The risk of urban floods caused by precipitation on the example of Bydgoszcz, Poland

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Abstract

The article concerns the flood risk assessment in Bydgoszcz in April–October 2010–2022. The distribution of daily precipitation sums for two meteorological stations in Bydgoszcz was analysed. The study confirmed that the risk of extreme precipitation is greatest in the summer months (May–August). It was found that some of the intense rainfall that might cause short-term flooding of urban areas was often local and caused by storm phenomena. Analysis of flood-related interventions by the State Fire Service in Bydgoszcz showed that 2022 had the highest number of incidents (117). The analysis of precipitation and State Fire Service interventions showed a small degree of dependence between the two, both at the city-wide scale and for individual city districts. The spatial distribution of these interventions allowed the Bydgoszcz city districts most exposed to the effects of pluvial flooding to be identified. The work showed the complexity of the issue of urban flood risk, of monitoring such phenomena at the city and district scales, and of countering the effects of such phenomena.

Keywords: flooding, extreme precipitation, intervention, State Fire Service, Bydgoszcz, Poland

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Introduction

Climate change refers to long-term changes in temperatures and weather patterns. Over the past decade, the world has warmed by 0.25 °C, following a roughly linear trend since the 1970s (Robinson, A. *et al.* 2021). In addition, there are increasing trends in extreme precipitation (Asadieh, B. and Krakauer, N.Y. 2015). In addition to the global scale, the climate is warming at all other spatial scales, although there are extreme fluctuations in the long-term trend of increasing temperatures. Also at regional and local scales, warming does not have a uniform rate (Kundzewicz, Z.W. 2011; Kocsis, T. *et al.* 2024). The occurring and projected climate changes and the resulting changes in recorded precipitation in Central Europe manifest themselves not so much in changes in mean annual precipitation totals, but in an unfavourable prolongation of drought periods and the occurrence of less frequent but more intense precipitation (Mikołajewski, K. *et al.* 2025).

Analysis of extreme precipitation in Poland showed that daily maximum precipitation in the summer half-year increased for many stations, and that increases in the summer half-year were more numerous than in the winter half-year (Pińskwar, I. *et al.* 2019). A study by Pińskwar, I. (2022) showed that between 1989 and 2018, total precipitation above the

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95th percentile decreased, but above the 99th percentile increased. In addition, increases in more extreme precipitation, i.e. in the 99th percentile more than in the 95th percentile, were shown with increasing global warming. The analysis of trends and frequency of extreme daily precipitation in Poland from 1951 to 2020 showed a significant positive trend for daily precipitation above 30 mm, 50 mm and 70 mm in September, and for daily precipitation above 100 mm in May. Spatially, the frequency of extreme precipitation in individual regions of Poland showed significant variations (Kalbarczyk, R. and Kalbarczyk, E. 2024).

Climate change is a serious threat and affects society in many ways, particularly in urban areas. The great sensitivity of cities and urbanised areas to climate change results primarily from the particular functional and spatial structural characteristics of such areas, i.e. their density of buildings and large populations (Short, J.R. and Farmer, A. 2021). These features make climatic phenomena a serious threat to city residents and their health (Kumar, S.V. and Singh, G.S.) and the urban fabric. Extreme weather events such as floods, droughts, heavy precipitation and heatwaves disrupt physical, social and institutional systems (Cho, S.Y. and Chang, H.J. 2017; Graczyk, D. *et al.* 2019; Kron, W. *et al.* 2019; Choryński, A. *et al.* 2022; Pińskwar, I. *et al*. 2023). Climate-change-related flooding is expected to increase in the future, thereby increasing existing flood risks (IPCC, 2014; Alfieri, L. *et al.* 2015; Tabari, H. 2020).

In addition to fluvial floods and storm surges, surface water flooding (also known as "pluvial flooding"), which is typically triggered by heavy rainfall, is expected to increase in urban areas (Falconer, R.H. *et al.* 2009; Huang, Y. *et al.* 2020). This is due to changing rainfall patterns, the expansion of urban areas and concomitant increase in area of sealed surfaces, and ageing and increasingly inefficient drainage infrastructure (Webber, J.L. *et al.* 2018; Guo, K. *et al.* 2021; Ajjur, S.B. and Al-Ghamdi, S.G. 2022). Research shows that the magnitude of urban floods increases non-linearly with increasing rainfall intensity. The maximum area of flooding also increases accordingly and is much more sensitive to flooding even in the case of milder rainfall (Sun, X. *et al.* 2021). The increasing frequency of urban floods is not caused solely by climate change, although their role is very significant. It is the effect of sealing the runoff surface accompanying urban changes in cities (Skougaard Kaspersen, P. *et al*. 2017). In cities, impermeable surfaces such as buildings, hardened concrete and asphalt surfaces dominate, which have a limited ability to absorb rainwater. As a result, the increase in impermeable surfaces increases the speed and volume of drained water. Halecki, W. and Młynski, D. (2025) found that in many European cities, the increase in impermeable surfaces often comes at the expense of a decrease in green and blue areas. The share of green areas within individual cities varies in terms of nature and function. The densely built-up cities of Central Europe contrast with the higher percentage of urban green areas in the Scandinavian countries (Halecki, W. and Młynski, D. 2025). There are clear indications that this trend will continue in the future, which will increase the risk of local floods. Europe's total share of sealed areas has increased by more than 6 percent since 2000. In addition, the urban population is expected to grow, which already accounts for three-quarters of the population living in EU countries (EEA, 2023).

Damage caused by weather phenomena has increased dramatically in recent decades. This damage means that such phenomena place an increasing burden on national economies and insurance companies, as do the rising costs of preventive measures (Kron, W. *et al.* 2019). In 2001–2019 alone, losses due to extreme phenomena in Poland amounted to EUR ~25 billion (Siwiec, E. 2022). This total included only direct losses, omitting indirect losses such as disruption costs to business operations and lost sales markets. Extreme weather and climate events caused economic losses to assets estimated at EUR 738 billion between 1980 and 2023 in the European Union, with over EUR 162 billion (22%) between 2021 and 2023 (EEA, 2023).

An essential part of the policy for countering the effects of extreme weather phenomena, especially in large urban agglomerations, is the targeted and centralised activity of public administration bodies involved in crisis management. In Poland, crisis management operates based on the 26 April, 2007 Act on crisis management (Act, 2007). This Act specifies the authorities responsible for crisis management and their tasks and principles of operation, and it regulates the principles for financing such tasks.

