more evident in the NE part of the city than in the NW.

The mean annual frequencies of the R ≥ 30 mm and R ≥ 40 mm EPEs showed a more similar pattern between the two datasets compared to the distribution of R ≥ 20 mm EPEs (see *Figure 9*, C and E). The OMSZ data revealed the highest frequencies in NE Pécs (grid 363, ~ 2.5 events per year) with a second maximum in the SW (2.12 events per year), based on R ≥ 30 mm events. Conversely, the PHN data showed a more marked dominance of higher frequencies in the central-eastern part of the city (~ 2.5 events/year). The highest frequencies were found in the south-central part of the city (Jegenyés) and in the north-eastern tip of Pécs, where OMSZ data indicated the lower frequency.

The spatial distribution of the R ≥ 40 mm EPEs of the PHN again showed a SW-NE gradient in contrast to the mosaic pattern of the OMSZ data (for the R ≥ 20 mm and R ≥ 30 mm events). The OMSZ data indicated no topographic influence with a maximum of about 0.6 events per year for the southern corner of the city, showing no effect of orography. Adversely, the PHN dataset showed a marked orographic gradient with a second SW-NE gradient in northern Pécs (see *Figure 9*, E and F).

Spatial pattern of seasonal frequencies of the EPEs

Our findings revealed profound seasonal differences for both the R ≥ 20 mm and R ≥ 40 mm events (*Figure 10*). Due to the climatic characteristics of the study area (Breuer, H. *et al.* 2017), the lowest frequencies of EPEs were found in winter (DJF), while the highest frequencies prevailed in summer (JJA) and fall (SON). As long as MAM, SON and DJF demonstrated higher frequencies in the northern neighbourhoods of Pécs. JJA presented a maximum in the centre of the city, separating lower frequency parts on the western and eastern locations while the OMSZ had a distinct maximum in the south (grid point 340). For the winter data, the PHN and the OMSZ datasets were rather similar. The largest differences were found during summer and autumn between the two datasets. While the PHN dataset showed a relatively centralized maximum in central Pécs for the summer, the maximum of the OMSZ was found in the south. A marked difference was found in the distribution of EPEs in SON where the OMSZ data was characterized with a distinct W-E separation in contrast to the NE dominance of EPEs in the PHN.

Discussion

Corroborating the findings of Kovács, A. and Kovács, P. 2007, and Kovács, E. *et al*. 2018 to a certain degree, the frequencies of EPEs were slightly higher on the southern slopes of the Mecsek Hills than in its southern foreground (Pécs Basin and Baranya Hills). The low orographic influence of the southern slopes of the Mecsek Hills, is in a partial accordance with the findings of Jakab, G. *et al.* (2019), and Lakatos, M. *et al.* (2020), who found higher frequencies of EPEs and maximum mean precipitation totals respectively for some of the hilly and mountainous areas of Hungary. Nonetheless, alongside with the higher annual rainfall totals, the orography-generated surplus frequency of EPEs in the Mecsek presumes the increasing likelihood of flash flood events, mass movements and intense soil erosion (Fábián, Sz. *et al.* 2006, 2009, 2016; Kovács, I.P. *et al.* 2015).

Consequently, monitoring networks do not only provide scientific data on rainfall pattern but may also function as a tool for flood mitigation and prevention (Czigány, Sz. *et al.* 2010b), management of ecosystem services (Syrbe, R.-U. and Grunewald, K. 2017) and may also be indispensable for the protection of farmlands, urban areas and habitats of endangered species (Nagy, G. *et al.* 2020). Additionally, weather monitoring networks seem to be suitable to reveal the

