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Flood risk analysis in urban areas and adaptation options based on the example of the city of Bialystok

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ABSTRACT

As a result of intensifying climate change, extreme weather events and local conditions, the city of Bialystok is vulnerable to urban and river flooding, as well as a combination of both. In addition, increasing dense development with large sealed surfaces intensifies these phenomena. In 2023, buildings and urban areas covered 54.23% of the city's territory, showing a steady upward trend compared to previous years. In order to protect the population and environment of Bialystok, which is the capital of the Podlaskie Province in Poland, statistical analyses were carried out taking into account changes in atmospheric temperature, total annual rainfall and annual rainfall above 20 mm between 1993 and 2023 in order to examine possible climate changes and determine their trend. The research showed that the share of annual rainfall above 20 mm in the total annual rainfall over 30 years increased by 15%, showing an average increase of 5% every 10 years with a stable frequency of rainfall events. The correlation between average air temperatures and average rainfall above 20 mm per 10 years showed a fairly strong correlation between the factors studied. This indicates a significant impact of the urban heat island (UHI) on the growing threat of urban flooding due to higher precipitation. Due to partial limitations on the possibility of modernising the sewers in Bialystok, it is important to introduce retention reservoirs and increase the absorption area, which can store water while relieving the main rainwater receiver, which is the Biala River, and additionally enable water retention in the city, greater infiltration of rainwater into the ground, and reduce the urban heat island effect during droughts.

Keywords: urban flood, climate, urban area, sealing surface, flood protection.

INTRODUCTION

Urban flooding becomes an increasingly serious problem in Europe and around the world. As a result of climate change and overlapping urban characteristics, city areas are extremely vulnerable to more frequent sudden weather changes, such as intense short-term and high daily rainfall [1]. The urban climate, which determines variable weather phenomena and conditions, is specific to a given location and is shaped by the physical and geographical factors of that area. However, as a result of the increasing influence of constantly introduced new urban variables, it is subject to local changes. In the past, climate change was the result of natural influences. Currently, however, human activity has an increasing impact. Heavy rainfall is dangerous, with the phenomenon becoming more intense over time [2, 3]. Although the annual rainfall total shows slight fluctuations, the height and intensity of individual rainfall events is noticeably increasing [4]. Among them, hourly rainfall above 20 mm is defined as short-term intense rainfall, and rainfall above 50 mm as extreme rainfall. In terms of daily totals, rainfall above 20 mm constitutes heavy rainfall, while rainfall of 30 mm poses a first-degree flood risk [5]. Climate change leads to alternating periods of severe drought interspersed with heavy rainfall. In addition, the drastic reduction in active surface area in many cities around the world in recent decades has meant that even with low rainfall, urban areas are at risk of flooding. Surface sealing increases the lack of rainwater infiltration into the ground. According to Blum et al. (2020), a 1% increase in surface sealing results in a 3.3% increase in flood risk [6].

Reports by the Intergovernmental Panel on Climate Change (IPCC) clearly indicate that climate change and the rise in average global temperatures are increasing the frequency and intensity of extreme events, including urban flooding [7]. The IPCC suggests adaptation efforts to better protect cities and reduce the risk of flooding by increasing retention in cities through sustainable infrastructure, as well as taking flood risk into account in spatial planning. These measures support carbon dioxide absorption and, by combining blue-green infrastructure with grey infrastructure, can reduce the risk of extreme events while benefiting people and the environment. In addition, according to Bezak et al. [8], the use of early warning systems reduces the number of fatalities. They also point out that some lower-income cities are insufficiently adapted to climate change due to limited finances, thus increasing the disparities between rich and poor cities and the subsequent scale of losses in the event of flooding. The IPCC adaptation plan for effective water use and conservation, with the highest effectiveness and feasibility by 2030, includes limiting the transformation of natural ecosystems, carbon sequestration in agriculture, and the restoration and reforestation of ecosystems. In the case of settlements and infrastructure, the report [7] showed that the best mitigation can be achieved through the introduction of effective construction. Scientific research conducted by Steinhausen et al. [9] showed that the use of sustainable infrastructure can reduce the risk of flooding in cities by 15%. Directive 2007/60/EC of 23 October 2007 of the European Parliament and of the Council introduced an obligation in European Union countries to carry out and update preliminary flood risk assessments, identifying areas potentially at risk of flooding. In addition, Member States are required to develop flood risk management plans, specifying protective and preventive measures and actions to be taken in the event of a flood [10]. It has also been noted that in some countries, historical rainfall data was used to determine compensation, which resulted in low compensation amounts [11]. Floods can have catastrophic consequences. They cause significant economic, environmental and cultural heritage damage, and can lead to personal injury and even loss of life. They also result in forced displacement of people. In addition, they increase pollution of rivers, seas and oceans as a result of surface runoff from urban areas [12]. The September 2024 flood report prepared by State Water Holding – Polish Waters stated that the estimated losses in municipal road infrastructure amounted to: Silesian Province PLN 166,493,909, 99 PLN, Silesia Province - 1,340,349,592.00 PLN, Lubusz Province - 124,032,617.42 PLN and Lower Silesia Province - 1,287,257,516.02 PLN [13].

Białystok, as the largest city in north-eastern Poland, is an interesting example of a medium-sized urban centre where dynamic urbanisation processes clash with spatial and natural constraints. Its location in a transition zone between agricultural and urbanised areas, combined with morphological diversity (including the presence of river valleys – the Biala and Dolistowka rivers), makes it a city particularly susceptible to the effects of extreme phenomena, especially heavy rainfall. In recent decades, Bialystok has experienced strong development pressure, manifested in the expansion of housing, road and commercial infrastructure. This process leads to a significant increase in sealed surfaces, which significantly reduces the infiltration capacity of the area and contributes to the intensification of surface runoff of rainwater.

In hydrological terms, although Bialystok is not located on large rivers of supra-regional importance, such as the Vistula or the Oder, it is located within a catchment area characterised by low natural retention and limited rainwater buffering capacity. In extreme rainfall conditions, urban watercourses – especially the Biala River – become the main recipients of rapidly increased water volumes, which causes their beds and accompanying infrastructure to become overloaded. Thus, the flood risk in Bialystok has not only a hydrological dimension, but also a planning and infrastructure dimension. Previous flood risk analyses in Poland have focused mainly on large urban agglomerations and large river valleys, leaving medium-sized cities with more complex and less studied environmental and urban conditions in the shadows. Bialystok is therefore a valuable case study for the analysis of contemporary flood risks in the context of climate and urbanisation.

The experiences of recent years confirm that the city has been and still is exposed to flooding. Its frequency and intensity increase due to the rise in torrential rainfall. In the 20th century, these phenomena occurred less frequently, and the spatial structure of the city favoured the natural absorption of water into the ground. Currently, with the intensification of development and the transformation of former biologically active areas into impermeable ones, there are increasingly frequent overloads of the stormwater drainage and drainage systems, as well as rapid rises in the water level of the Biala River. Particularly alarming are the data from 2009, indicating extreme variability in river valley flows, reaching a ratio of 1:200 – a value typical for mountain catchment areas with large slopes, which in the case of a lowland city indicates a significant disturbance in the water balance. The source of this situation is not only the sealing of the surface, but also the elimination of retention areas and the marginalisation of the protective functions of river valleys, which have been built up by residential, commercial and industrial developments, often carried out under pressure from developers' interests [14–17].