In Bydgoszcz, as in all major cities in Poland, the Bydgoszcz Crisis Management Centre (BCMC) has been operating since 2008 and is responsible for coordinating the activities of individual rescue units. The centre's main tasks involve collecting all information regarding the current and expected situation in the city and surrounding area, warning the population of threats, and coordinating all the activities of rescue and firefighting units of the State Fire Service (SFS), police and municipal guards. Based on annual reports on interventions by individual services provided by the centre, the number of interventions related to crisis management amounted to an average of 16.1 percent of all events recorded by BCMC officers in the city of Bydgoszcz and wider Bydgoszcz poviat in 2013–2022 (Raport, 2023). This number increased systematically, especially in the years 2013–2019. Therefore, analyses were carried out on the basis of the areas, most at risk to these phenomena in the city of Bydgoszcz, as well as areas not at risk.

The main aim of the work is to assess the risk of flooding of urban infrastructure and flood threats based on long-term precipitation data. Another goal is to examine the relationships between the occurrence of these events and interventions by the State Fire Service, at both city-wide scale and for individual districts. Of the many tasks performed by the State Fire Service, the article focuses only on interventions related to flooding.

Methods and data

Study area

The study focuses on the city of Bydgoszcz, which is the largest city in the Kuyavian-Pomeranian Voivodeship. The area of the city is 176 km^2. In terms of number of inhabitants, Bydgoszcz ranks 9th in Poland. At the end of 2022, there were 330,038 inhabitants, and the population density in the city was 875 people/km^2 (Statistics Poland, 2022). The city's administrative area is elongate; the western part stretches along the Bydgoszcz Canal and the centre and east extend along the Brda river to its confluence with the Vistula river, which is also the city's eastern border. The city extends 22 km from east to west and 10 km from north to south. The city's topography follows the patterns of classic flat-bottomed river valleys *(Figure 1).* The elevation of the terrain increases with the distance from the city's central districts, located on the banks of the Brda and Vistula. The lowest point in the city is on the banks of the Vistula at 28 m a.s.l. The highest point in the city is the summit of Góra Mielęcińska, 107 m above sea level, located a short distance to the east of the IHAR meteorological station ITP. Relative heights in Bydgoszcz increase towards the east, where they reach a maximum of 68 m in Fordon in the Vistula valley and 40 m in the Łęgnowo district.

In land use, forests (44.4%) and built-up (40.1%) occupy the largest area. Other land uses such croplands, herbaceous vegetation, herbaceous wetland, and waterbodies account for 15.5 percent of the city's area *(Figure 2).*

The climate of Bydgoszcz is usually conditioned by westerly polar maritime air masses that cause frequent weather changes in the area. Periods of more stable weather are provided by continental air masses and, less frequently, by Arctic air.

Total annual precipitation in Bydgoszcz is among the lowest in Poland (Grzywna, A. *et al.* 2020). In the World Meteorological Organization-recognised reference year 1991–2020, the mean annual precipitation

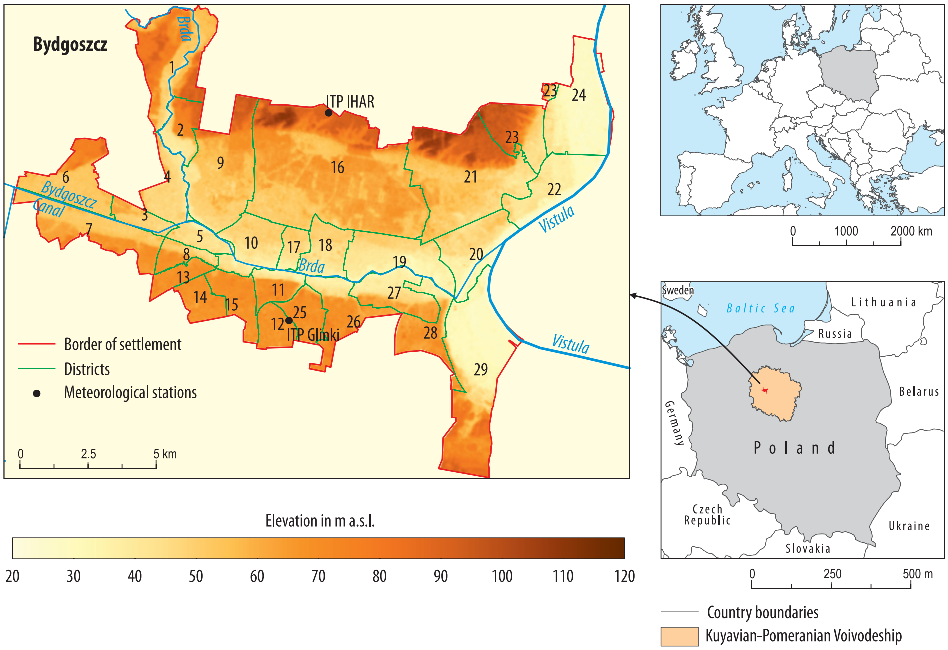

Fig. 1. Geographical position of the research area inside of Kuyavian-Pomeranian Voivodeship. Districts: 1 = Smukała-Opławiec-Janowo; 2 = Piaski; 3 = Flisy; 4 = Czyżkówko; 5 = Okole; 6 = Osowa Góra; 7 = Miedzyn-Prądy; 8 = Wilczak-Jary; 9 = Jachcice; 10 = Bocianowo-Śródmieście-Stare Miasto; 11 = Wzgórze Wolności; 12 = Glinki-Rupienica; 13 = Błonie; 14 = Górzyskowo; 15 = Szwederowo; 16 = Leśne; 17 = Bielawy; 18 = Bartodzieje; 19 = Bydgoszcz Wschód-Siernieczek; 20 = Brdyujście; 21 = Nowy Fordon; 22 = Stary Fordon; 23 = Tatrzańskie; 24 = Tereny Nadwiślańskie; 25 = Wyżyny; 26 = Kapuściska; 27 = Zimne Wody-Czersko Polskie; 28 = Łęgnowo; 29 = Łęgnowo Wieś. *Source*: Authors' own compilation.

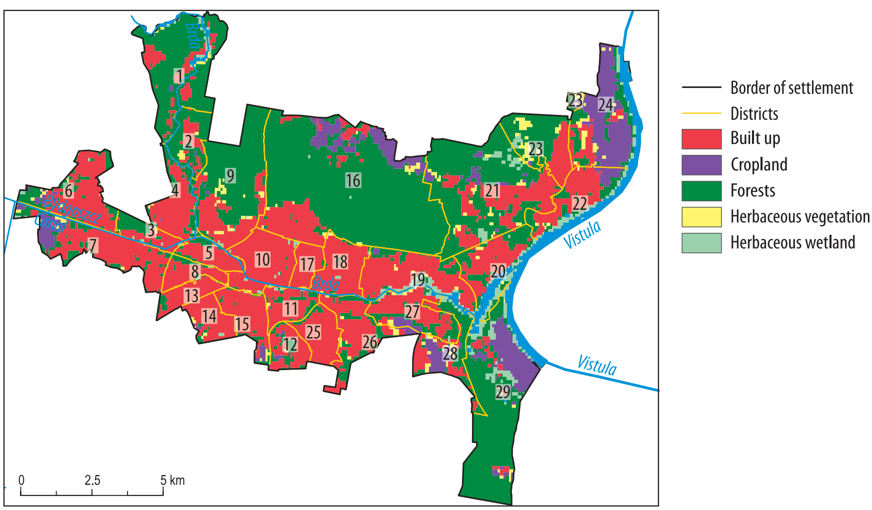

Fig. 2. Land use of the research area. District names 1–29: see *Figure 1*. *Source*: Authors' own compilation.

was 524 mm and varied from 666 mm (2010) to 377 mm (1991, 2003).

