Flash floods in Moravia and Silesia during the nineteenth and twentieth centuries

OLGA HALÁSOVÁ[1,2], RUDOLF BRÁZDIL[1,3]

[1] Masaryk University, Faculty of Science, Department of Geography, Brno, Czechia; e-mail: olga.halasova@upol.cz, brazdil@sci.muni.cz
[2] Palacký University, Faculty of Science, Department of Geography, Olomouc, Czechia
[3] Czech Academy of Sciences, Global Change Research Institute, Brno, Czechia

ABSTRACT A range of documentary evidence and systematic meteorological/hydrological observations were employed to create a database of flash floods for Moravia and Silesia (the eastern part of Czechia) in the 19th and 20th centuries. The data extracted were used for an analysis of the spatiotemporal variability of flash floods, based on the frequency of days with flash floods and the number of municipalities affected. The dynamic climatology of flash floods was interpreted using the Czech Hydrometeorological Institute classification of synoptic types. Descriptions of flash-flood-related damage enabled their further division into six different types. Examples of three outstanding flash floods are described in more detail. All interpreted results are discussed with respect to spatiotemporal data uncertainty and their national and broader central European context. Flash floods constitute significant extreme natural events in Moravia and Silesia; knowledge of them, and more detailed investigation, are important to risk reduction.

KEY WORDS flash flood – documentary data – meteorological observations – spatiotemporal analysis – dynamic climatology – types of flash floods – victims – damage – Moravia and Silesia

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1. Introduction

Meteorological factors enable the definition of different types of floods: rain floods (originating from continuous, abundant precipitation or from torrential rains – flash floods), snow floods, mixed floods and ice floods (Brázdil et al. 2005a). Flash floods stand out among the group, differing quite sharply in causes, course, areal extent and impacts. Flash floods, originating in relatively short-term, intense rainfall, are characterised by sudden onset, a rapid increase in water level and water flow, erosion, transport, and the deposition of a large amount of various fluvial materials; they are among the most dangerous types of floods (Borga et al. 2014). According to Barredo (2007), they made up 40% of all flood events in Europe in the 1950–2005 period. Flash floods are often accompanied by great material damage and loss of human lives. There exist many European papers analysing individual extreme flash floods from several points of view: meteorological (e.g. Borga et al. 2014), hydrological (e.g. Gaume et al. 2004; Ruiz-Bellet et al. 2015), climatological (e.g. Thorndycraft et al. 2006), impacts (e.g. Bryndal et al. 2017) and risk management (e.g. Marchi et al. 2010; Braud et al. 2016) in particular, while other papers have concentrated on the climatology of flash floods in individual countries over the course of past decades or centuries (e.g., Gaume et al. 2009; Llasat et al. 2010; Bryndal 2015; Archer, Parkin, Fowler 2016; Trobec 2017; Archer et al. 2019).

The Czech professional literature includes a similar range of contributions as that which appears on the European scale. Papers analysing various aspects of individual flash floods in detail are based on past events described both by documentary evidence alone (e.g. Munzar 2003; Elleder et al. 2014; Munzar, Ondráček 2014) and flash floods recorded more precisely from the second half of the 20th century to the present (e.g. Čerkašin 1959; Balatka, Sládek 1980; Chamas, Kakos 1988; Polišenský 1990; Sochorec, Doležel 1996; Hančarová et al. 1999; Cyroň, Kotrnec 2000; Soukalová 2002; Kubát, ed. 2009; Daňhelka, Elleder, eds. 2012). Particular attention has been devoted to an infamously tragic flash flood on 25 May 1872 in the River Berounka catchment that claimed around 240 victims or more (Müller, Kakos 2004). The Mladotice landslide lake, the only one of its kind recorded in the Czech Lands, arose out of this event (Janský 1976, 1977). Studies investigating flash floods over a greater area or longer time periods are less frequent; examples include Polách and Gába (1998) for the Šumperk and Jeseník regions, and Brázdil and Kirchner (eds. 2007) for Moravia and Silesia. Raška and Brázdil (2015) indicated how knowledge of a number of historical flash floods in north-western Bohemia could be employed for current risk reduction.

In this context, the present study is a continuation of the systematic research activities devoted to flash floods in Czechia. Concentrating on the eastern part of Czech territory, the aim of this article is a comprehensive study of flash floods that have occurred in Moravia and Silesia during the 19th–20th centuries, with particular attention to their spatiotemporal variability, their dynamic-climatological background, classification, and descriptions of certain outstanding events. Section 2 considers data about flash floods derived from documentary evidence and systematic observations. After a methodology description in Section 3, Section 4 gives the results that follow from the basic analysis. These are discussed in Section 5 from the point of view of data uncertainty, and in both national and European contexts. The last section summarises the study.

2. Data

Information related to flash floods was collected for the territory of Moravia and Silesia, consisting broadly of the catchments of the River Morava (including the River Dyje) and the River Odra, encompassing an area of 27,383 km². Generally, three different types of data sources were used.