The increasing threat results in a growing risk not only of physical material losses, but also of serious social and economic consequences. The city's response to these challenges is modernisation measures, including the separation of the combined sewer system into sanitary and storm sewers, which aims to reduce the overload of sewage treatment plants during heavy rainfall. Investments in retention reservoirs, increasing the share of biologically active areas, and improving the condition of the Biala River as the main watercourse are also planned. However, the effectiveness of these measures is limited by organisational, financial and implementation problems. Some of the planned projects have not been implemented due to a lack of contractors, delays in tendering or costs exceeding the city's budgetary capabilities. Strategic documents, such as the 'Strategy for the Development of the City of Bialystok until 2030', clearly emphasise that the city has an insufficiently developed water retention system and too low a share of biologically active areas, which hinders effective adaptation to climate change.

Although local infrastructure projects are underway, the scope and pace of changes in the city's structure – especially in river valley areas – mean that exposure to the effects of flooding continues to grow. Places that historically served as buffers have been replaced by intensive development, resulting in the almost complete loss of natural retention. In these conditions, development concepts based on blue-green infrastructure are becoming increasingly important, allowing not only to collect and slow down water runoff, but also to improve the quality of life of residents and increase the city's resilience to extreme events [18].

At the same time, despite increasingly frequent and intense rainfall exceeding 20 mm in a short period of time, there is a lack of detailed analyses of such events in relation to the local hydrological conditions in Bialystok. Existing flood risk forecasts often do not take into account real changes in rainfall intensity and its spatial distribution on a micro-urban scale. There is also a lack of economic assessment of flood damage and opportunity costs, i.e. a comparison of the costs of repairing the effects of extreme events with the benefits of implementing systems based on sustainable stormwater management. The omission of an analysis of spatial risk variation – both in terms of differences between river and rainfall floods, and in relation to building density and land use functions – is an additional limitation to effective adaptation planning.

In light of the above challenges, an in-depth diagnosis of hydrological risks at the local level becomes particularly important, taking into account not only observed climate change and its effects, but also the spatial development of the city and the potential of the existing infrastructure. It is important to identify which urban areas are most vulnerable to the effects of heavy rainfall, what are the dominant mechanisms generating flood risk, and which green-blue infrastructure solutions can most effectively reduce this risk. The analysis will take into account long-term changes in rainfall totals above 20 mm, average air temperatures and changes in the structure of buildings between 1993 and 2023. The aim is to develop a basis for creating local adaptation strategies based on a realistic assessment of the direction and pace of change, as well as on an analysis of the effectiveness and cost-effectiveness of various types of spatial interventions, especially those that can be implemented with the limited financial resources of local governments.

MATERIAL AND METHODS

Characteristics of the research area

The area of analysis covers the city of Bialystok – the capital of the Podlaskie Province, located in eastern Poland, on the border with Lithuania and Belarus, which also forms the eastern border of the European Union. Bialystok covers an area of 102.13 km² and stretches between the geographical coordinates 23°03’57’“E–23°14’50”’E and 53°04’00’“N–53°11’19”’N [19]. The city’s terrain is characterised by moderate elevations located within the Białystok Upland (part of the North Podlasie Lowland), shaped by the last glaciations. The terrain includes terminal moraines, kames and eskers, which divide the city into four morphological units: northern, north-eastern, central and south-western. Relative heights range from 120 to 160 metres above sea level.

The climate of Bialystok and the entire province differs from the rest of Poland, where it is described as moderate transitional. The greatest influence is exerted by continental air, which brings longer and colder winters, a fairly short early spring, and hotter summers than in other lowland regions. January is usually the coldest month of the year, and July is the warmest, especially the second half of the month and the beginning of August. According to statistics from 2000 to 2025, the average number of days with snow cover is 107.4 days, but this number is decreasing due to global warming [19]. The growing season lasts 190–205 days [20]. The main element of the hydrographic network is the Biala River – a left-bank tributary of the Suprasl River, belonging to the Vistula River basin. It flows through the city centre, serving as the main recipient of urban rainwater. The river is 31.90 km long, its catchment area covers 133.44 km², and the average slope of the riverbed is 0.2%. The valley is dominated by brown and podzolic soils, as well as anthropogenic, poorly developed soils with limited permeability [20, 22, 23]. The Biala River is strongly and extremely vulnerable to drought, while during heavy rainfall the water level rises rapidly [21–26]. Due to the need to drain rainwater, the riverbed is artificially regulated along almost its entire length, with storm sewer outlets. However, the river’s capacity as a receiver has now been exhausted, resulting in an increase in the number and severity of floods, mainly during heavy rainfall.

The ecological status of the river has been assessed as poor, mainly due to intensified development and urban runoff. The catchment area is dominated by urbanised areas (45%), agricultural land (42%) and forests (12%). Pollution comes mainly from transport, municipal services and surface runoff, which significantly affects the hydrological functioning of the city.

Figure 1 shows the land use structure within the administrative boundaries of Bialystok, with a clear dominance of development (54.23%). Agricultural land, meadows and pastures account for 25.60%, while forest and shrub land account for 18.50%. Areas under surface water occupy only 0.84% and wasteland only 0.43%. Such proportions testify to the significant anthropopression and the decreasing capacity of the city to retain rainwater. The reduction of biologically active and absorptive areas results in reduced infiltration and thus increases the risk of urban flooding. The distribution of green areas, parks and reserves is banded and uneven, which makes it difficult to counteract the effects of extreme precipitation in a uniform manner throughout the urban structure.

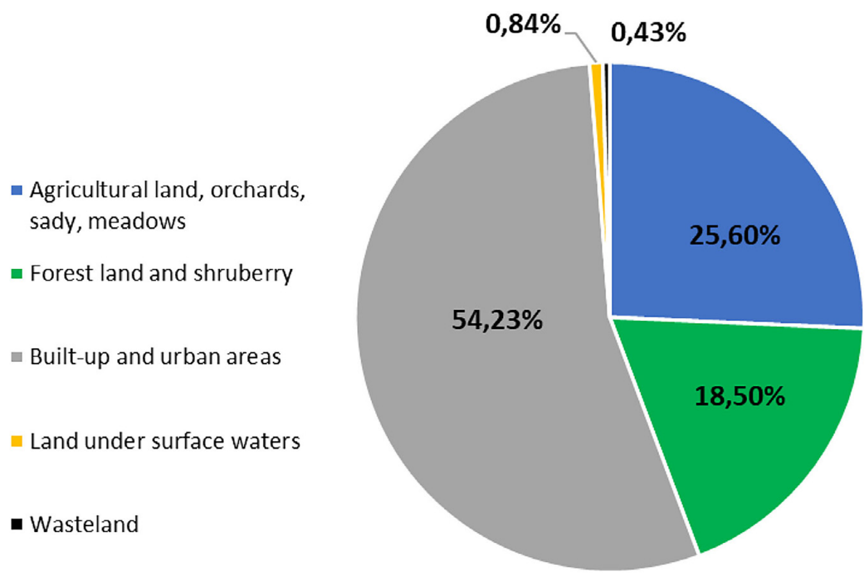

Figure 1. Share of land area in Bialystok [18]