During the spring and summer months (April–October), the average seasonal precipitation was 353 mm for the period 1991–2020 analysed, with a high variability of precipitation: from 189 mm (1992) to 555 mm (2017). Precipitation during the April–October season accounted for 67 percent of annual rainfall. July was the wettest month, with an average rainfall of 81 mm, and April was the driest, with 27 mm. No significant decreasing or increasing trends were observed in the course of this precipitation, although periodic fluctuations were found, which is also confirmed by observations carried out at other measuring stations in Poland (Kubiak-Wójcicka, K. 2020; Ziernicka-Wojtaszek, A. and Kopcińska, J. 2020).

Bydgoszcz's average annual air temperature in the studied multi-year period was 9.4 °C. The warmest year (2019) was 10.7 °C, the coolest (1996) was 7.3 °C. The average annual amplitude was 4.4 °C. The pattern of air temperature by month is typical of Central Europe. Winters are colder and summers are warmer. The coldest months are January (-0.2 °C) and February (0.1 °C), and the warmest months are July (19.8 °C) and August (19.3 °C). The temperature distribution between 1991 and 2020 shows a clear upward trend. Climate warming was observed not only in the Kujawy region (Kubiak-Wójcicka, K. *et al.* 2021, 2024), but also in other regions of Poland (Marosz, M. *et al.* 2023) in different time periods.

The course of mean annual air temperature and annual precipitation totals in Bydgoszcz in the 1991–2020 period is presented in *Figure 3.*

Data and research methods

In order to characterise the meteorological conditions in the area under analysis, annual sums of precipitation and mean annual air temperature for the multiannual period 1991–2020 were used, which is a broader reference to the meteorological conditions prevailing in Bydgoszcz. On the basis of the average monthly and annual precipitation

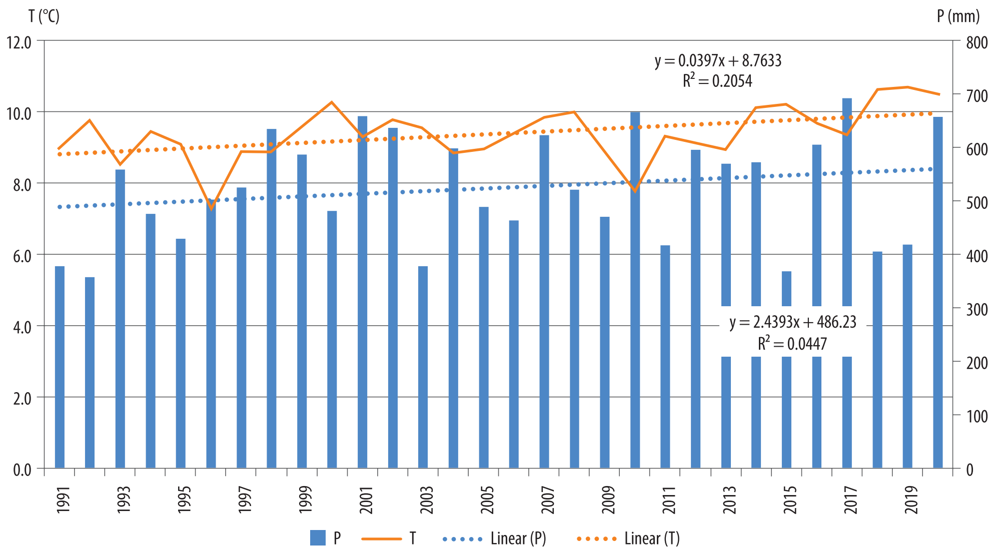

Fig. 3. Mean annual air temperature (T) and annual precipitation (P) totals at the station in Bydgoszcz in the years 1991–2020. *Source*: Authors' own research based on data from ITP-PIB.

and air temperature, trends of changes in the analysed multi-year period were calculated. Precipitation data from measurements performed by two automatic meteorological stations of the Institute of Environmental and Life Sciences – National Research Institute (ITP-PIB) were used for detailed analyses. The first (ITP Glinki) is located in the Glinki estate in the south of Bydgoszcz. This is a built-up district of the city lying at approximately 80 m a.s.l. The second station (ITP IHAR) is located on the premises of The Plant Breeding and Acclimatisation Institute – National Research Institute in the north of the city in an area adjacent to the Forest Park of Culture and Recreation (Poland's largest city park, at 800 ha). The distance between the two weather stations is approximately 8 km.

The data from both stations comprises daily rainfall totals for the years 2010–2022, measured in the period April–October. It is in these months that the highest rainfall sums are observed in Bydgoszcz at various time scales. In order to describe the rainfall distribution at individual locations in more detail, days were distinguished that met criteria for daily rainfall total thresholds of 10 mm, 20 mm, 30 mm, 40 mm, and 50 mm and more. This made the study sensitive to differences resulting from the uneven spatial distribution of rainfall and thus to the causes of local flooding. The next step was to indicate dates and periods in the rainfall calendar that repeatedly exhibit increased rainfall potentially conducive to flooding. Information on the rainfall situation in Bydgoszcz will be supplemented with information on the most important causes of synoptic situations that favour heavy rainfall.

In situations where there is a risk of flooding, the activities of the State Fire Service, which protects or eliminates the effects of both phenomena, are important. Similar to the preparation of rainfall data, the detailed analysis of interventions was limited to a common observation period, which covers the months of April to October in 2010–2022. These data were obtained from the Municipal Headquarters of the State Fire Service in Bydgoszcz and contain information on the date and time, address of, and reason for each intervention. The data were grouped and presented spatially, according to the city's division into districts.