2.1. Documentary evidence

Documentary evidence, which may contain information about flash floods, their courses and impacts in both the pre-instrumental and the instrumental periods, is in widespread use as a source of data in historical climatology (Brázdil et al. 2005b, 2010) and in historical hydrology (Brázdil et al. 2006). It consists of various types of written sources, such as annals, chronicles, diaries, administrative records, ecclesiastical records, private and official letters, epigraphic records (Fig. 1a, b), songs (Fig. 1c), newspapers, etc. Important information was extracted from a range of newspapers (e.g. *Brünner Zeitung*, *Brünner Morgenpost*, *Lidové noviny*, *Moravan*, *Moravská Orlice*, *Moravské noviny*, *Moravský národní list*, *Moravský sever*) as the following example illustrates (*Moravské noviny*, 1895, No. 136, non-paginated): "*The villages of Tučapy and Luleč were affected by a great disaster in the early evening of Wednesday 5 June. A cloudburst and hailstorm destroyed all the field crops,* [and] *the water tore down a house and barn in Tučapy. The water was* [still] *carrying pieces of wood, hay and drowned goslings even two hours after the disaster*." Secondary sources, in the form of the regional histories published in the *Vlastivěda moravská* series also proved a useful source of information for the second half of the 19th century – see, for example, a note on the flash flood of 29 June 1899 that occurred in Velké Meziříčí (Kratochvíl 1907, p. 127): "*On 29 June 1899, a terrible thunderstorm with a cloudburst occurred. The water stood a metre deep in the Židovská Street*."

Fig. 1 – Examples of documentary sources related to the flash floods of 12 June 1825 in south-east Moravia: (a) location of the epigraphic record in Zlechov (the Zlechovský potok Brook); (b) text of the epigraphic record: *"In the year 1825, on 12 June, the* [high] *water stood here, at this stone, and stayed* [here] *for five hours"* (Daniel et al. 2013); (c) title (right) and last (left) pages of printed broadsheet song about the same flood in the Velehrad, Buchlov and Bzenec domains (Brázdil et al. 2019).

2.2. Meteorological and hydrological observations

Observations from the meteorological and hydrological stations of the national networks, entered into the archives of the Czech Hydrometeorological Institute (CHMI) in Brno and Ostrava, provide an important source of information about flash floods from the second half of the 19th century. Notes added to observed accompanying phenomena (precipitation total, intensity of rainfall, the occurrence and intensity of thunderstorms, hailstorms, and strong winds, among other things), often supplemented by newspaper stories (when conditions were extreme enough to merit public interest), also serve to build a more complete picture. For example, the climatological observations taken by the Velké Meziříčí meteorological station on 29 June 1899 contain information on a flash flood: *"29 June 1899.* [Precipitation] *total 83.0 mm. Flood between 10 p.m. and 12 p.m. Height of water 4.8 m around 11 p.m. Total of three thunderstorms above the station, extending c. 20 km over the whole catchment* [of the River Oslava]. *Houses, bridges, etc. were washed away, fields eroded."*

2.3. Professional papers

The above information may be further complemented by flash floods described in a great detail in many professional publications. One example of such information may be found in a paper by Hrádek and Ondráček (1986), who described a flash flood on the Besének in the Tišnov region that took place on 19 June 1986 (for examples of other such studies, see references in Section 1).

It follows from the previous characterisation of data sources that, up to 1865, only data on flash floods derived from documentary evidence have been used, while for subsequent years these were combined with information obtained from meteorological and hydrological observations and professional papers.

3. Methods

The data sources described in Section 2 were used to compile a database of flash floods in Moravia and Silesia for the 19th–20th centuries. Records of individual flash floods include date, course, municipalities affected, human casualties, and other impacts. In certain cases, this data may be supported by the precipitation total measured at a given place or a nearby station, and/or by the measured or estimated flow rate or water level the watercourses involved.

Subsequent analysis employed three variables: (i) a day with flash flood was considered a day with one or more flash floods attributable to the same meteorological factor (e.g., cold front, intense convection); (ii) a flood event was considered a single flood confined to a certain catchment; (iii) a flash flood could also be defined in terms of a municipality, a village or settlement affected by a given flash flood.

The results of temporal analysis were presented at annual, monthly and decadal resolution in graphs representing frequencies of days with flash floods and numbers of municipalities affected. Maps were drawn up to express the spatial variability of flash floods. A classification of 28 synoptic types, as defined by CHMI (Kolektiv pracovníků synoptické a letecké služby HMÚ 1967), applied to the years 1946–2000, was employed to investigate the dynamic climatology of flash floods.

Table 1 – Types of flash flood according to the damage done by them and estimated peak discharges corresponding to them

Type	Flash flood	Damage	Peak discharge
1	Flash flood detected (FFD)	not specified	not identified
2	Significant surface runoff (SSR)	erosion, accumulation of transported material, minor damage to meadows, flooded cellars and communications at some distance from normal watercourses	not identified
3	Minor flash flood (MFF)	minor damage to meadows and fields, small inundations along the watercourse, flooded cellars and communications	Q_2–Q_{10}
4	Significant flash flood (SFF)	damage to buildings, footbridges and bridges	Q_{10}–Q_{50}
5	Extraordinary flash flood (EFF)	major damage to buildings and bridges	> Q_{50}
6	Catastrophic flash flood (CFF)	riverbed(s) and surroundings changed, destruction of buildings and infrastructure	> Q_{100}

The damage done by flash floods (specific damage to buildings, to communications and to fields, general damage and erosion, together with less direct consequences) was used to classify individual flash floods into six types (Table 1): (1) flash flood detected (FFD); (2) significant surface runoff (SSR); (3) minor flash flood (MFF); (4) significant flash flood (SFF); (5) extraordinary flash flood (EFF); and (6) catastrophic flash flood (CFF). Combining information from papers to relate peak discharges to the extent of damage (e.g. Elleder, Tyl, Šimandl 2008; Benito, Hudson 2010; Schroeder et al. 2016), types 3–6 were further supplemented with the estimated peak discharges expressed with respect to N-year return period (e.g., Q_2 corresponds to a peak discharge with a return period of two years).