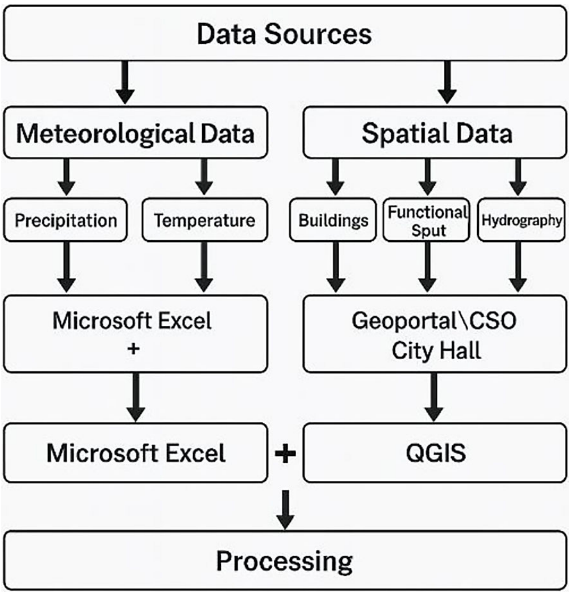

Figure 2. Data flow diagram

Source data

Data from a variety of sources were used in this study (Figure 2). Meteorological data including daily precipitation and temperature values were obtained from the Institute of Meteorology and Water Management (IMGW) [28] for the Białystok synoptic station (no. 295). The data cover the period from 1993 to 2023 and was saved in ".sdt" format, converted to Microsoft Excel files. Spatial and cartographic data, including administrative boundaries, land use layers, river valleys, hydrographic networks and the functional division of the city, were obtained from the Geoportal (EPSG 2180 layout), the Central Statistical Office, the Bialystok City Hall and the Public Information Bulletin. Information on infrastructure and land use was obtained from project studies and the "Strategy for the Development of the City of Bialystok until 2030" [17, 18, 25, 26, 34].

Sources of data on flood risks were reports of the State Water Holding – Polish Waters, press articles, local documents and archival data on flood losses from 2007 to 2017 [27].

Data analysis methods

Figure 3 presents a diagram illustrating the research procedure – from problem identification, data collection, statistical and spatial analysis, to the formulation of conclusions. It takes into account the use of appropriate software, modelling and statistical analysis. The analysis of precipitation and temperatures was based on the processing of daily data using Microsoft Excel. The calculations included the summation of daily precipitation above 20 mm for each year of the analysed period (1993–2023) and the counting of the number of days on which this threshold was exceeded. The 'SUMIF' and 'COUNTIF' functions

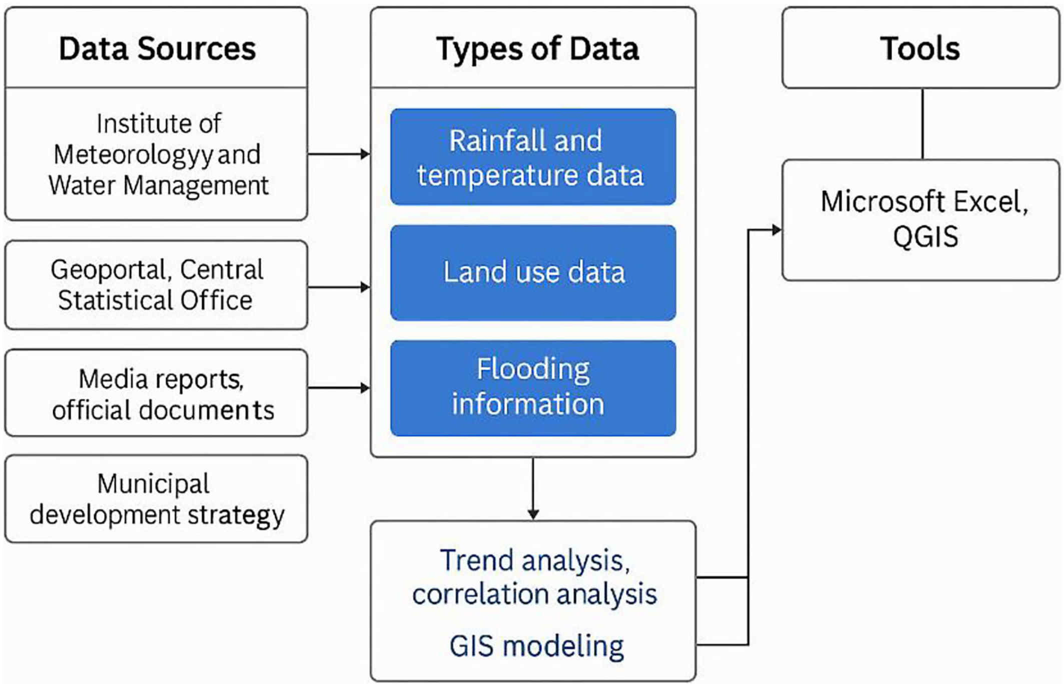

Figure 3. Research procedure

were used to obtain annual indicators of intense precipitation events. The average air temperature values for each year were calculated using the 'AVERAGE' function from daily data. The time period was then divided into three decades (1993–2002, 2003–2012, 2013–2023) in order to perform a co-variability analysis. The correlation coefficient between the average annual temperatures and the sum of precipitation above 20 mm was determined using the 'CORRELATION' function, which allowed the assessment of the relationship between temperature increase and precipitation frequency and intensity.

The spatial analysis used QGIS (Geographic Information System) software, which enables the integration and visualisation of spatial data and the development of thematic maps. The input data included raster and vector layers relating to land use, hydrography, urban infrastructure, as well as the location of precipitation events and flood zones. Thanks to spatial analysis functions, flood risk maps were created, river valleys with retention potential were identified, and the distribution of absorbent surfaces in relation to urban areas was assessed. QGIS was also used to analyse spatial conflicts between the building structure and the natural drainage network layout [28, 29]. The results of spatial analyses in conjunction with meteorological data formed the basis for assessing Bialystok's vulnerability to urban flooding and identifying priority areas for the implementation of green-blue infrastructure, including retention reservoirs, green roofs, rain gardens and infiltration areas.

RESULTS AND DISCUSSION

Today's cities, including Bialystok, more and more often feel the effects of climate change in the form of heavier rainfall and longer dry spells, which mess up the local water balance and overload the drainage system. In the case of Bialystok, this problem is particularly significant due to the specific geographical, climatic and hydrological conditions of the city, as well as the intensification of urbanisation processes, which in recent decades have led to a significant transformation of urban space and a reduction in retention areas. From a physiographic point of view, Bialystok is located on a moraine plateau, within the Bialystok Plateau macroregion, which is morphologically diverse due to the activity of the Pleistocene ice sheet. The terrain includes numerous depressions, river valleys and elevated forms, which affect the way rainwater drains and the susceptibility to local flooding and flash floods. In particular, the valley of the Biala River – the main watercourse within the city limits – plays an important role as a rainwater collector. However, with increasing development and decreasing biologically active area, its capacity to retain and safely transport rainwater is limited. From a hydrological point of view, the Biała River is a watercourse with a relatively low base flow, but with a high dynamic rise in water levels during heavy rainfall. As previous measurements indicate, the variability of flow in individual sections of the valley can reach values typical of mountain catchment areas. At the same time, studies show significant changes in the structure of land cover – according to data from the Central Statistical Office, more than half of the city's area is built-up and urbanised, and the share of biologically active areas is gradually decreasing. This significantly reduces the possibility of infiltration and increases the intensity of surface runoff, which, combined with inadequate sewage infrastructure, leads to local system overloads and flooding [17, 18, 30].

In the context of the above conditions, a detailed analysis of precipitation as the main factor triggering urban flooding becomes justified. For this reason, this chapter is devoted to the study of changes in the frequency and intensity of precipitation in the city of Bialystok in the years 1993–2023, with particular emphasis on events exceeding the threshold of 20 mm per day. This threshold was adopted on the basis of the findings of previous studies as the limit value conducive to the formation of flooding in urban conditions, where surface retention and infiltration are significantly limited [5, 10, 31]. The analysis of meteorological data was carried out in conjunction with information on average air temperature, which made it possible to assess potential links between climate change and an increased risk of flooding. The collected data was then compared with data on land use structure, sewerage network distribution, location of critical infrastructure points and documented flood episodes. In this way, it was possible not only to capture climate trends, but also to place them in the context of urban space functioning and local hydrological conditions. The results presented in this paper provide a basis for assessing flood risk at the local level and identifying areas requiring urgent infrastructure and planning intervention.