Results and discussion

Precipitation from 2010 to 2022

During the multi-year period 2010–2022 study, annual precipitation totals showed a decreasing trend, which was related to the prevalence of annual precipitation totals below the multi-year averages. Precipitation totals for the April–October season 2010–2022 accounted for between 58.0 percent (2010) and 80.3 percent (2017) of annual precipitation. On average, total precipitation in the April to October season accounted for 67.1 percent of total annual precipitation over the 2010–2022 period, comparable to the 1991–2020 period. The research showed that the average total seasonal rainfall (April–October) at the two stations in 2010–2022 was 355.9 mm (ITP Glinki) and 311.2 mm (ITP IHAR). The wettest month in the studied period was July at the ITP Glinki station (75.7 mm), and at the ITP IHAR station, it was 57.8 mm *(Figure 4).* The highest precipitation totals at the ITP Glinki station were recorded in June 2020 (180.8 mm) and in July 2017 (125.8 mm). At the ITP IHAR station, the highest precipitation totals were recorded in June 2011 (149.5 mm) and October 2017 (120.3 mm). This difference probably results from the uneven distribution of rainfall from storm activity, which is particularly noticeable in these months. There were also some very dry months in the rainfall distribution. In April 2020, only 0.7 mm of precipitation fell at the ITP Glinki station, and in October 2014 – 1.6 mm. Slightly higher precipitation was found at the ITP IHAR station, where 1.1 mm was recorded in April 2019 and 2020 and 3.0 mm was recorded in October 2010.

The difference in the values of the average monthly precipitation totals at the two stations during the season (April–October) from 2010 to 2022 was characterised by high variability. In most months (58.2%), the difference

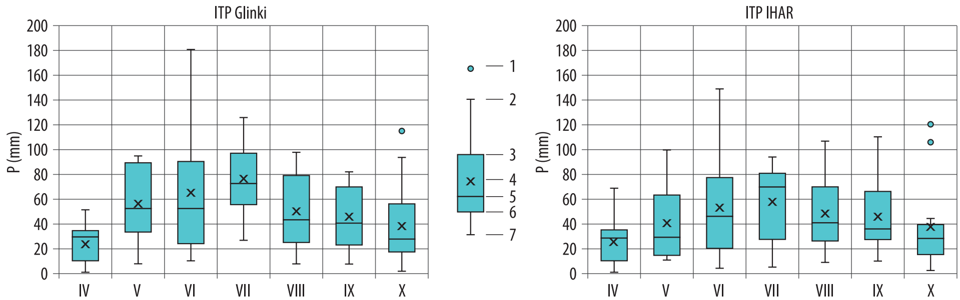

Fig. 4. Distribution of monthly rainfall totals at the ITP Glinki (left) and ITP IHAR (right) meteorological stations in April–October, 2010–2022. 1 = outlier points; 2 = maximum; 3 = 75 percentile; 4 = mean; 5 = median; 6 = 25 percentile; 7 = minimum. *Source*: Authors' own research based on data from the Institute of Environmental and Life Sciences – National Research Institute.

between the mean monthly precipitation at the two stations was less than 10 mm. The largest difference between monthly precipitation totals at the two stations was recorded in July 2016 (106.8 mm), in June 2020 (93.3 mm) and in May 2019 (75.9 mm). Only in 4 months (April 2010, and April, June and October 2022) was the rainfall total at both stations equal.

The correlation coefficient of the precipitation totals in the individual months remained at r = 0.76 throughout the entire multi-year study period. In the particular months, the interrelationships varied. In those months when precipitation totals were similar, the correlation coefficient ranged from r = 0.74 in June to r = 0.96 in April, while in months extremely differentiated in terms of precipitation, these relations were weaker. Such weak relationships were found in July (r = 0.40) and May (0.66). Thus, not in all months could the precipitation data from any one measuring station be representative of the entire city area.

Daily precipitation for the April–October season

Analysis of daily precipitation totals at both stations showed that the number of days with precipitation decreased with increasing precipitation totals. At the ITP Glinki station, the number of days with precipitation meeting the condition (P ≥ 10 mm) accounted for 10 percent of all days with precipitation in the studied multi-year period, and the number of days with P < 10 mm accounted for 90 percent, with no daily precipitation sum exceeding 50 mm recorded *(Table 1)*.

At the ITP IHAR station, such days with P > 10 mm precipitation were even less, i.e. 8 percent *(Table 2)*. Despite the small share of days with precipitation above 10 mm, the total daily precipitation amounted to as much as 49 percent of the total precipitation at the ITP Glinki station, and 42 percent at the ITP-IHAR station in the analysed multi-year period. This indicates a significant share of extreme precipitation (above 10 mm). At the same time, it should be noted that there was no precipitation > 50 mm at the ITP Glinki station and only one case of daily precipitation above 50 mm was recorded at the ITP IHAR station (9 June 2011 – 75.5 mm). Considering the sums of extreme precipitation recorded in individual ranges, the largest shares of the number of days and the total sum of precipitation were recorded in the 10–20 mm and 20–30 mm precipitation ranges.

In the distribution of average daily rainfall during the months of April to October, several frequently recurring days and periods of increased rainfall can be distinguished, which can cause localised flooding. The wettest days between 2010 and 2022 were 25 June (average daily rainfall of 6.6 mm) and 13 July (5.3 mm).

Table 1. Number of days (n) with precipitation (P) and sum of precipitation (∑) at ITP Glinki station meeting precipitation criteria in 2010–2022

P/year		P<10	10<P<20	20<P<30	30<P<40	40<P<50	P>50	∑P
2010	n	86	7	2	0	1	0	–
	∑	194.2	99.2	51.4	0	41.2	0	386.0
2011	n	78	5	1	1	0	0	–
	∑	190	57.2	25.2	36.4	0	0	308.8
2012	n	95	9	0	2	0	0	–
	∑	207.2	131.8	0	66.4	0	0	405.4
2013	n	73	8	2	1	0	0	–
	∑	153.9	112.6	52.6	34.2	0	0	353.3
2014	n	78	2	3	1	0	0	–
	∑	193,5	31.0	74.6	31.8	0	0	330.9
2015	n	80	5	0	0	0	0	–
	∑	148.2	65.2	0	0	0	0	213.4
2016	n	86	8	2	1	1	0	–
	∑	206.7	113.5	40.7	38.9	41.4	0	441.2
2017	n	97	10	6	2	0	0	–
	∑	203.8	141.8	138.4	71.2	0	0	555.2
2018	n	59	6	2	0	0	0	–
	∑	123.5	82.7	43.1	0	0	0	249.3
2019	n	77	4	1	0	0	0	–
	∑	166.0	63.6	21.4	0	0	0	251.0
2020	n	82	8	7	2	0	0	–
	∑	184.0	116.3	160.8	65.6	0	0	526.7
2021	n	86	4	1	1	0	0	–
	∑	180.4	60.9	23.1	35.2	0	0	299.6
2022	n	83	6	1	0	0	0	–
	∑	198.8	84.5	23	0	0	0	306.3
2010–2022	∑n	*1060*	*82*	*28*	*11*	*2*	*0*	–
	∑P	*2350.2*	*1160.3*	*654.3*	*379.7*	*82.6*	*0*	*4627.1*
	%	*51*	*25*	*14*	*8*	*2*	*0*	*100*

Source: Authors' own research.

In addition, rainfall between 4 mm and 5 mm was observed on several days. Such days included 1, 17 and 23 July and 17 June and 31 August.