4. Results

4.1. Spatiotemporal variability of flash floods

A total of 616 days with flash floods were identified for Moravia and Silesia during the 1801–2000 period, of which 287 (46.6%) occurred in the 19th century and 329 (53.4%) in the 20th century. This corresponds to an average of *c.* 3.1 days with flash floods per year. As follows from Figs. 2a and 2c, their generally highest frequencies were recorded between 1865 and 1900, 1925 and 1966, and in the second half of the 1980s. The maximum of days with flash floods (15) was detected in 1879, followed by 11 such days in 1886 and 10 days in another three years. On a decadal scale, 1881–1890 exhibited the highest frequency (67 days), followed by the 1951–1960 decade (60). The lowest frequencies of days appeared particularly in the first

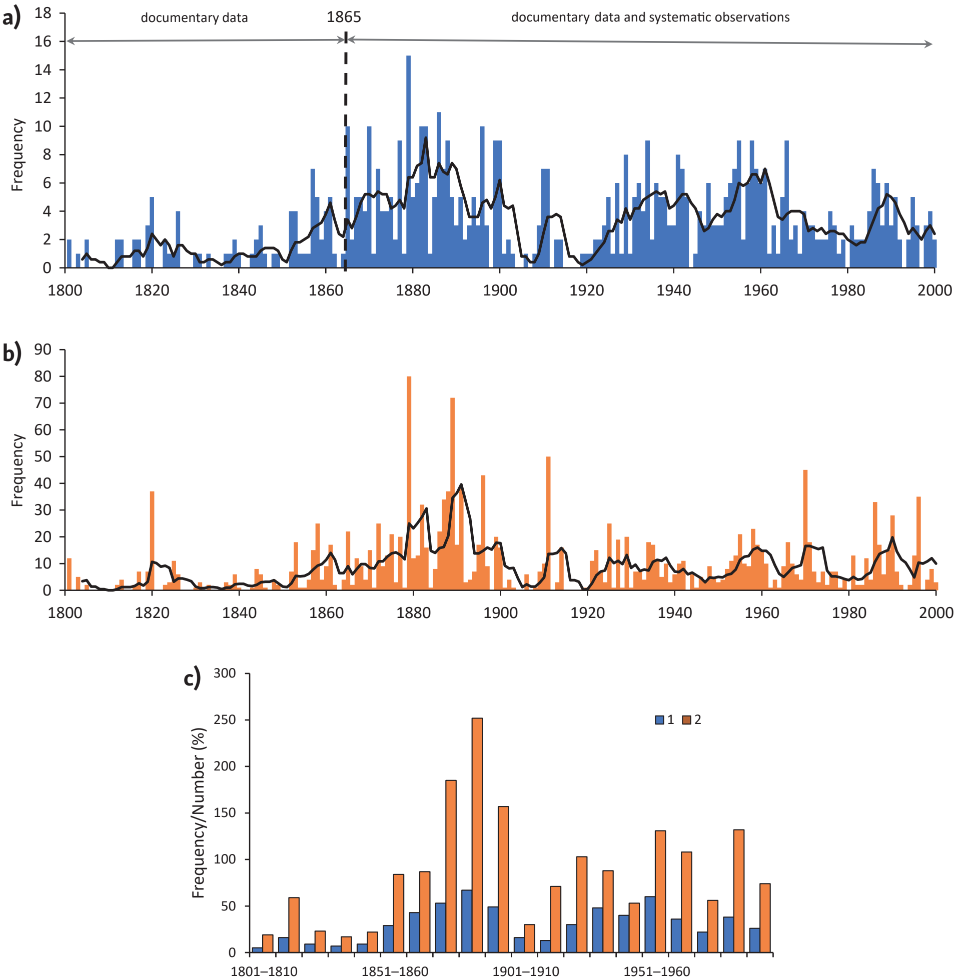


Fig. 2 – Spatiotemporal variability of flash floods in Moravia and Silesia in the 1801–2000 period: (a) frequency of days with flash floods, (b) number of municipalities affected by flash floods, (c) decadal frequencies of days with flash floods (1) and decadal numbers of municipalities affected (2). Data in (a) and (b) are smoothed by running averages for five years.

half of the 19th century, but also in the two first decades of the 20th century. No flash flood was detected in 39 of the years (27 in the 19th century and 12 in the 20th century). Only 5 days with flash floods were recorded in 1801–1810 and 7 days in 1831–1840. In terms of annual variation (Fig. 3), days with flash floods predominate in June (30.0%), followed by May (23.6%) and July (21.9%). Apart from 5 cases (0.8%) in the winter half-year (October–March), all the flash floods detected (99.2%) occurred in the summer half-year (April–September).