Analysis of the variability of precipitation above 20 mm from 1993 to 2023

As urban flooding becomes more common and the risk of flooding in densely populated areas of north-eastern Poland grows, research into extreme rainfall variability takes on special importance. One of the important indicators for assessing this risk is the sum of daily rainfall exceeding 20 mm, which, according to the findings of Kundzewicz et al. (and IPCC analysts), represents a critical limit for drainage systems in cities with poor retention. In the context of the city of Bialystok, which, as shown in previous chapters, is characterised by a high proportion of sealed areas, an outdated and unevenly developed stormwater drainage network, and the valley morphology of the Biala River basin, the analysis of rainfall >20mm is crucial for assessing flood risk dynamics. The research was based on a 31-year time series of data obtained from the IMGW-PIB station (No. 295), covering the period 1993–2023. These data were statistically analysed using Microsoft Excel analytical tools, aggregating annual rainfall totals exceeding 20 mm and the number of days on which they occurred [32, 33].

Figure 4 shows the annual rainfall sum >20 mm between 1993 and 2013. Significant interannual variability and an increasing trend in annual sums after 2010 are clearly visible. In 2017, 2019 and 2021, these values exceeded 150 mm, which is consistent with reports in the literature on the increased number of extreme precipitation events in central-eastern Poland in recent decades [5, 10, 34]. Most of the events occurred within just a few years, from 2007 to 2017. No urban floods had been reported before. Of the eight events, only two involved rainfall occurring within an hour or less. On 9 August 2007, 30 mm of rain fell within 60 minutes, while on 1 July 2009, 27.2 mm of rainfall over 20 minutes caused a sudden flood. The longest rainfall lasting 24 hours occurred on 29 June 2009, with a total of 44.5 mm, which corresponds to a rainfall intensity of only 1.9 mm/h [34]. Studies of the Biała River cross-section conducted at that time showed that after the rain on that day, the water level rose rapidly and peaked within an hour. A water level increase of 0.95 m was observed, which corresponds to an increase in flow of almost 5 m^3/s [15]. The highest rainfall in the analysed period occurred in 2003, amounting to 95.2 mm. This also marked the beginning of increasing rainfall totals. In previous years, the totals remained at an average of 64.8 mm. Over the next twenty years, precipitation was lower than in 2003 only four times, reaching 91.2 mm in 2005, 23.4 mm in 2008, 57.6 mm in 2015 and 87.1 mm in 2023. In the remaining years between 2003 and 2023, rainfall increased steadily. Extreme rainfall episodes were recorded in 2010 and 2017, with intensities exceeding 30 mm/h and rainfall reaching 250.1 mm in 2010 and 249.9 mm in 2017. At that time, Bialystok was the station with the highest recorded rainfall

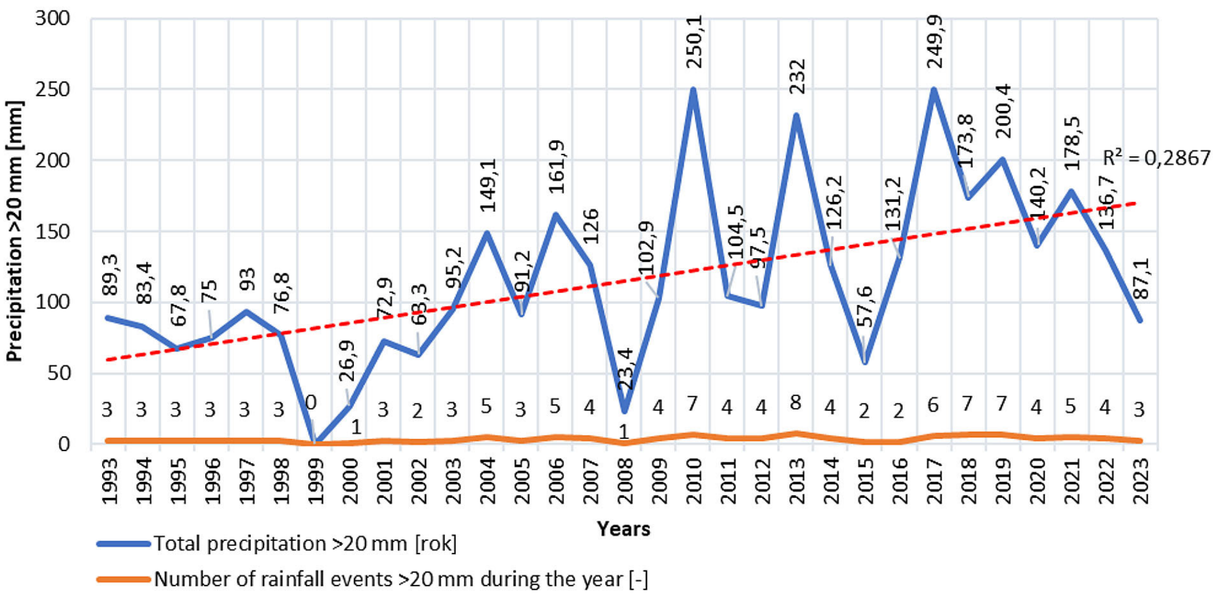

Figure 4. Total annual rainfall above 20 mm and number of rainfall events in the city of Białystok between 1993 and 2013

in Poland. Such high rainfall led to serious disruptions in the functioning of the city, including street flooding, transport paralysis and damage to private property [35, 36].

These phenomena can be interpreted in the light of global climate forecasts indicating that the Central European region is in a zone of increasing amplitude of weather extremes – both droughts and torrential rains [13,36]. Studies conducted in cities such as Krakow, Poznan and Lublin have shown similar trends – an increase in the annual number of days with rainfall above 20 mm and a growing total [7, 11, 20]. At the same time, attention is drawn to the strong correlation between these changes and rising air temperatures, which favour the formation of strong convective storm systems – this will be discussed in the next section of the paper. The results obtained confirm that the city of Bialystok is experiencing an increasing load on its urban and hydrological drainage system, whose main recipient – the Biala River – is a watercourse with low capacity, reacting violently to rainfall impulses (a drop of 0.2% and an average flow of 1.2 m^3/s). In light of the data presented, there is a growing need for sustainable nature-based solutions, such as green-blue infrastructure, which can effectively counteract the effects of heavy rainfall by increasing urban retention and local infiltration [6, 9, 37].

A detailed analysis focuses on 10-year time periods, i.e. 1993–2003, 2004–2013 and 2014–2023. It was noted that in 1993–2003, the average rainfall above 20 mm was 67.6 mm with an average number of rainfall events of n = 2.5. In 2004–2013, the average rainfall was 133.86 mm with 4.5 rainfall events. This was a twofold increase in rainfall above 20 mm and a nearly twofold increase in the number of rainfall events. In the last decade analysed, 2014–2023, the average was 148.16 mm with n = 4.4 rainfall events. It is worth noting that in recent years, the number of rainfall events has remained stable, but the average value of higher rainfall has continued to increase. This is significant because it indicates increasing amounts of single rainfall events. For this reason, the percentage share of the analysed rainfall over the years studied was calculated to confirm the increase in elevated rainfall in terms of annual precipitation.