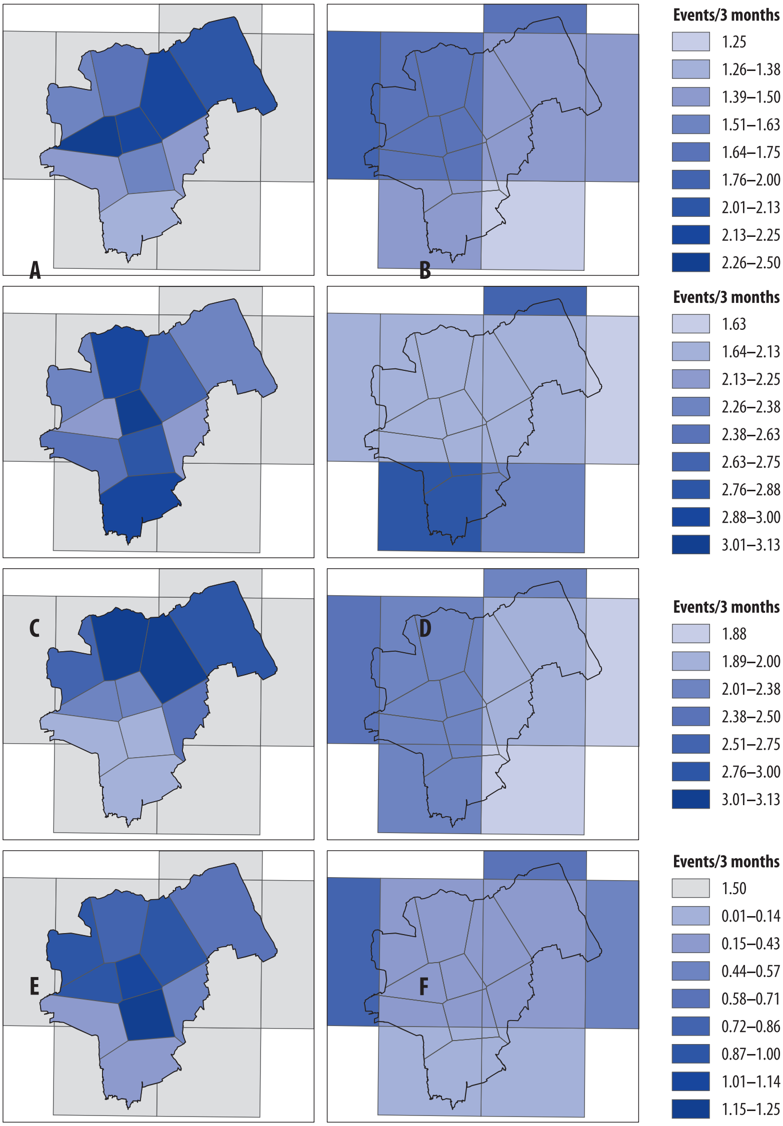

Fig. 10. Spatial distribution of the seasonal mean frequencies of the R ≥ 20 mm PHN EPEs (A, C, E and G) and the corresponding values of the OMSZ grids (B, D, F and H) over the period of 2013 to 2020 in Pécs, from spring (A and B) to winter (G and H), from top to bottom.

intensity, location and timing of EPEs, especially in developed areas, where hydrologic, erosional and geomorphic consequences of intense rainfall may threaten human lives and generate significant economic losses.

We found gridded OMSZ data suitable for the characterization of short-term mesoclimatic conditions of Pécs. However, compared to the PHN, some EPEs were absent in the OMSZ due to the different locations of the points of observation in the two datasets. Additionally, due to the blurring of the interpolation algorithm significant differences were generated between the two analysed datasets. Whereas the city of Pécs only covers a land area of 164 km^2, still, its rugged topography may contribute to the sporadic nature and large spatial heterogeneity of intense rainfalls especially in summer. Our results pointed out the adequacy of interpolated datasets for mesoscale detection of EPE distribution. Nonetheless, topographically representative monitoring networks provide more detailed microscale data for the hydrological management of urban areas. Additionally, data of dense rain gauge networks may complement interpolated datasets, facilitating the feasibility of complex environmental management strategies and precautionary measures, particularly during weather related catastrophes.