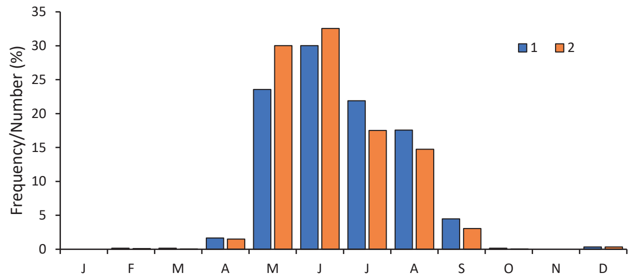


Fig. 3 – Annual variation of relative frequency of days with flash floods (1) and relative number of municipalities affected by flash floods (2) in Moravia and Silesia during the 1801–2000 period

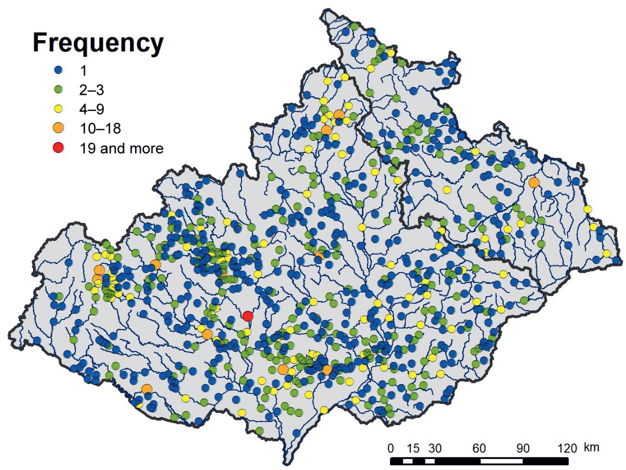


Fig. 4 – Geographical distribution of frequency of detected flash floods in individual municipalities over the territory of Moravia and Silesia during the 1801–2000 period

All the flash floods recorded affected a total of 805 municipalities in Moravia and Silesia during the 1801–2000 period. Because flash floods occurred repeatedly in some municipalities, the total sum of affected municipalities achieved 1751, of which 905 (51.7%) appeared in the 19th century and 846 (48.3%) in the following century. This corresponds to an average of *c*. 8.8 municipalities affected by flash flood per year. As might be expected, the numbers of affected municipalities generally follow the frequency of days with flash floods (Fig. 2b). Their highest number occurred in 1879 (80 municipalities), followed by 1889 (72 municipalities). Both extremes contributed to a decadal maximum in 1881–1890 (252), followed by the two adjacent decades of 1871–1880 (185) and 1891–1900 (157). The total of 594 affected municipalities during these three decades makes up 34.0% of all the places impacted during the 1801–2000 period (Fig. 2c). In terms of annual variation (Fig. 3), affected municipalities were recorded particularly in June (32.6%) and in May (30.0%).

Figure 4 shows the frequency of flash floods detected in each of the 805 municipalities in Moravia and Silesia during the 1801–2000 period. The spatial

Table 2 – Municipalities with the highest frequency of flash floods in Moravia and Silesia during the 1801–2000 period

Municipality	1801–2000	1801–1900	1901–2000
Brno	53	33	20
Šumperk	18	8	10
Ostrava	16	10	6
Plumlov	13	1	12
Tišnov	13	4	9
Brtnice	12	10	2
Klobouky u Brna	12	9	3
Kyjov	11	3	8
Velké Losiny	11	6	5
Ivančice	10	4	6
Velké Meziříčí	10	4	6
Znojmo	10	6	4

distribution is relatively uneven. There are several core areas with higher spatial density and frequency of flash floods, such as the Hanušovická vrchovina Highlands, the Hornosvratecká vrchovina Highlands, the Brtnická vrchovina Highlands, the Bobravská vrchovina Highlands, the Chřiby Highlands and the Žďánický les Highlands. While in 445 municipalities there is only one record of a flash flood, in some places such events occurred more frequently. Apart from the city of Brno, with 53 flash flood events during the 1801–2000 period, a further 11 places were subject to flash floods at least 10 times (Table 2).

4.2. Dynamic climatology of flash floods

In order to characterise the synoptic situations prevailing on days with flash floods in Moravia and Silesia, the relative frequencies of individual synoptic types, as defined by CHMI classification (http://portal.chmi.cz/historicka-data/pocasi/typizace-povetrnostnich-situaci#), were calculated for 201 days with flash floods in the 1946–2000 period. Because flash floods may easily be anticipated in association with the heavy convective rainfall that accompanies thunderstorms, situations with transport of warm and moist air and the passing of cold fronts over the territory of Moravia and Silesia would appear to be the most likely to facilitate them. Of a total of 28 synoptic types covered by the above classification, days with flash floods were attributed to 17 types, of which 13 were of a cyclonic character (76.5%) and occurred on 176 of the days with flash floods (87.6%). Predominant among them were synoptic types classified as the trough over central Europe B (14.9% of days studied), the cyclone over central Europe C (10.4%), the south-western cyclonic of the 2nd type SWc_2 (9.4%), the eastern cyclonic Ec (9.0%), the north-eastern cyclonic NEc and the south-western cyclonic of the 3rd type SWc_3 (8.0% each). If the south-western cyclonic of the 1st type SWc_1 is added, these 7 types were responsible for 66.2% of all days with flash floods. Of the four anticyclonic types attributed to the days studied, the western anticyclonic situation of summer type Wal, with fronts passing from west to east, contributed to the origin of flash floods in 7.5% of all cases.