Another aspect of the analysis was the assessment of changes in the frequency of intense precipitation, defined as precipitation exceeding the threshold of 20 mm per day. This type of precipitation is considered a significant risk factor for urban flooding, as it exceeds the infiltration capacity of most urban soils and often exceeds the capacity of existing storm water drainage systems [38, 39].

Figure 5 shows the number of days with precipitation exceeding 20 mm in individual years in the period 1993–2023. The analysis showed clear differences between years, with fluctuations from just a few events in some years (e.g. 1996, 2003) to more than 10 days with intense precipitation in extreme years such as 2010, 2017 and 2021. Noteworthy is the upward trend in the number of days with heavy rainfall after 2007, coinciding with a period of increased urbanisation of the city and observed changes in climatic conditions in north-eastern Poland [40]. Such changes are consistent with the findings of regional and international studies indicating an increase in the frequency and intensity of short-term rainfall in Central and Eastern Europe in recent decades [33, 41]. In urban conditions, especially in cities with a relatively low proportion of biologically active areas, such as Bialystok, such phenomena have direct hydrological consequences, leading to overloading of sewage systems, local flooding and erosion of surface watercourses. From the point of view of flood risk management, it is particularly important to note that since 2010, not only has the frequency of events increased, but they have also become more concentrated in the summer months (June–August), which may be due to the increasing seasonality of convective storm systems as well as the urban heat island effect, which intensifies local convection processes [42, 43]. Observations show that over the analysed years, the number of intense rainfall events does not show a clear upward trend, but periods of significantly increased frequency can be identified, especially after 2007. This is consistent with national trends indicating an increase in the number of extreme rainfall events associated with climate change, which has also been observed in other Polish cities with a similar urban structure [32, 44].

The increase in the number of precipitation events above 20 mm is significant in the context of the functioning of the urban drainage system in Bialystok, which, as indicated in previous chapters, is overloaded in many places and partially outdated. The increased number of such rainfall events results in more frequent overloading of storm drains and local flooding, especially in densely built-up areas without effective retention

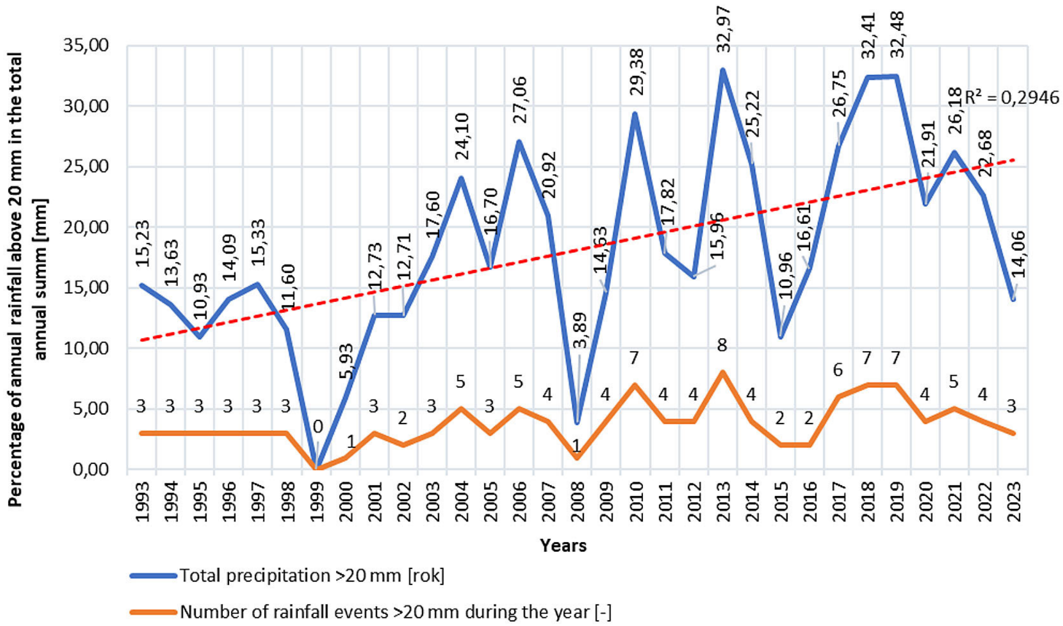

Figure 5. Share of annual precipitation above 20 mm in the total annual sum in the years 1993–2023 in the city of Białystok

areas. According to literature data [45], even a single rainfall of 20–30 mm can lead to flooding of roads and basements in conditions of inadequate infrastructure. Thus, the results of the analysis confirm the need to implement adaptation strategies based on green-blue infrastructure (GBI), which aim to disperse and retain excess rainwater directly at the point of occurrence.

In the context of the increasing frequency of extreme events, the analysis of the co-variation between air temperature and intense rainfall is becoming increasingly important. For the Bialystok area, a city with specific hydrological and geographical conditions, this study is particularly important due to the synergistic impact of rising temperatures and increasing rainfall on the risk of urban flooding. The analysis covered data from a 31-year period (1993–2023), comparing average annual air temperatures with rainfall totals exceeding the threshold of 20 mm per day. The results presented in Figure 6 reveal a clear upward trend for both average temperatures and intense rainfall.

It has been observed that years characterised by higher average air temperatures correlated with

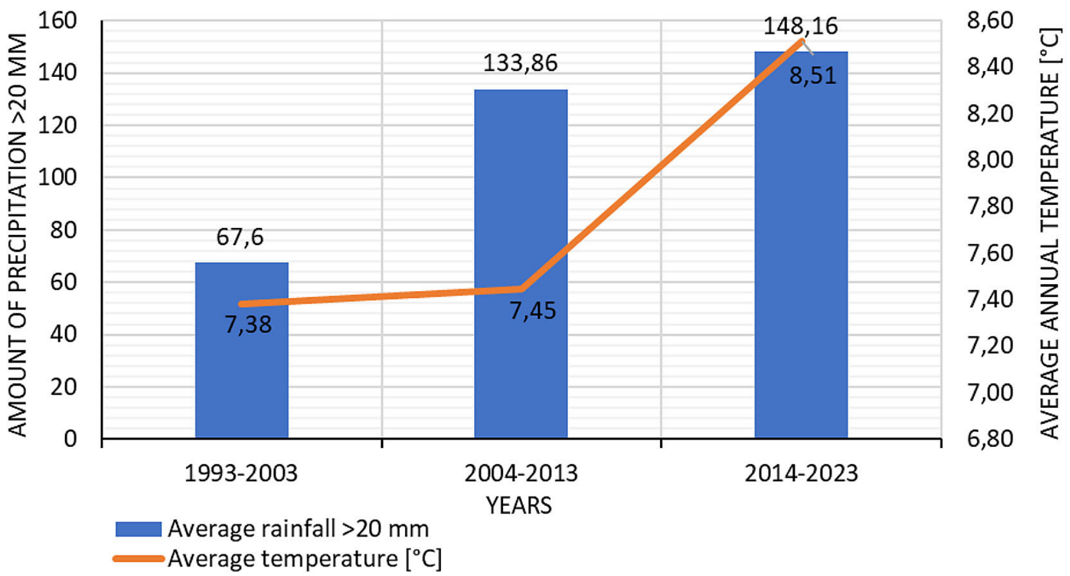

Figure 6. Relationship between average air temperature and precipitation above 20 mm

higher total daily extreme precipitation. For example, in the years 2010–2023, when the average temperature exceeded 8.5 °C, the number of days with precipitation above 20 mm was significantly higher than in previous decades. This relationship indicates a potential intensification of the hydrological cycle in a warming climate – a phenomenon confirmed by numerous scientific studies pointing to an increased capacity of the atmosphere for water vapour as temperatures rise [46, 41]. Similar correlations are also described in studies conducted for cities in Central Europe [32, 47], which allows the results obtained for Bialystok to be placed in a broader international context.