Conclusions

The following conclusions have been drawn from the present study:

i. The spatial pattern of the EPEs revealed differences between the OMSZ and the PHN datasets; on mesoclimatic scale OMSZ data is suitable for spatial analysis, however, particularly in summer, measured data are indispensable for flood forecasting. The PHN stations demonstrate a rather heterogeneous environment in respect of elevation, aspect and land use class among others. Nonetheless, the value of the grid point is not necessarily representative for the entire grid box, as precipitation values may be altered by various environmental factors (such as topography, land use type, vegetation, etc.). Given synoptic situations may be corrected in terms of the differences when the two datasets are compared, provided that the situations are correctly identified, and the comparative analysis is sufficiently long and contains a large number of EPEs. Therefore, the PHN can be used for the enhancement of the spatial pattern and resolution of the OMSZ dataset. Ground monitoring will also point out the spatial heterogeneity of climate in relatively small urban areas with rugged topography.

ii. In partial accordance with the OMSZ gridded dataset, the spatial pattern of the PHN-based EPEs in Pécs demonstrated a slight effect of topography and elevation;

iii. The temporal trend of the annual frequency of EPEs indicated a slight increase over the period of 1971 to 2020 for the OMSZ data;

iv. Compared to the PHN data, the annual frequency of the OMSZ dataset demonstrated an ambivalent picture, i.e., showed similar frequencies based on the R ≥ 20 mm and the R ≥ 30 mm EPEs but revealed higher frequencies for the R ≥ 40 mm EPEs over the period of 2013 to 2020.

v. Although the elevation-corrected gridded OMSZ dataset reflected the actual pattern of EPEs for Pécs with a relatively high accuracy, it cannot entirely replace data obtained by a dense rain gauge network.

vi. Our findings could potentially contribute to the correct parameterization of hydrological models, hence may be employed by urban planners. This study and its key conclusions may serve as a basis for the development and clarification of currently operating water resources management models. The experience gained will be used during practical water management activities to ensure a more even water supply for the end-users.

***Acknowledgement*:** The authors are grateful to Attila Sárosi and Tettye Forrásház Ltd. for their support and work on the maintenance and smooth operation of the rain gauge network. We thank the editors and the reviewers for careful thoughts and useful comments. The authors are indebted to Dénes Lóczy for revising and proofreading the English of the manuscript.'

REFERENCES

Ács, F., Breuer, H. and Skarbit, N. 2015. Climate of Hungary in the twentieth century according to Feddema. *Theoretical and Applied Climatology* 119. (1–2): 161–169. Available at https://doi.org/10.1007/s00704-014-1103-5

Balatonyi, L., Lengyel, B. and Berger, Á. 2022. Nature-based solutions as water management measures in Hungary. *Modern Geográfia* 17. (1): 73–85. Available at https://doi.org/10.15170/MG.2022.17.01.05

Bartholy, J. and Pongrácz, R. 2007. Regional analysis of extreme temperature and precipitation indices for the Carpathian Basin from 1946 to 2001. *Global and Planetary Change* 57. (1–2): 83–95. Available at https://doi.org/10.1016/j.gloplacha.2006.11.002

Berényi, A., Pongrácz, R. and Bartholy, J. 2021. Changes in extreme precipitation patterns in the southern lowland regions of Europe during the 1951–2019 period. *Modern Geográfia* 16. (4): 85–101. Available at https://doi.org/10.15170/MG.2021.16.04.05

Bötkös, T. 2006. Precipitation trends in Pécs. In *Sustainable Development in Central Europe. Pollution and Water Resources.* Ed.: Halasi-Kun, G.J., Columbia University Seminar Proceedings, Vol. 36. Pécs, PTE. 171–177.

Breuer, H., Ács, F. and Skarbit, N. 2017. Climate change in Hungary during the twentieth century according to Feddema. *Theoretical and Applied Climatology* 127. (3–4): 853–863. Available at https://doi.org/10.1007/s00704-015-1670-0

Cheval, S., Dumitrescu, A. and Birsan, M-V. 2017. Variability of the aridity in the South-Eastern Europe over 1961–2050. *Catena* 151. 74–86. Available at https://doi.org/10.1016/j.catena.2016.11.029

Czigány, Sz., Pirkhoffer, E. and Geresdi, I. 2010a. Impact of extreme rainfall and soil moisture on flash flood generation. *Időjárás – Quarterly Journal of the Hungarian Meteorological Service* 114. (1–2): 79–100.