4.3. Types of flash floods

Table 3 shows how the 616 detected days and 805 municipalities with flash floods detected in Moravia and Silesia during the 1801–2000 period are distributed among the six individual types of flash floods that appear in Table 1. The highest number of days with flash floods (242, i.e. 39.3% of the total) were classified as minor flash floods (MFF), affecting 276 municipalities (34.3%). Significant flash floods (SFF) affected more municipalities (301, i.e. 37.4%), occurring on 183 days (29.7%). This means that minor and significant flash floods occurred on 69% of the corresponding days, affecting 71.7% of the respective municipalities. Taking into account that only 60 extraordinary flash floods (9.7%) occurred, they affected 125 municipalities (15.5%), particularly in the areas of the Hornosvratecká vrchovina Highlands (the Upper Svratka catchment), the Hanušovická vrchovina Highlands (the Upper Morava catchment), the Nízký Jeseník Mountains (the Upper Opava catchment), the Kyjovská pahorkatina Hilly Land (the Kyjovka catchment) and the Ždánický les Highlands (the Trkmanka catchment; Fig. 5). Only one event, on 1 June 1921, was evaluated as a catastrophic flash flood (see Polách, Gába 1998); it affected seven municipalities in the Hrubý Jeseník Mountains (the Desná and the Bělá catchments).

Some of flash floods were accompanied by loss of human lives. Over the 1801–2000 period, 48 flash floods with at least 130 fatalities in total were documented in Moravia and Silesia. These were recorded in 64 municipalities (Fig. 6).

Table 3 – Frequency of days with flash floods and number of affected communities attributed to the six basic types of flash flood (see Table 1) in Moravia and Silesia during the 1801–2000 period (a – absolute values, b – relative values expressed as percentages)

Characteristics		Type of flash flood						Total
		FFD	SSR	MFF	SFF	EFF	CFF	
Days with flash floods	a	61	69	242	183	60	1	616
	b	9.9	11.2	39.3	29.7	9.7	0.2	100.0
Municipalities affected	a	70	26	276	301	125	7	805
	b	8.7	3.2	34.3	37.4	15.5	0.9	100.0

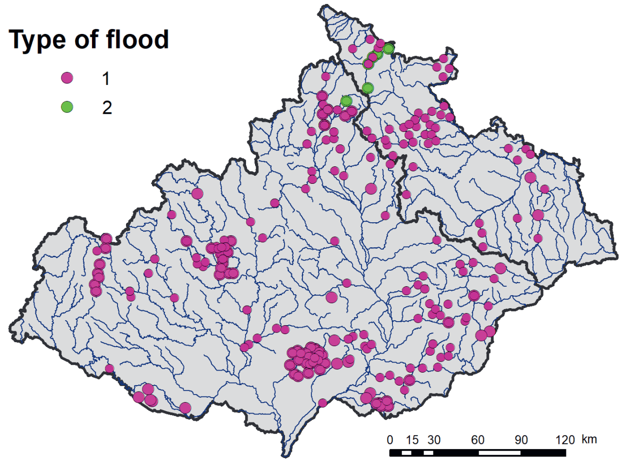


Fig. 5 – Geographical distribution of municipalities affected by extraordinary (1) and catastrophic (2) flash floods in Moravia and Silesia during the 1801–2000 period

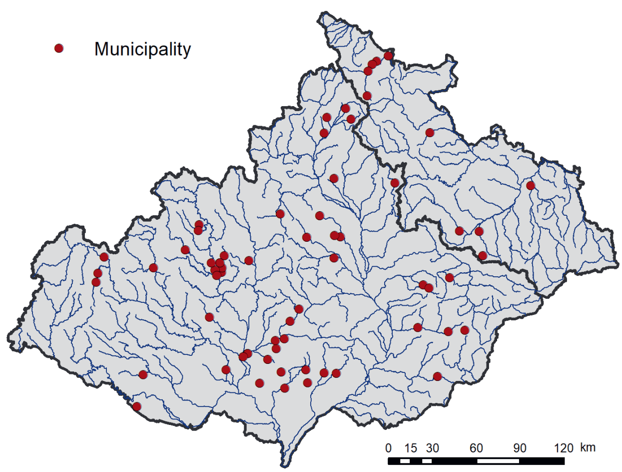


Fig. 6 – Geographical distribution of municipalities with fatalities during the occurrence of flash floods in Moravia and Silesia during the 1801–2000 period