The calculated Pearson correlation coefficient for the data studied was r = 0.67, which indicates a moderate but statistically significant positive relationship between the variables studied. This result confirms the hypothesis that, in conditions of rising global temperatures, more frequent and intense rainfall should be expected – particularly dangerous in the context of heavily urbanised areas, such as the centre of Bialystok, characterised by a large proportion of impermeable surfaces and limited retention capacity. The results obtained indicate the need to take into account air temperature variability as a factor contributing to the increased risk of flooding in cities. This is also confirmed by the IPCC report [33], which highlights the increasing frequency of so-called 'flash floods' in temperate zones, resulting from the interaction between climate warming and heavy rainfall. In the case of Bialystok, the increased temperature not only intensifies evaporation and local moisture circulation, but also, through the urban heat island effect, may additionally promote convection and the initiation of storm rainfall.

Taking the above into account, the areas at risk of flooding are marked in Figure 7. These include areas located in the north-western part of the city along the Suprasl and Biala rivers. The area stretches from Aleja Jana Pawla II Street at the Antoniuk Park and around the breeding ponds in the Dojlidy housing estate in the south-eastern part of the city. Transport routes passing through the Biala River valley and its tributaries are also at risk. The flood risk posed by the river is mainly due to its overload with rainwater, and the construction of the riverbed in the form of narrowings further increases the risk. However, the increasing reduction in permeable areas combined with increased rainfall intensity leads to an increased risk of flash floods. The areas particularly at risk include the city centre and housing estates with dense development and insufficiently protected depressions in the terrain [17, 35].

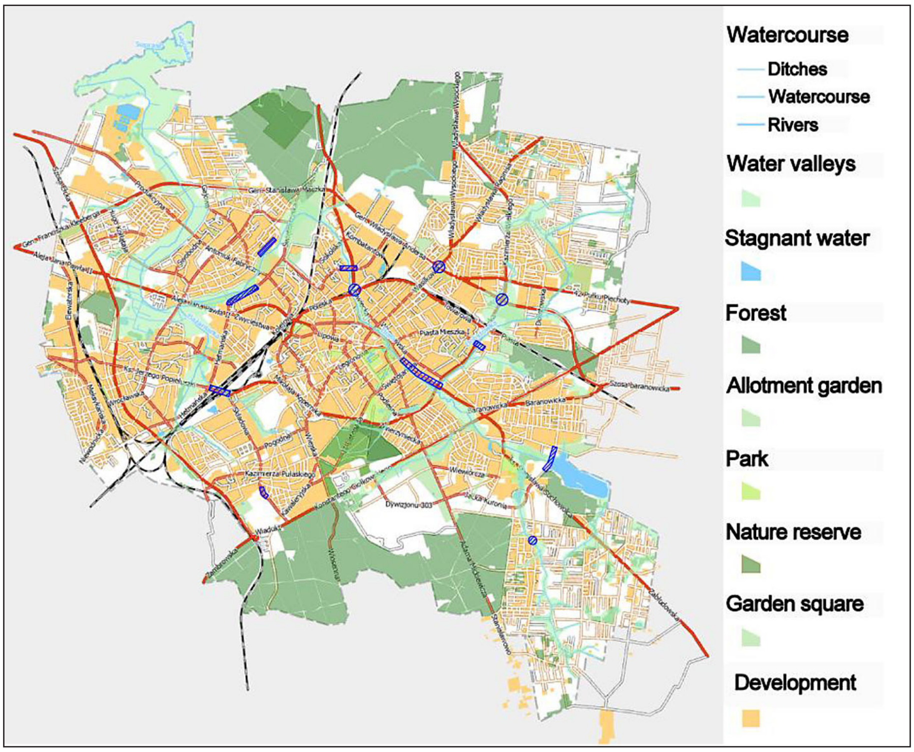

Figure 7. Map of areas at high risk of flooding [17, 35, 48]

On 7 May 2017, as a result of rainfall lasting 7 hours, 81.8 mm of water fell, with an intensity of 11.7 mm/h. This resulted in extensive flooding of the city, while the Biala River, overflowing several metres beyond the shoreline in some places, turned into a raging river. The water level on the streets reached dozens of centimetres. Many basements of residential buildings were flooded and cars were destroyed. The water also reached single-family housing areas located near the river valley. Figure 7 shows the main areas affected by the flood.

Identification of flood risk factors

In the light of hydrological and climatic analyses carried out, the city of Bialystok shows increasing vulnerability to the occurrence of flood phenomena, especially in the form of so-called flash floods resulting from heavy rainfall. Evaluation of precipitation data from 1993 to 2023 to date has shown not only an increase in total precipitation totals above 20 mm, but also an increase in the frequency of their occurrence. These trends, combined with extensive urbanisation and the limited capacity of drainage systems, lead to the occurrence of localised flooding, particularly in densely built-up parts of the city. This chapter identifies the key determinants of flood risk in Bialystok, including geographical, climatic, hydrological and anthropogenic conditions, the interaction of which influences the scale and intensity of risks. This approach is in line with current paradigms of urban climate risk assessment, where the analysis should take into account not only meteorological data but also local morphology and land use.

Geographical and morphological factors

One of the main factors contributing to urban flooding in Bialystok is the morphology of the terrain. The city is located on the border of the Bialystok Upland, which is part of the North Podlasie Lowland, at an altitude of 120 to 160 metres above sea level. The terrain is varied, with numerous glacial formations such as terminal moraines, kames and eskers, which shape the local slopes and surface runoff directions. Lower-lying areas, especially along the Biała River valley and its tributaries, are natural corridors for rainwater flow, the retention of which is now limited due to intensive urbanisation and land sealing. As noted by Lu et al. [49], in cities with diverse terrain, local depressions and river valleys are of key importance, which, in the absence of adequate retention infrastructure, become the main axes of flood runoff. In Bialystok, areas at particular risk of flooding are located along the Biala Valley – both in the city centre and in the Antoniuk and Nowe Miasto housing estates, where significant impermeable surfaces and outdated stormwater drainage systems are additional factors contributing to the risk. Natural depressions in the terrain, often located in the vicinity of transport routes or urbanised areas, fill up quickly with water in the event of heavy rainfall, as confirmed by observations from 2007, 2009 and 2017, when extensive flooding occurred [34]. In addition, as spatial analyses indicate, areas with a greater slope are more vulnerable to rapid water runoff, which, combined with the lack of indirect retention, increases the speed and force of flood flow. The literature of the subject describes these morphological features as classic determinants of increased urban flood risk in urbanised areas [14, 38, 39, 41, 44]. According to research by Agonafir et al. [39], areas with significant differences in elevation and intensive development are particularly susceptible to rapid flooding, especially when catchment areas are small and the concentration time of precipitation is short. In the case of Białystok, such conditions occur in the Biala River basin, whose area (approx. 133 km^2) and relatively low average flow (1.2 m^3/s) do not allow for the effective drainage of large amounts of water in a short time.