Czigány, Sz., Pirkhoffer, E., Balassa, B., Bugya, T., Bötkös, T., Gyenizse, P., Nagyváradi, L., Lóczy, D. and Geresdi, I. 2010b. Villámárvíz, mint természeti veszélyforrás a Dél-Dunántúlon (Flash floods as a natural hazard in Southern Transdanubia). *Földrajzi Közlemények* 134. (3): 281–298.

Czigány, Sz., Pirkhoffer, E., Lóczy, D. and Balatonyi, L. 2013. Flash flood analysis for Southwest-Hungary. In *Geomorphological Impacts of Extreme Weather.* Ed.: Lóczy, D., Springer Geography series. Dordrecht, Springer, 67–82.

Dövényi, Z. (ed.) 2010. *Magyarország kistájainak katasztere* (Inventory of microregions in Hungary). Budapest, MTA Földrajztudományi Kutatóintézet. (in Hungarian)

Fábián, Sz.Á., Kovács, J., Lóczy, D., Schweitzer, F., Varga, G., Babák, K., Lampért, K. and Nagy, A. 2006. Geomorphologic hazards in the Carpathian foreland, Tolna County (Hungary). *Studia Gemorphologica Carpatho Balcanica* 40. 107–118.

Fábián, Sz.Á., Görcs, N.L., Kovács, I.P., Radvánszky, B. and Varga, G. 2009. Reconstruction of flash flood event in a small catchment: Nagykónyi, Hungary. *Zeitschrift für Geomorphologie* 53. Suppl. 2. 123–138. Available at http://dx.doi.org/10.1127/0372-8854/2009/0053S3-0123

Fábián, Sz.Á., Kalmár, P., Józsa, E. and Sobucki, M. 2016. Hydrogeomorphic exploration of a local headwater stream in low mountainous environment following detailed field survey protocol (Mecsek Mountains, Hungary). *Revista De Geomorfologie* 18. 77–90. Available at https://doi.org/10.21094/rg.2016.134

Geresdi, I., Xue, L. and Rasmussen, R. 2017. Evaluation of orographic cloud seeding using bin microphysics scheme: Two-dimensional approach. *Journal of Applied Meteorology and Climatology* 56. (5): 1443–1462. Available at https://doi.org/10.1175/JAMC-D-16-0045.1

Geresdi, I., Xue, L., Sarkadi, N. and Rasmussen, R. 2020. Evaluation of orographic cloud seeding using bin microphysics scheme. Three-dimensional simulation of real cases. *Journal of Applied Meteorology and Climatology* 59. (9): 1537–1555. Available at https://doi.org/10.1175/JAMC-D-19-0278.1

Grazzini, F., Craig, G., Keil, C., Antolini, G. and Pavan, V. 2019. Extreme precipitation events over Northern Italy. Part I: a systematic classification with machine learning techniques. *Quarterly Journal of the Royal Meteorological Society* 146. (726): 69–85. Available at https://doi.org/10.1002/qj.3635

Hanel, M., Vizina, A., Máca, P. and Pavlásek, J. 2012. A multi-model assessment of climate change impact on hydrological regime in the Czech Republic. *Journal of Hydrology and Hydromechanics* 60. (3): 152–161. Available at https://doi.org/10.2478/v10098-012-0013-4

Houze, R.A. 2012. Orographic effects on precipitating clouds. *Reviews of Geophysics* 50. (1): 1–47. Available at https://doi.org/10.1029/2011RG000365

Houze, R.A. 2014. Clouds and precipitation associated with hills and mountains. *Cloud Dynamics* 104. 369–402. Available at https://doi.org/10.1016/B978-0-12-374266-7.00012-3