Several wet and recurrent periods were found in the rainfall distribution, when the cumulative rainfall in some years exceeded even 50 mm. Such dates may include: 11–16.05 (52.9 mm); 5–12.06 (59.6 mm); 1–7.07 (61.8 mm) and 26–31.08 (57.1 mm). The maximum accumulation of precipitation of 85.9 mm was found on 11–17.07. Based on our own research and observations by other authors, the period 6.07–19.07 shows the highest storm activity combined with intense precipitation.

A review of synoptic situations favourable for the occurrence of high-intensity precipitation in the Bydgoszcz area allowed us to separate the most frequently recurring synoptic situations:

a) An area of low pressure over Bydgoszcz and the Kujawy region. This situation usually causes long-term, low- and medium-intensity rainfall lasting up to several tens of hours,

b) Rapid movement of atmospheric fronts and changes in air-mass types. Usually, hot

Table 2. Number of days (n) with precipitation (P) and sum of precipitation (∑) at ITP IHAR station meeting precipitation criteria in 2010–2022

P/year		P<10	10<P<20	20<P<30	30<P<40	40<P<50	P>50	∑P
2010	n	92	5	4	1	0	0	–
	∑	192.6	65.4	90.6	36.4	0	0	385.0
2011	n	66	9	0	0	0	1	–
	∑	174.2	126.7	0	0	0	75.1	376.4
2012	n	92	5	1	0	0	0	–
	∑	258.8	63.3	28.7	0	0	0	350.8
2013	n	81	9	0	2	0	0	–
	∑	176.8	123.7	0	70.6	0	0	371.1
2014	n	78	6	1	0	0	0	–
	∑	216.6	72.6	21.4	0	0	0	310.6
2015	n	70	1	0	0	0	0	–
	∑	123.7	11.6	0	0	0	0	135.3
2016	n	83	5	1	0	0	0	–
	∑	177.8	69.8	20.4	0	0	0	268.0
2017	n	97	9	4	3	0	0	–
	∑	258.3	137.5	90.7	104.9	0	0	591.4
2018	n	64	3	1	0	0	0	–
	∑	120.3	48.9	23.3	0	0	0	192.5
2019	n	63	1	0	0	0	0	–
	∑	110.2	10.1	0	0	0	0	120.3
2020	n	91	6	2	2	0	0	–
	∑	177.7	81.4	47.6	64.4	0	0	371.1
2021	n	92	4	1	0	0	0	–
	∑	159.6	49.1	28.3	0	0	0	237.0
2022	n	84	4	1	0	1	0	–
	∑	211.6	57.0	21.5	0	46.6	0	336.7
2010–2022	∑n	*1053*	*67*	*16*	*8*	*1*	*1*	*–*
	∑P	*2358.2*	*917.1*	*372.5*	*276.3*	*46.6*	*75.1*	*4045.8*
	%	*58.3*	*22.7*	*9.2*	*6.8*	*1.2*	*1.9*	*100.0*

Source: Authors' own research.

and dry continental air masses are displaced by cooler and humid polar–marine air. Thunderstorms occurring on atmospheric fronts are generally short-lived and accompanied by intense local rainfall,

c) Slow movement of a wavy cold front. This process leads to the formation of mesoscale low-pressure centres along a front line, where different air masses mix, which favours heavy rainfall.

d) Precipitation caused by storms within an air mass. These usually appear locally, during periods of high air temperature. Their formation is influenced by various factors, the most important of which are related to topography and land-cover type, as well as local temperature distribution.

In many cases, local storms and rainfalls occurred in the city. One such situation was observed on 19 July, 2015, when a storm front was moving over the city. Then, 19.2 mm fell at the ITP Glinki station, while no rainfall was recorded at the ITP IHAR station. Similarly, on 14–15 July, 2016, local storms caused 41.4 mm and 14.5 mm of rainfall at the ITP Glinki station, while, in the same period, only 0.2 mm of rain was recorded at the ITP IHAR station on the first day and none the next. A similar situation occurred on August 16, 2022, when a storm with heavy rainfall occurred in the west of the city. No precipitation was recorded at the ITP Glinki station on that day, while there was 4.2 mm at the ITP IHAR station. It is worth noting that these sums of precipitation were not record-breaking, but the effects of the downpours were determined by the short duration and high intensity of the rainfall. In addition, at that time, the air temperature remained high, above 30 ºC.

State Fire Service interventions

Based on the data on interventions by the State Fire Service (SFS), pumping water from flooded streets and apartments, such activities increased throughout the years 2010–2022. The greatest annual number of such interventions was recorded in 2022 (117) and 2014 (74), while the lowest was in 2013 (3) *(Figure 5, a).*

The monthly distribution was dominated by interventions in July (227 in total), which accounts for 42 percent of all interventions in 2010–2022. There were far fewer in August (153) and June (132) *(Figure 5, b).* On average, 42 interventions were made per season (April–October), of which 18 in July and 12 in August.

Most interventions were recorded in city districts in the west of the city, where topography is a factor that increases the risk of flooding. There are significant slopes here (the valley edge), which favour the rapid flow of water and its accumulation in the lower parts. These districts are Osowa Góra (141 interventions) and Miedzyń-Prądy (50), where houses predominate. A significant risk of flooding (112 interventions) was also found in the densely populated city centre in the Bocianowo-Śródmieście-Stare Miasto district. High-density buildings, little ability for water to percolate into the soil, and storm water systems that are not always cleared were all factors contributing to flooding.

Another area with an increased number of interventions is the housing estates located in the southern part of the city, in the Kapuściska

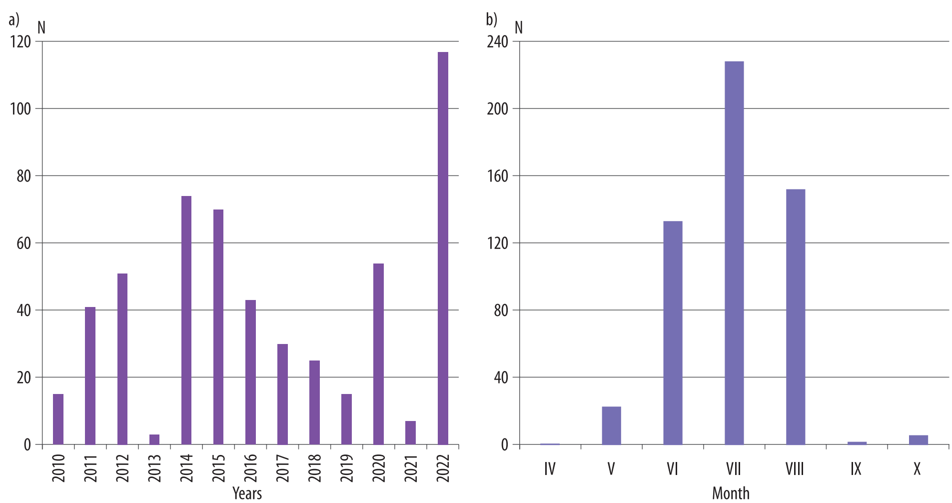

Fig. 5. Number of State Fire Service interventions (N) in Bydgoszcz to pump water from flooded streets and apartments in the years 2010–2022. a = in the multiannual period; b = in individual months of the season (April–October). *Source*: Authors' own study based on SFS data.