Climatic factors

The climate of Bialystok, classified as temperate cool with transitional characteristics between maritime and continental, is characterised by high annual and seasonal variability in precipitation and significantly varied air temperatures. According to data from the GUS, weather portals and Environment protection Institute [18–20], the average annual precipitation in Bialystok fluctuates around 580–650 mm, but in the last three decades there has been an upward trend in both annual precipitation and the frequency of extreme precipitation events. In particular, there has been an increase in the number of precipitation events exceeding 20 mm per day, which, as shown in previous chapters, have a direct impact on the increased risk of urban flooding. These phenomena are consistent with broader climate observations in the Central and Eastern European region, where climate change is leading to an increase in the frequency of so-called ‘torrential rains’ and intense short-term precipitation episodes [32]. In the case of Bialystok, the increase in air temperature, averaging +0.35 °C per decade (1993–2023), leads to the intensification of convective processes, increasing the risk of violent downpours, especially in the summer months. Importantly, statistical analysis has shown a positive correlation between the increase in average annual temperature and annual precipitation >20 mm, which indicates the synergistic effect of both variables on flood conditions.

International literature points out that changing climatic conditions in lowland cities, especially those with limited biologically active areas, lead to an increased risk of so-called urban flash floods [50–52]. Bialystok, as a densely built-up city with a large proportion of impermeable surfaces, is particularly vulnerable in this context. Climate change, manifested not only by rising temperatures but also by prolonged periods of drought interrupted by episodes of torrential rain, disrupts the existing water balance, hindering infiltration and increasing the rate of surface runoff. In addition, the growing number of so-called hot and tropical days, also recorded in Bialystok, contributes to soil drying, which becomes less absorbent and therefore less effective in absorbing rainwater in the event of sudden rainfall. This phenomenon, known as the ‘dry sponge’ effect, has been widely described in studies on urban hydrology [39]. As a result, even moderate rainfall can lead to rapid runoff and local flooding, especially in areas without retention infrastructure.

Hydrological factors

The hydrological conditions in Bialystok are one of the key components determining the local flood risk. The city’s water network, dominated by the Biala River and its tributaries, such as the Dolistowka, Bazantarka and Horodnianka, is characterised by limited retention capacity and high sensitivity to heavy rainfall. The Biala River, which is the main recipient of rainwater from the city’s storm drainage system, is characterised by a low base flow (average 1.2 m^3/s), a slight gradient (approx. 0.2%) and a relatively shallow and narrow riverbed with a variable cross-section, often artificially transformed. This hydrological configuration is conducive to rapid changes in water levels during rainfall episodes, and the river’s low retention capacity leads to its rapid overload. Hydrological data from measurements taken on the Biala River indicate that during heavy rainfall, the water level can rise by several dozen centimetres within a few dozen minutes, leading to flooding and local urban flooding. This type of river response resembles the characteristics of mountain streams, where flow variability reaches a ratio of 1:200 – which was also observed in the Biala valley during measurements taken in 2009. In a lowland city such as Białystok, this type of dynamics is a clear sign of anthropogenic pressure, resulting primarily from excessive urbanisation and a reduction in infiltration areas [15].

According to the literature one of the main factors influencing the hydrological resilience of urban systems is the adaptability of watercourses, e.g. through natural floodplains, meanders or buffer zones [41, 53]. Meanwhile, in Bialystok, many sections of the Biala River have been regulated, built up or narrowed, which limits the possibility of slowing down the runoff and leads to the so-called ‘fast runoff’ effect. In addition, urbanisation processes have caused the sealing of areas adjacent to the riverbed, including through the construction of housing estates, shopping centres and the development of former industrial areas, which has reduced surface retention and rainfall infiltration capacity. Another significant hydrological problem is the insufficient flow capacity of drainage ditches and numerous unnamed watercourses, which, according to technical studies, require deepening, cleaning or regulation. Their blockage or overflow leads to local water stagnation, which during extreme rainfall can result in flooding of roads, buildings and critical infrastructure, such as water treatment plants and power grids.

In international literature, many studies point to the critical importance of maintaining hydrological continuity in urban areas, including avoiding excessive concreting of river valleys and protecting natural and semi-natural retention areas [54, 55]. In this context, the current rainwater management policy in Bialystok needs to be redefined, particularly in terms of strategic spatial planning and the management of river valleys as key hydrological buffers.

Urbanisation and infrastructure factors

The rapid urban development of Bialystok in recent decades is a significant factor increasing the risk of urban flooding. According to data from the Central Statistical Office, the built-up area of the city increased by over 4% between 2015 and 2023, from 51.26 km² to 53.36 km², with a simultaneous 70% increase in the number of building permits issued for residential buildings. The building structure is dominated by residential areas (over 40%), which, with dense spatial intensification, results in a significant reduction in biologically active areas and open spaces that can serve as retention areas. The urbanisation of these areas leads to the progressive degradation of the local water balance and the worsening of urban flood impact [18]. In recent years, there has also been strong investment pressure on the outskirts of the city. The spatial expansion of Bialystok takes place at the expense of areas previously used for agriculture or as informal green and wetland areas. These areas are now the site of new housing estates, shopping centres, service facilities and industrial facilities, which translates into a significant increase in sealed areas, such as roads and car parks. It translates into a significant increase in sealed surfaces, such as roads, car parks and building roofs. Such surfaces completely prevent rainwater infiltration and increase the rate of surface runoff, which, in heavy rainfall, leads to a sharp increase in the load on the urban drainage infrastructure. At the same time, river valleys are being transformed and former wetlands, which historically served as natural hydrological buffers, are being drained. Development along the Biała River and its tributaries often encroaches on floodplains and seasonally wet areas, which, if their structure were preserved, would allow excess water to be dispersed. This process is particularly evident in the southern and north-eastern parts of the city, where peat bogs and local wetlands used to exist. As research shows [56,57], the degradation of such areas not only reduces retention, but also limits the city's ability to adapt to climate change.

Spatial analysis showed that areas with a high degree of surface sealing, located in river valleys and in drainage-free zones, are particularly susceptible to flooding. Many older city districts, densely built-up, are characterised by a low proportion of tall greenery and a lack of infrastructure to retain rainwater in situ. The situation is exacerbated by the inadequacy of the existing stormwater drainage network – a hydraulic analysis carried out by AquaRD in 2018 showed that over 2.250 sections of the drainage system operate at full capacity or under pressure, which clearly suggests that the system is overloaded during heavy rainfall. Although the most obvious solution would be to modernise the network by increasing the diameter of the sewers, this would require complex and costly engineering calculations. This is because changing the cross-section of a single section affects the flow conditions throughout the entire network. Therefore, under the current conditions, it is recommended to use supporting solutions, such as local retention reservoirs, rain gardens, infiltration ditches or drainage systems, which can partially take over the functions of the sewage system and reduce surface runoff [30]. Sewer blockages and insufficient pipe diameters (cross-sections from 0.2 to 2.0 m) are the result of a mismatch with current climatic and structural realities. Some sections of the sewerage system do not have documented inlet elevations, manhole bottoms or data on their location in relation to the terrain, which significantly hinders effective hydraulic analysis. The literature points out that such documentation gaps in drainage systems constitute a significant limitation in the implementation of integrated rainwater management strategies [58, 59].

An additional problem is the lack of adequately developed retention infrastructure. Although the construction of retention reservoirs was planned in municipal strategies, their implementation encountered procedural and financial difficulties. Some investments were cancelled due to a lack of contractors or exceeding cost estimates. As a result, Bialystok still has an insufficient system of distributed urban retention – including infiltration reservoirs, rain gardens and green roofs – which was identified as a weakness of the city in the Development Strategy until 2030 [17].

According to the approach presented in the literature [8, 9, 16, 60], effective urban flood prevention requires the implementation of GBI, which is an alternative to costly and inflexible sewerage expansion. Integrating this approach with spatial planning allows rainwater to be retained close to where it falls, increasing infiltration and reducing the risk of hydraulic overload. In the case of Bialystok, intensive urbanisation combined with limited retention capacity of the area and inadequate drainage infrastructure directly translates into an increased likelihood of flash floods.