Jakab, G., Biró, T., Kovács, Z., Papp, Á., Sarawut, N., Szalai, Z., Madarász, B. and Szabó, Sz. 2019. Spatial analysis of changes and anomalies of intense rainfalls in Hungary. *Hungarian Geographical Bulletin* 68. (3): 241–253. Available at https://doi.org/10.15201/hungeobull.68.3.3

Józsa, E., Lóczy, D., Soldati, M., Drăguţ, L.D. and Szabó, J. 2019. Distribution of landslides reconstructed from inventory data and estimation of landslide susceptibility in Hungary. *Hungarian Geographical Bulletin* 68. (3): 255–267. Available at https://doi.org/10.15201/hungeobull.68.3.4

Karlsson, I.B., Sonnenborg, T.O., Refsgaard, J.Ch., Trolle, D., Børgesen, C.D., Olesen, J.E., Jeppesen, E. and Jensen, K.H. 2016. Combined effects of climate models, hydrological model structures and land use scenarios on hydrological impacts of climate change. *Journal of Hydrology*

535. 301–317. Available at https://doi.org/10.1016/j.jhydrol.2016.01.069

Kis, A., Pongrácz, R., Bartholy, J. and Szabó, J.A. 2020. Projection of runoff characteristics as a response to regional climate change in a Central/Eastern European catchment. *Hydrological Sciences Journal* 65. (13): 2256–2273. Available at https://doi.org/10.1080/02626667.2020.1798008

Kirshbaum, D., Adler, B., Kalthoff, N., Barthlott, C. and Serafin, S. 2018. Moist orographic convection: Physical mechanisms and links to surface-exchange processes. *Atmosphere* 9. (3):80. Available at https://doi.org/10.3390/atmos9030080

Kocsis, T. and Anda, A. 2017. Analysis of precipitation time series at Keszthely, Hungary (1871–2014). *Időjárás – Quarterly Journal of the Hungarian Meteorological Service* 121. (1): 63–78.

Kovács, A. and Kovács P. 2007. Árvíz a Szinván: az orografikus csapadéktöbblet egy extrém esete (Flood on the Szinva Stream: an extreme case of orographic precipitation surplus). *Légkör* 52. (4): 5–8.

Kovács, A. and Jakab, A. 2021. Modelling the impacts of climate change on shallow groundwater conditions in Hungary. *Water* 13. (5): 668. Available at https://doi.org/10.3390/w13050668

Kovács, E., Puskás, J., Bán, Zs.B. and Kozma, K. 2018. Agro-climatological investigation in Kőszeghegyalja and Vas-hegy (Hungary). *Légkör* 63. (2): 68–74.

Kovács, I.P., Czigány, Sz., Józsa, E., Varga, T., Varga, G., Pirkhoffer, E. and Fábián, Sz.Á. 2015. Geohazards of the natural protected areas in Southern Transdanubia (Hungary). *Dynamiques Environnementales* 35. 97–110. Available at https://doi.org/10.4000/dynenviron.1182

Kovács, I.P., Czigány, Sz., Dobre, B., Fábián, Sz.Á., Sobucki, M., Varga, G. and Bugya, T. 2019a. A field survey–based method to characterise landslide development: a case study at the high bluff of the Danube, south-central Hungary. *Landslides* 16. 1567–1581. Available at https://doi.org/10.1007/s10346-019-01205-8

Kovács, I.P., Bugya, T., Czigány, Sz., Defilippi, M., Lóczy, D., Riccardi, P., Ronczyk, L. and Pasquali, P. 2019b. How to avoid false interpretations of Sentinel-1A TOPSAR interferometric data in landslide mapping? A case study: recent landslides in Transdanubia, Hungary. *Natural Hazards* 96. 693–712. Available at https://doi.org/10.1007/s11069-018-3564-9

Kunz, M. and Kottmeier, C. 2006. Orographic enhancement of precipitation over low mountain ranges. Part I: Model formulation and idealized simulations. *Journal of Applied Meteorology and Climatology* 45. (8): 1025–1040. Available at https://doi.org/10.1175/JAM2389.1