and Wyżyny districts. Here, the State Fire Service intervened 42 times. There are also areas in Bydgoszcz where interventions by the State Fire Service (SFS) were absent or very occasional. Such districts include Zimne Wody-Czersko Polskie, Łęgnowo and Łęgnowo-Wieś, which are characterised by low-density development and a large amount of biologically active areas *(Figure 6).*

The year 2022 deserves special attention for having the highest annual number of interventions (117) *(Figure 7)*. In August, during the wet period of 14–21 August, the State Fire Service intervened 105 times as a result of local rainfall. According to rainfall data from 14 August, a daily total of 5.9 mm of rainfall was recorded at the ITP Glinki station and 6.8 mm at the ITP IHAR station, whereas no rainfall was recorded on the remaining days. However, on 16 August, 2022, in the Osowa Góra and Miedzyń-Prądy districts in the west of Bydgoszcz, the State Fire Service intervened due to flooding 37 and 13 times, respectively. Unfortunately, there is no rainfall measurement point in the areas of these settlements, so only based on the number and locations of State Fire Service interventions can it be concluded that rainfall was intense and local.

The second highest number of interventions was in 2014 (a total of 74 interventions), of which interventions in July (55) and August (18) predominated *(Figure 8)*. Interventions in July were related to rainfall that occurred at the beginning and end of the month. On 6–8 July, rainfall of 1.4 mm, 26.4 mm and 6.4 mm was recorded at the ITP station. Glinki. As a result of this rainfall, as many as 46 interventions were recorded over the 3 days, which mainly took place in the central part of Bydgoszcz. Most interventions on these days were recorded in the Bielawy and Bocianowo districts. At the ITP IHAR station, precipitation was considerably lower at 8.5 mm, 11.5 mm and 5.4 mm. On 30 July 2014, a total of 9 interventions were recorded in the western part of Bydgoszcz (Okole and Osowa Góra districts). No intense rainfall was recorded at either station on this day. Further interventions (18 in

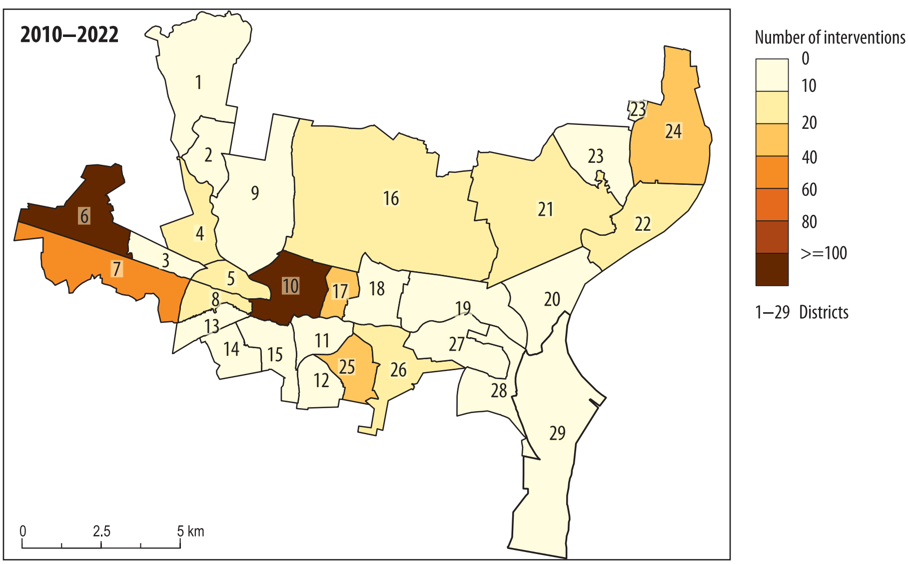

Fig. 6. Number of interventions by the State Fire Service between 2010 and 2022. District names 1–29: see *Figure 1. Source*: Authors' own compilation.

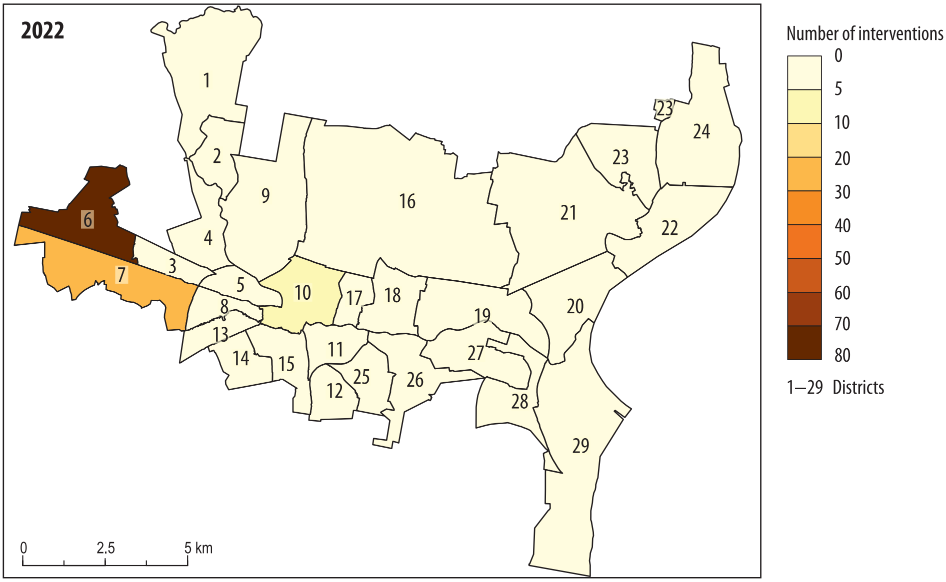

Fig. 7. Number of interventions by the State Fire Service in 2022. District names 1–29: see *Figure 1*.
Source: Authors' own compilation.