The most tragic event occurred on 9 June 1970 in Šardice and Kyjov, when a flash flood led to the deaths of 35 people (Cyroň, Kotrnec 2000; see Section 4.4.2.). Lower numbers of fatalities were recorded in other cases: a total of 11 fatalities on 1 June 1921 in the region of Jeseník (7 fatalities) and of Šumperk (4 fatalities, of whom 2 died during the rescue operation) (Polách, Gába 1998); 5 fatalities on 26 May 1858 were mentioned from a house destroyed in Rousínov (*Moravské noviny*, 1858, No. 41, p. 163) and 5 on 14 August 1865 in Hustopeče (*Brünner Zeitung*, 1865, No. 188, p. 1092). A report of 7 fatalities on 10 July 1872 in Hluboké Mašůvky is rendered relative by inclusion of the word "supposedly" in the newspaper story (*Moravské noviny*, 1872, No. 84, non-paginated). In the majority of other cases involving loss of human lives, one or two fatalities per flash flood were reported.

4.4. Outstanding flash floods

Of the 61 extraordinary and catastrophic flash floods disclosed in Moravia and Silesia, three selected examples are described in more detail below.

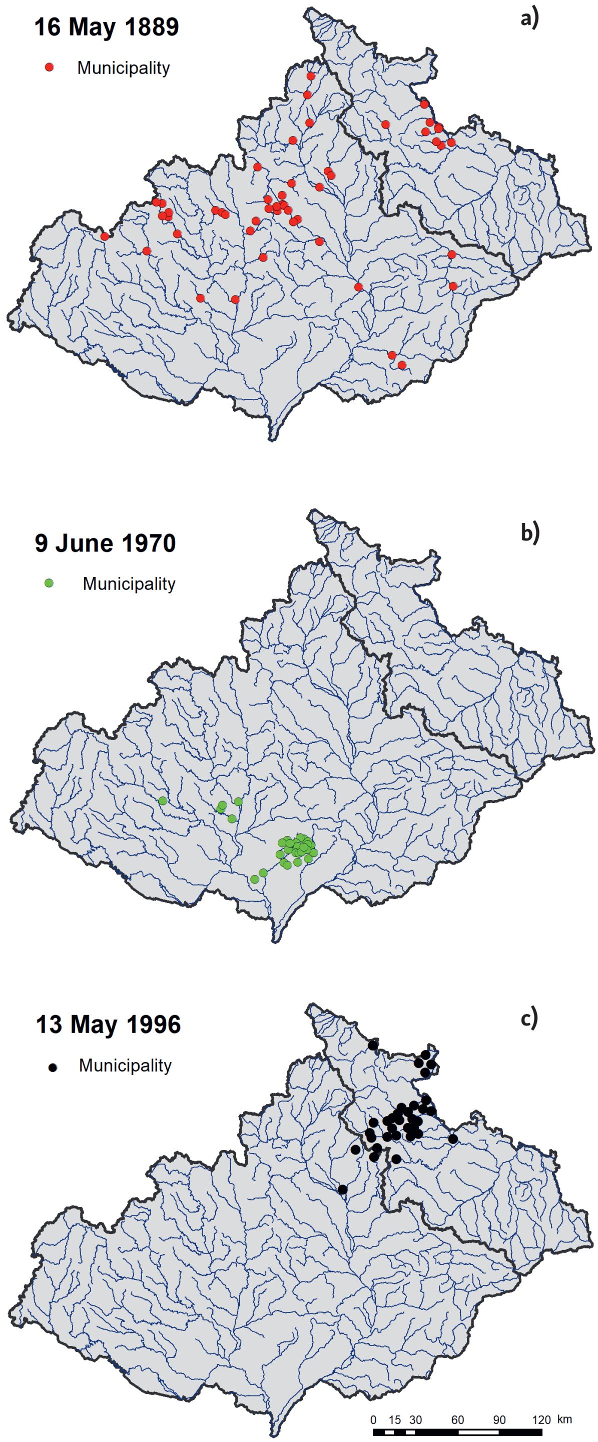
4.4.1. 16 May 1889

Cloudbursts with hailstorms during heavy thunderstorms on 16 May 1889 gave rise to flash floods in various parts of Moravia and Silesia. According to the *Moravské noviny* newspaper (1889, No. 117, non-paginated), 108 municipalities of what were then 11 political districts (Fig. 7a) were significantly affected: damage to houses, agricultural and riverine structures (e.g. stables, barns, bridges, footbridges), roads, fields, gardens, etc. A public collection was organised to assist the people affected. The number of 108 affected municipalities formally constitutes the highest number of affected places for one event in Moravia and Silesia among all the flash floods detected for the 1801–2000 period; however, it proved possible to localise exactly only 50 of the municipalities. An example from Vsetín serves to typify events (*Brünner Zeitung*, 1889, No. 116, p. 3): *"A devastating cloudburst and a hailstorm fell on that day* [16 May] *around Vsetín. The Jasenka Brook, swollen and wild, flooded the Jasenka road to Vsetín in such way that two houses, three barns and four stables were swept away and more buildings were flooded. Bridges and footbridges over the brook have been swept away. Extensive damage to field crops is apparent*." According to the Paul Hess and Helmut Brezowsky classification of *Grosswetterlagen* for Europe (Werner, Gerstengarbe 2010), synoptic patterns for 16 May 1889 were classified as of the north-eastern type, cyclonic over central Europe (NEZ).