Lakatos, M. and Hoffmann, L. 2019. Növekvő csapadékintenzitás, magasabb mértékadó csapadékok a változó klímában (Increasing trend in short term precipitation and higher return levels due to climate change). In *Országos Települési Csapadékvízgazdálkodási Konferencia tanulmányai*. Ed.: Biró, T., Budapest, Dialóg Campus Kiadó, 8–16. Available at https://vtk.uni-nke.hu/document/vtk-uni-nke-hu/K%C3%A9zik%C3%B6nyv_csapad%C3%A9k.pdf (in Hungarian)

Lakatos, M., Izsák, B., Szentes, O., Hoffmann, L., Kircsi, A. and Bihari, Z. 2020. Return values of 60-minute extreme rainfall for Hungary. *Időjárás – Quarterly Journal of the Hungarian Meteorological Service* 124. (2): 143–156.

Lovász, Gy. 1977. *Baranya megye természeti földrajza* (Physical geography of Baranya county). Pécs, Baranya Megyei Levéltár.

Lovino, M., García, N.O. and Baethgen, W. 2014. Spatiotemporal analysis of extreme precipitation events in the Northeast region of Argentina (NEA). *Journal of Hydrology: Regional Studies* 2. 140–158. Available at https://doi.org/10.1016/j.ejrh.2014.09.001

Maheras, P., Tolika, K., Anagnostopoulou, C., Makra, L., Szpirosz, K. and Károssy, Cs. 2018. Relationship between mean and extreme precipitation and circulation types over Hungary. *International Journal of Climatology* 38. (12): 4518–4532. Available at https://doi.org/10.1002/joc.5684

Malby, A.R., Whyatt, J.D., Timmis, R.J., Wilby, R.L. and Orr, H.G. 2007. Long-term variations in orographic rainfall: analysis and implications for upland catchments. *Hydrological Sciences Journal* 52. (2): 276–291. Available at https://doi.org/10.1623/hysj.52.2.276

Minder, J.R., Durran, D.R., Roe, G.H. and Anders, A.M. 2008. The climatology of small-scale orographic precipitation over the Olympic Mountains: Patterns and processes. *Quarterly Journal of the Royal Meteorological Society* 134. (633): 817–839. Available at https://doi.org/10.1002/qj.258

Nagy, G., Lóczy, D., Czigány, Sz., Pirkhoffer, E., Fábián, Sz.Á., Ciglič, R. and Ferk, M. 2020. Soil moisture retention on slopes under different agricultural land uses in hilly regions of Southern Transdanubia. *Hungarian Geographical Bulletin* 68. (2): 263–280. Available at https://doi.org/10.15201/hungeobull.69.3.3

Napoli, A., Crespi, A., Ragone, F., Maugeri, M. and Pasquero, C. 2019. Variability of orographic enhancement of precipitation in the Alpine region. *Scientific Reports* 9. 13352. Available at https://doi.org/10.1038/s41598-019-49974-5

Pásztor, L., Waltner, I., Centeri, Cs., Belényesi, M. and Takács, K. 2016. Soil erosion of Hungary assessed by spatially explicit modelling. *Journal of Maps* 12. Supplement 1, 407–414. Available at https://doi.org/10.1080/17445647.2016.1233913

Pavelsky, T.M., Sobolowski, S., Kapnick, S.B. and Barnes J.B. 2012. Changes in orographic precipitation patterns caused by a shift from snow to rain. *Geophysical Research Letters* 39. L18706. Available at https://doi.org/10.1029/2012GL052741

Péczely, Gy. 1981. *Éghajlattan* (Climatology). Budapest, Tankönyvkiadó.

Pieczka, I., Pongrácz, R. and Bartholy, J. 2011. Comparison of simulated trends of regional climate change in the Carpathian Basin for the 21st century using three different emission scenarios. *Acta Silvatica and Lignaria Hungarica* 7. 9–22.