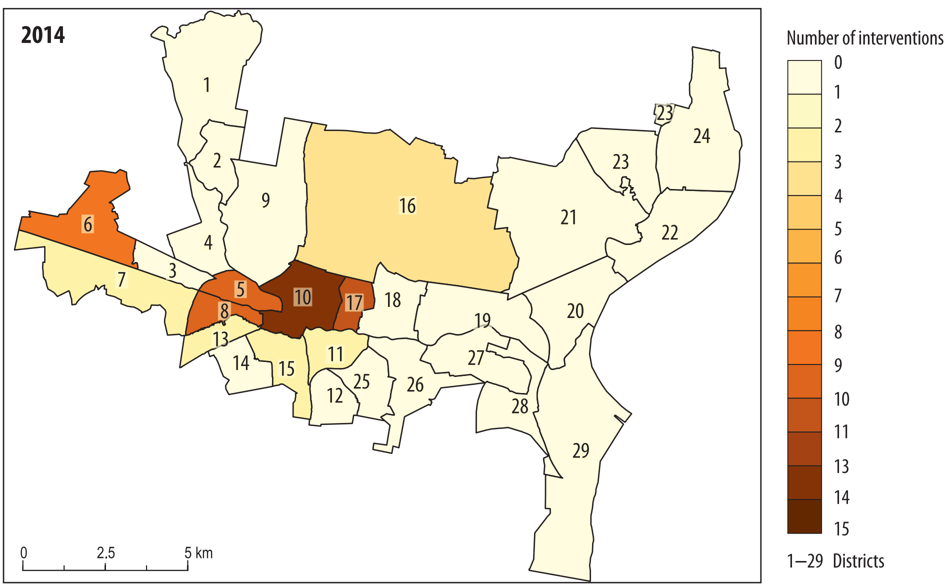

Fig. 8. Number of interventions by the State Fire Service in 2014. District names 1–29: see *Figure 1*.
Source: Authors' own compilation.

total in August) took place at the beginning of August 2014 and were the result of heavy rainfall recorded on 5 August (31.8 mm) at the ITP Glinki station, while 8.6 mm of rainfall was recorded at the ITP IHAR station on that day.

The study showed that only on some dates could the recorded precipitation totals be correlated with fire brigade interventions. Most often, interventions occurred as a result of several days of rainfall accumulation, less often as a result of a single high-intensity rainfall event. Such incidents occurred most often during the typical summer months, from June to August. The calendar of rainfall and fire brigade interventions for each month distinguishes several such dates: 7–9, 17–20 and 25–30 in June, 1–3, 6–8, 11–13, 15–19 and 28–29 in July, and 5–7, 14–16, 20–21 and 27–28 in August.

As an example, in the period 7–9.06.2011, as a result of accumulated rainfall (ITP Glinki – 59.6 mm, ITP IHAR – 98.8 mm), flooding occurred in Bydgoszcz and the state fire brigade had to intervene 36 times. However, the highest number of interventions (64) was recorded on 19.07.2015, which were caused by heavy rainfall (ITP Glinki – 19.2 mm, ITP IHAR – 0.0 mm). In the history of fire brigade operations, there were also interventions when no or little rainfall was recorded. Such a situation occurred on 16.08.2022 in the Osowa Góra district, where as many as 52 interventions were made. On that day, no rainfall was recorded at the ITP Glinki station, and at the ITP IHAR station, the rainfall total was 0.2 mm, as well as no rainfall was recorded on the previous day, i.e. 18 August. A similar situation occurred on 20 and 21 August 2022, when 31 and 18 interventions were recorded, respectively, with 0.2 mm and 3.2 mm rainfall. Unfortunately, the lack of a measuring point in this district did not allow to determine the intensity of the local rainfall.

Discussion

Research by Pradhan, P. *et al.* (2022) has shown that in Europe over the last seven decades (1950–2019), climate extremes are becoming more frequent, co-occurring and persistent. Increases in frequency and precipitation totals have been a characteristic feature of extreme precipitation changes. Seasonal changes in the spatial patterns of extreme precipitation trends may have resulted from seasonal changes in the prominence of precipitation drivers (Łupikasza, E.B. 2017). Due to the stronger fluctuations of extreme precipitation in summer, which are often associated with free convection, the anthropogenic signal is masked by internal variability (Tabari, H. *et al.* 2020). Averaged over Europe, anthropogenic influences contributed to larger increases in extreme precipitation anomalies (99.5% percentile) in all seasons of the year (Tabari, H. *et al.* 2020).

The results of rainfall monitoring in the years 2010–2022 at both measuring stations confirmed that the highest monthly rainfall in Bydgoszcz occurs in the summer months (April–October), and especially in June, July and August. This phenomenon has been observed by other authors in Central Poland (Kubiak-Wójcicka, K. 2020). In the analysed long-term rainfall distribution, it was found that rainfall was frequently concentrated in brief periods of time, leading on the one hand to an increased risk of flooding and, on the other, to periods with little or no rainfall being extended and, consequently, to the occurrence of various types of droughts (Bąk, B. and Łabędzki, L. 2013; Kuśmierek-Tomaszewska, R. and Żarski, J. 2021).

Based on the rainfall calendar in the studied multiannual period 2010–2022, several frequently recurring days and periods of increased rainfall were found. In at least some of them, rainfall caused local flooding. 6–19 July was considered the wettest period, with intense rainfall. Usually, frontal storms appeared during this period, preceded by a period of high temperature.

Local rainfall played an important role in the rainfall distribution in Bydgoszcz. This is evidenced by, among others, the areas where State Fire Service interventions were most common, which were remote from the stations recording rainfall. In some situations, flooding was limited to only a few streets and residential blocks while little to no rainfall was recorded at either station. Despite the distance of only 8 kilometres between the stations, the measured daily rainfall sums differed, which also translated into differences in rainfall sums at the monthly or seasonal (April–October) scales.

Precipitation from storms has a significant share in rainfall, especially the heaviest rainfalls. Research by Łaszyca, E. (2018) showed that, in Bydgoszcz in the years 1971–2010, most storm days occurred in July and June, and fewer in August and May. The number of storm days in the Bydgoszcz region shows an increasing trend (0.82 days per year), as shown by Sulik, S. and Kejna, M. (2022), who associate this fact with an increase in air temperature of 0.04 °C per year in the months from April to September. Piasecki, K. and Żmudzka, E. (2022) note that, if in highly urbanised areas the temperature distribution gives rise to strongly differentiated heat islands and at the same time the pressure distribution is not uniform, conditions for the formation of local storm activity arise. In such situations, local downpours occur, which can cause significant damage in relatively small areas.

The number of State Fire Service interventions to pump water from flooded streets and apartments was characterised by high temporal and spatial variability. The city's topography includes areas sensitive to pluvial flooding (e.g., districts in the west and centre of the city), areas at greater risk of fluvial flooding (areas in the immediate vicinity of the Vistula and Brda Rivers), and small, sparsely inhabited districts at practically no risk of pluvial or fluvial flooding.

The authors are aware that conducting rainfall monitoring at only two measurement points in such a large city as Bydgoszcz (176 km^2) turned out to be insufficient. For comparison, Maier, R. *et al.* (2020), who analysed the spatial variability of rainfall in the city of Graz (Austria), had at their disposal rainfall data from 22 rain gauges distributed over an area of 125 km^2. These studies confirmed that low- and medium-intensity rainfall shows good correlation among stations, while the relationships for larger rainfall sums are much weaker.