4.4.2. 9 June 1970

On 9 June 1970, a cloudburst with extreme precipitation totals struck the region of Kyjov and Ždánice (the Trkmanka and Kyjovka catchments), where 23 municipalities were affected (Fig. 7b). Although the Ždánice meteorological station recorded a daily total of 133.5 mm, in some other areas around 195 mm of precipitation fell in two hours. Water spouts flooded and buried the Dukla lignite mine in Šardice and led to the deaths of 34 miners; a three-year old girl died further off, in Kyjov-Boršov. The material damage ran to millions of Czechoslovak crowns. Apart from many agricultural structures, 317 residential houses were also damaged or destroyed. Around 8,000 hectares of agricultural soil were flooded, ruining grain in particular, but also fodder crops. Vineyards were damaged. Roads and railway communications were interrupted at a number of points, while some bridges were destroyed. Certain villages were without drinking water, electrical power and telephone connections (for more details see Cyroň, Kotrnec 2000). According

Fig. 7 – Geographical distribution of municipalities affected in the course of three outstanding flash floods: (a) 16 May 1889, (b) 9 June 1970, (c) 13 May 1996



to the CHMI classification, the synoptic patterns for 9 June corresponded to the eastern cyclonic type Ec (according to Hess and Brezowsky, classified as a high over Fennoscandia, anticyclonic over central Europe HFA – Werner, Gerstengarbe 2010).

4.4.3. 13 May 1996

The event of 13 May 1996 affected the areas around the Bruntál and Opava districts (the Čižina, Opava, Moravice and Osoblaha catchments; Fig. 7c). It originated in torrential rain of a cloudburst character in the early evening and night hours. During a relatively short time, just a few hours, rainfall intensity exceeded 50 $mm.h^{-1}$. Nearly 200 km^2 was subjected to highly intensive rain. The major part of the precipitation fell between the hours of 18.15 and 21.20; the daily total exceeded 100 mm (Lichnov 110.0 mm, Mezina 100.0 mm). High peak discharges on waterways led to heavy material damage and the death of one person (see Sochorec, Doležel 1996 for more details). According to the CHMI classification, the synoptic patterns for 13 May corresponded to the eastern cyclonic type Ec (according to Hess and Brezowsky, classified as of north-eastern type, cyclonic over central Europe NEZ – Werner, Gerstengarbe 2010). The high precipitation totals triggered a hydrological response on the River Morava at Moravičany on 14 May and Olomouc on 15 May, where discharges achieved the second level of flood activity.

5. Discussion

5.1. Data uncertainty and results obtained

The results of this analysis of flash floods in Moravia and Silesia over the past two centuries may have been partly influenced by some uncertainties in the data. These are partly related to the fact that flash floods may occur in remote areas, with no damage immediately visible to people and society; they may also affect watercourses that lack measurement or monitoring. Moreover, they may also appear in places that have no streams, but with geomorphologic conditions that enable the rapid surface runoff of a great quantity of water from rain (see "significant surface runoff" type in Table 1). All this means that many past events remained undetected, depending on the spatiotemporal density of information extracted from documentary sources, as is evident, for example, in fewer flash floods recorded in the first half of the 19th century. A further source of "social bias" in these types of data is related to periods of crisis within greater society, such as wars, when attention concentrates on matters other than natural phenomena. The increase in the frequency of flash floods from 1865 onwards (see Fig. 2) clearly documents the inclusion of other data sources represented by systematic observations at the meteorological/hydrological stations and an increase in published newspaper stories (e.g. *Moravská Orlice* from 1863 and *Brünner Morgenpost* from 1865).

The above uncertainties are reflected not only in temporal terms, but also in spatial matters. This is partly apparent from areas that lack detected floods, such as the Jevišovská pahorkatina Hilly Land, the Nízký Jeseník Mountains (the Libavá Military Area in particular), the Zlatohorská vrchovina Highlands, the eastern part of the Svitavská pahorkatina Hilly Land, the Podorlická pahorkatina Hilly Land and the Kladská kotlina Basin. In evaluation of these regions, their peripheral nature and the corresponding lower availability of data sources should be taken in account, together with any physico-geographical assumptions that bear on their potential for flash-flooding.

The results of the dynamic-climatological analysis of flash floods in Section 4.2 may be supported by investigations of thunderstorms and days with daily precipitation totals of ≥ 20.0 mm for South Moravia in the 1946–1995 period (Brázdil, Štěpánek, Vais 1998). While the most important CHMI types, B, Wal and Wc (western cyclonic) proved most conducive to thunderstorm occurrence, extreme precipitation was at its most frequent in types B, C and SWc_3. These results are in agreement with Bryndal (2015) for Poland, who laid special emphasis on two particular types of synoptic situation: a trough of low pressure with a cold front passing over Poland, and low pressure over central Europe with the occurrence of a quasi-stationary or an occluded front. These situations correspond to CHMI types B and C. While these synoptic types provide only general patterns, it remains important to associate flash floods with intense precipitation falling during the passing of cold fronts (Kakos 2001); however, this information was not available for Moravia and Silesia.