Pirkhoffer, E., Czigány, Sz. and Geresdi, I. 2009. Impact of rainfall pattern on the occurrence of flash floods in Hungary. *Zeitschrift für Geomorphologie* 53. Supplementary Issue 2. 139–157. Available at http://dx.doi.org/10.1127/0372-8854/2009/0053S3-0139

Pongrácz, R., Bartholy, J. and Kiss, A. 2014. Estimation of future precipitation conditions for Hungary with special focus on dry periods. *Időjárás – Quarterly Journal of the Hungarian Meteorological Service* 118. (4): 305–321.

Roe, G.H., Montgomery, D.R. and Hallet, B. 2003. Orographic precipitation and the relief of mountain ranges. *Journal of Geophysical Research: Solid Earth* 108. (B6): Available at https://doi.org/10.1029/2001JB001521

Roe, G.H. 2005. Orographic precipitation. *Annual Review of Earth and Planetary Sciences* 33. 645–671. Available at https://doi.org/10.1146/annurev.earth.33.092203.122541

Ronczyk, L., Czigány, Sz., Balatonyi, L. and Kriston, Á. 2012. Effects of excess urban runoff on wastewater flow in Pécs, Hungary. *Riscuri si Catastrofe* 11. 144–159.

Sarkadi, N., Geresdi, I. and Thompson, G. 2016. Numerical simulation of precipitation formation in the case of an orographically induced convective cloud: Comparison of the results of bin and bulk microphysical schemes. *Atmospheric Research* 180. 241–261. Available at https://doi.org/10.1016/j.atmosres.2016.04.010

Scaff, L., Rutllant, J.A., Rahn, D., Gascoin, S. and Rondanelli, R. 2017. Meteorological interpretation of orographic precipitation gradients along an Andes west slope basin at 30°S (Elqui Valley, Chile). *Journal of Hydrometeorology* 18. (3): 713–727. Available at https://doi.org/10.1175/JHM-D-16-0073.1

Schneck, T., Telbisz, T. and Zsuffa, I. 2021. Precipitation interpolation using digital terrain model and multivariate regression in hilly and low mountainous areas of Hungary. *Hungarian Geographical Bulletin* 70. (1): 35–48. Available at https://doi.org/10.15201/hungeobull.70.1.3

Syrbe, R.-U. and Grunewald, K. 2017. Ecosystem service supply and demand – the challenge to balance spatial mismatches. *International Journal of Biodiversity Science, Ecosystem Services & Management* 13. (2): 148–161. Available at https://doi.org/10.1080/21513732.2017.1407362

Szentimrey, T. and Bihari, Z. 2007. Mathematical background of the spatial interpolation methods and the software MISH (Meteorological Interpolation based on Surface Homogenized Data Basis). In *Proceedings from the Conference on Spatial Interpolation in Climatology and Meteorology*, Budapest, Hungary, 2004. COST Action 719, Budapest, COST Office, 17–27.

Veals, P.G., Steenburgh, W.J. and Campbell, L.S. 2018. Factors affecting the inland and orographic enhancement of lake-effect precipitation over the Tug Hill Plateau. *Monthly Weather Review* 146. (6): 1745–1762. Available at https://doi.org/10.1175/MWR-D-17-0385.1

Waltner, I., Saeidi, S., Grósz, J., Centeri, Cs. Laborczi, A. and Pásztor, L. 2020. Spatial assessment of the effects of land cover change on soil erosion in Hungary from 1990 to 2018. *International Journal of Geo-Information* 9. 667. Available at https://doi.org/10.3390/ijgi9110667

APPENDIX

Missing or incorrect data were found on the following days at the PHN stations:

Kertváros	4–12 March, 2020
Damjanich	15–26 October, 2015 from 11 November, 2016 to January, 2017
Megyeri	7–8 March, 2015
Szentkút	from 1 January to 31 March, 2013 from 28 December to 11 January, 2015 28 March, 2018 3–4 April, 2018 from 16 April to 6 May, 2018
Tubes	26–27 September, 2015 10–11 October, 2015 22–25 September, 2017
Meszes	from 1 January to 31 March, 2013 23–28 February, 2016
Rezgő út	22–30 November, 2015 3 April, 2016 13–28 August, 2016 4–8 January, 2017 20–22 February, 2017 21–24 September, 2017