The lack of more rainfall measurement points in Bydgoszcz and the local nature of rainfall meant that it was impossible to demonstrate direct relationships between the recorded rainfall and the number of SFS interventions. According to Kaszewski, B.M. and Flis, E. (2014), a characteristic feature of extreme events is their small number, which means that the standard statistical methods used are unusable or do not give satisfactory results, and too low a density of meteorological stations also means that not all such events are recorded. Moreover, as Pińskwar, I. (2022) points out, data regarding SFS data may be subject to errors, as not every pluvial or fluvial flood is reported. Moreover, some interventions may also be due to the poor or improper functioning of technical infrastructure. This means that the assessment of flood risk in urbanised areas should be considered from a multi-aspect perspective (Kubal, C. *et al.* 2009). Taking into account the location of places frequently flooded due to rainfall, a detailed analysis of rainwater runoff in housing estates susceptible to flooding is recommended. One of the options for preventing flooding is to limit the total area of impervious surfaces and to propose concepts for water management in the form of green and blue infrastructure solutions. In this case, local adaptation to cope with future urban floods becomes important. A study by Zhou, Q. *et al.* (2018) in China showed that the volume of urban floods increases non-linearly with changes in rainfall intensity. A comparison of reduced flood volumes in mitigation and local adaptation scenarios (through drainage improvements) suggests that local adaptation is more effective than mitigation in reducing future flood volumes.

The vulnerability of urban areas to climate change and the need to strengthen their resilience to climate phenomena have been recognized in EU policies and continue to be an essential objective of the EU strategy on adaptation to climate change. The framework for a standard policy of EU Member States is set out in the document 'Adapting to climate change: Towards a European framework for action' (CEC, 2009). Based on these guidelines, each

EU Member State prepared its climate change adaptation strategy, first covering cities with more than 100,000 inhabitants, and then cities with smaller populations.

Cities across Europe have very diverse contexts, capacities and experiences and are at very different stages of readiness for adaptation, but all are taking some form of action (EEA, 2024). A comprehensive review of pluvial flood policies and strategies in urban areas across the European continent is provided by Prokić, M. *et al.* (2019). Perera, A.C.S. *et al.* (2024) reviewed 12 urban blue-green policies, tracking their evolution and comparing five common categories in European cities such as Berlin, Helsinki, London, Malmö and Southampton. The results indicate that most policies focus on increasing urban vegetation cover. Despite existing adaptation strategies, the issue of their implementation in individual regions is at different stages of advancement. A city's vulnerability to climate change's effects may vary within its administrative borders. Therefore, the first step should be to conduct a vulnerability analysis of the city, which will identify areas sensitive to extreme hydrometeorological phenomena.

Different methods exist to identify sensitive areas within the city in the literature. Various criteria are used to assess and area's vulnerability to the threat of pluvial floods, such as land use and cover, terrain height, terrain slope, and existing technical infrastructure. Research by Radu, C. *et al.* (2021) in one of the oldest districts of Bucharest in terms of development showed that the streets in the southeastern and north-western parts of the district are most vulnerable to flooding, which requires modernization of the sewage system. Similar research was conducted by Kamenská, M. and Smatanová, K. (2022) for selected Slovak cities, i.e. Hlohovec, Kežmarok, Košice-Západ, and Prešov. In these cases, the factors increasing the risk of flooding are: historically formed dense development of city centres, lack of vegetation and trees, extensive parking lots with impermeable surfaces and insufficient capacity of sewage networks. In turn, research conducted by Ullah, I. *et al.* (2023) in the historical city of Győr in Hungary allowed to determine the level of the city's resistance to floods using the integration of the physical typology of settlements with ecological factors in the study area. The research resulted in flood hazard maps.

Adaptation measures were also taken in Bydgoszcz. The Bydgoszcz City Adaptation Plan to Climate Change by 2030 (2021) took into account the main threats and four sectors most sensitive to climate change: public health, transport, water management and areas of high-intensity residential development. To increase the city's resistance to the occurrence of extreme phenomena, adaptation measures were planned, which included the development of blue-green infrastructure, modernization of the storm water drainage system, and introduction of systems for informing residents about threats. One of the effects of the implementation of the Adaptation Plan is the completed first stage of the project "Bydgoszcz green and blue. Retention and management of rainwater or meltwater" implemented by the Municipal Water and Sewage Company (MWiK) for 2025. The tasks consist of managing excessive amounts of rainwater by building retention reservoirs, developing small retention facilities and using rainwater for the needs of, among others, watering urban greenery. The implementation of the planned activities began in 2021. The assessment of the effectiveness of the planned and implemented adaptation activities to climate change in Bydgoszcz should be postponed until the completion of the construction of retention reservoirs, which is planned for 2027. Initial experiences indicate that the planned activities are bringing the expected effects.

Conclusions

The analysis performed in this study showed that:

– In this precipitation category, most days were recorded with daily precipitation in the range of 10–20 mm and 20–30 mm.
– Despite the small share of days with precipitation above 10 mm, the total daily pre-

cipitation constituted as much as 49 percent of the total precipitation at the ITP Glinki station and 42 percent at the ITP IHAR station in the analysed multi-year period. This indicates a significant share of extreme precipitation (above 10 mm). At the same time, it should be noted that there was only one case of daily precipitation above 50 mm at the ITP IHAR station and no such precipitation at the ITP Glinki station.

– The highest number of events related to flooding and waterlogging in Bydgoszcz took place in 2022 (117 fire brigade interventions) and in 2014 (74 interventions), while the lowest number was in 2013 (3 interventions).
– The monthly distribution was dominated by interventions in July (a total of 227), which accounted for 42 percent of all interventions in the period 2010–2022. There were significantly fewer in August (153) and June (132).
– The analysis of the distribution of daily precipitation and interventions by the State Fire Service showed three possible interrelationships:

1) Fire brigade interventions occurred as a result of several days' accumulation of precipitation;

2) Flooding causing fire brigade interventions was caused by incidental, extreme precipitation, while such precipitation was not always recorded simultaneously at both measuring stations;

3) Fire brigade interventions were not related to the recorded precipitation because it was absent or small.

The precipitation was of local character and appeared most often in the districts of Bydgoszcz, which were more distant from the measurement points. In such cases, the number of interventions was not only the result of extreme precipitation, but was also conditioned by local factors.

Areas most at risk of flooding were housing estates in the west and centre of Bydgoszcz. These are areas with unfavourable topographical conditions (steep slopes) and high proportions of sealed surfaces. Increasing biologically active areas that will delay surface runoff through appropriate land development using green and blue infrastructure is recommended.

In order to improve the monitoring of flood threats in Bydgoszcz, it is recommended to create an integrated network of rainfall measurement points in the city, especially in those areas where the largest number of fire brigade interventions are observed.

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