From a hydrological point of view, it is problematic that flash floods occur most frequently on ungauged waterstreams, do not allowing their systematic hydrologic evaluation. Some available quantitative data have rather episodic character, often difficult to be compared with other events. Despite it, the peak discharge of 206 $m^3.s^{-1}$ at Ivančice on the River Jihlava measured during flash flood on 22 June 1939 was the highest value during hydrologic measurements at this station since 1915 (Pöyry Environment a.s. 2007). The highest water level achieved was 583 cm, recorded during a flash flood on 16 August 1959 on the River Olšava at Uherský Brod (archival source AS1), and followed by 550 cm measured on the River Dřevnice at Zlín on 27 June 1987 (AS2). More recently, a water level of 609 cm was achieved on the River Jičínka at Nový Jičín during a flash flood on 24 June 2009 (AS3), for which a peak discharge of 340 $m^3.s^{-1}$ was calculated (Kubát, ed. 2009).

Impacting upon communities, from the single to dozens, flash floods constitute significant extreme natural events in Moravia and Silesia. Events that have led to the loss of human lives have, of course, become the centres of attention. The number of 130 documented fatalities during the 1801–2000 period tends towards the lowest estimate of the real toll upon human life. However, determining a more exact number is difficult, since some documentary sources speak only generally of "loss of lives" without closer specification. Quite apart from the tragedies of human lives lost, great material damage to buildings, property, industrial and water infrastructure, communications, arable land, gardens, and more, have to be added. As shown by Prosová (2005), flash floods endanger most urban landscapes, slightly fewer cultivated landscapes and, at the least, natural landscapes.

5.2. The European context

Results of the analysis of flash floods in Moravia and Silesia may be compared, at least in part, with several other European studies. Gaume et al. (2009) presented flash floods for four Mediterranean regions in Spain, France, Italy and Greece and for three "Inland Continental" regions of Austria, Slovakia and Romania for a number of time intervals between 1953 and 2007. To render the information comparable with Moravia and Silesia, their data were recalculated to the number of flash floods for areas of 10,000 km^2 per 10 years; Romania 1.8 flash floods within 10,000 km^2 per 10 years, Austria 2.1 and Slovakia 10.6. The corresponding value of 11.4 days with flash floods within 10,000 km^2 per 10 years for Moravia and Silesia is closely comparable only with Slovakia. The previous three countries also differ in their maxima for flash floods in terms of annual variation: compared to June in Moravia and Silesia, the maximum was in July for Romania and Slovakia and in August for Austria. A July maximum of flash floods also appears for Poland in the study by Bryndal (2015) covering the 1932–2009 period. The majority of the 108 flash floods detected occurred in mountain and upland regions, located especially in south-eastern Poland. Trobec (2017) documented 138 flash floods for Slovenia between 1550 and 2005, of which only 9 were recorded before 1870 and 45 between 1871 and 1950. Analysing the 1951–2005 period, he found an average of 1.3 flash floods per year and an August maximum in annual variation; 90% of flash floods in Slovenia occurred in the June–November months.

According to Solín (2008), analysing the 1996–2006 period in Slovakia, 1,367 Slovak municipalities (46.7% of their total number) were affected by floods exceeding the third level of flood activity. Floods occurred repeatedly in 562 municipalities. Flash floods affected 1061 municipalities, but Solín (2008) does not state how many municipalities experienced repeated floods. If only significant, extraordinary or catastrophic flash floods in Moravia and Silesia in 1801–2000 are taken into account, those very probably exceeding the third level of flood activity, the figure of 433 affected municipalities emerges, which is significantly lower than in Slovakia.

6. Conclusion

The following conclusions may be formulated from this analysis of flash floods over the territory of Moravia and Silesia during the 19th–20th centuries:

(i) The data relevant to flash floods are derived from various documentary evidence as well as systematic meteorological/hydrological observations. These sources may involve a degree of data uncertainty, perhaps appearing in flash-flood chronologies and their spatial coverage, as well as in descriptions of their impacts.

(ii) The first half of the 19th century and the first two decades of the 20th century are periods poorly covered by available data. The highest frequency of days with flash floods appears between 1871 and 1900. During the year, they occur predominantly from April to September. The numbers of affected municipalities also accord with these results.

(iii) Flash floods may occur in any part of the territory of Moravia and Silesia when meteorological and physical-geographical conditions favour them, but their occurrence was far more frequent in highlands and hilly areas.

(iv) Together with other hydrometeorological extremes, flash floods must be taken seriously as extreme natural events in Moravia and Silesia, since they lead to loss of human lives and have the potential to do great damage to residential buildings, to commercial constructions and the structures associated with waterways, to a wide range of property, communications, arable fields, fodder and market gardens, etc. Expanding knowledge of flash floods may have important implications for flood risk management.

(v) The results of this study of flash floods over the territory of Moravia and Silesia in the past two centuries significantly complement knowledge of these phenomena in the European scale, adding much to existing studies by virtue of the length of the period studied and by their high spatial resolution.

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ORCID

OLGA HALÁSOVÁ
https://orcid.org/0000-0002-0584-2210

RUDOLF BRÁZDIL
https://orcid.org/0000-0003-4826-2299