Urban heat island (UHI)

The urban heat island (UHI) phenomenon has been observed in cities. Research conducted by Berg et al. [61] suggest that UHI has an impact on the increase in the frequency and amount of precipitation as a result of the accumulation of higher temperatures in urban areas compared to suburban areas by several to a dozen degrees Celsius. This leads to the intensification of convective processes in the air and vertically structured clouds, which are mainly characterised by heavy rainfall. In addition, according to Ward [62], warmer air has a higher water capacity, which in turn leads to increased precipitation, as confirmed by analyses of precipitation and atmospheric temperature in Bialystok [63]. Sauter et al. [64] report that the intensity of the UHI depends mainly on the degree of surface sealing, building density and the economic character of the city. Studies conducted in Bialystok showed a clear occurrence of an urban heat island, which reached its maximum in the evening and was highest in spring in the annual perspective. The highest measured difference between the city centre and the outskirts was 8.2 °C [60,61,62,63,65]. According to the Institute of Meteorology and Water Management – National Research Institute, the average temperature in Poland in 2024 was 10.9 °C, which was 2.2 °C higher than the long-term average for 1991–2020, making it an extremely warm year. For comparison, in 2023, the average annual temperature was 9.3 °C. In Bialystok, in January, August, September and December 2024, average temperatures were classified as extremely warm, exceeding 0.95 quantiles from the long-term average. From March to July and in December, the thermal classification was determined to be abnormally warm in the range of 0.90–0.95 quantile [36].

The phenomenon of rapid growth of impermeable surfaces, combined with a lack of proportional development of urban greenery and open spaces, has a direct impact on the local water balance and increases the risk of flash floods [66]. This problem is particularly evident in densely built-up areas of the city, which do not have an effective retention system and whose sewage infrastructure often operates at the limits of its capacity. Richards et al. [67] note that in view of these challenges, it is necessary to strategically transform the urban spatial structure, taking into account local hydrological conditions and the retention potential of individual areas. Shirao recommends [65] that an important element of this approach should be to strengthen the role of tall and low greenery, restore the infiltration capacity of biologically active areas, and implement nature-based solutions such as infiltration basins, rain gardens, green roofs and infiltration systems. These measures, integrated with spatial planning policy and supported by local climate and hydrological data, can effectively reduce the negative effects of urbanisation and increase the city's resilience to changing climatic conditions.

In summary, the urban drainage system in Bialystok is currently under severe pressure due to intensified development, climate change and limited possibilities for technical expansion of the sewage network. Although measures are being taken to modernise infrastructure and implement nature-based solutions, the effectiveness of these measures will depend on their scale, consistency of implementation and integration with spatial planning. The preservation and development of the urban greenery system is also of key importance, as it plays a significant role in stormwater management and increasing the city's resilience to extreme events, in addition to its recreational function.

Social and organisational factors

On top of environmental and infrastructure challenges, social and organisational factors play a big role in shaping flood risk in cities, affecting both how well emergency response systems work and how aware and ready local communities are. In the case of Bialystok, the increasing threat of flash floods and flooding reveals a number of shortcomings in risk management and social resilience to hydrological hazards. One of the most important risk factors is the insufficient level of education and public awareness of flood hazards. In many settlements located in river valleys, especially in urban areas with a high degree of sealing, residents are unaware of potential flood scenarios, which limits their ability to respond appropriately in emergency situations (Fu et al., 2025). There is also a lack of sufficient dissemination of information on local evacuation plans, emergency points and rules of conduct in the event of flooding of critical infrastructure [68].

From an organisational point of view, the fragmentation of institutional responsibility for water management and natural hazards is a significant barrier to effective risk management [68]. Competences in this area are scattered among various local government units, central institutions (such as the State Water Holding – Polish Waters) and private entities responsible for technical infrastructure. As indicated in the literature, the lack of a coordinated flood risk management system can lead to organisational gaps and delays in taking preventive measures, especially in the case of sudden floods [69]. Another problem is the insufficient consideration of flood risk in planning documents and localisation decisions. As shown in the analysed cases, decisions on development were often made without sufficient consideration of local hydrological conditions, such as proximity to watercourses, terrain slope or susceptibility to rainwater stagnation. The lack of an integrated planning policy combining urbanisation objectives with climate adaptation exacerbates the city's vulnerability to extreme weather events [68,69]. In social terms, increasing suburbanisation and development pressure are also significant, leading to the rapid transformation of peripheral areas into new housing estates, often without full hydrotechnical protection. In such cases, sewage and drainage infrastructure is built late or is inadequate for the scale and intensity of development, which increases the risk of local flooding already at the stage of operation of new investments [8, 9].

Research conducted in other European cities shows that soft factors are key to reducing flood risk, such as the involvement of local communities in spatial management, participation in decision-making processes, and local civic initiatives for the development of green-blue infrastructure [68, 69]. In Białystok, activities of this type are still incidental in nature and are mainly limited to projects implemented as part of the participatory budget or occasional information campaigns.

Recommended adaptations in light of research findings

The analysis of urban flood risk in Bialystok presented in this paper showed a clear link between increasing rainfall intensity, an increase in sealed surfaces and the limited retention capacity of the urban area. Geographical and climatic conditions – including varied terrain, the presence of heavily transformed river valleys and the concentration of rainfall in short time intervals – combined with urbanisation pressure and insufficient development of drainage infrastructure, lead to an increased flood risk. In this context, it is necessary to develop and implement multidimensional adaptation strategies that integrate engineering, nature-based and planning solutions. The key direction of action should be the promotion and development of green-blue urban infrastructure. Dispersed forms of retention, such as rain gardens, infiltration basins and green roofs, are an effective way of mitigating surface runoff during heavy rainfall in highly urbanised areas. This is confirmed by numerous studies conducted in cities with similar hydrological conditions, which have shown that the implementation of elements with high absorption potential significantly reduces the frequency of flash floods and reduces the load on sewage systems [70, 71].

The revitalisation of urban river valleys – in particular the Biala River – should include not only hydrotechnical measures, but also the restoration of natural forms of retention, including floodplains, wetlands and riverside vegetation. The current investment pressure, leading to the development of formerly green spaces, exacerbates the problem of urban retention and contributes to the concentration of losses in critical areas. Particularly worrying is the intensive use of areas adjacent to rivers for residential and service investments, which increases the vulnerability of these areas to the effects of heavy rainfall and sudden floods. An equally important element of adaptation should be the inclusion of flood risk issues in spatial planning. It is necessary to fully integrate current flood hazard maps and rainfall flow models into the city's planning documents. Restricting development in low-lying areas, in areas directly adjacent to watercourses, and revising existing location decisions in light of projected climate change are priority actions. The experience of other European cities shows that adaptation to extreme weather events requires the parallel implementation of planning and investment instruments based on cooperation between different sectors [7–9, 15, 24].

The rainwater drainage system in Bialystok requires comprehensive modernisation. Previous studies commissioned by the local officials [30] showed that a significant part of the sewage system operates at full capacity, which contributes to flooding, backflow and local flooding. Given the city's limited financial resources, it seems reasonable to implement intermediate solutions, such as buffer tanks, absorption ditches and the separation of combined sewer systems. However, the optimisation of the drainage system must take into account not only hydraulic conditions, but also climate change and long-term urbanisation trends [17]. The social and organisational aspects cannot be overlooked either. As Derkzen et al. [72] point out, environmental education can increase support for effective adaptation measures. Insufficient awareness among residents about the causes and effects of urban flooding limits the effectiveness of preventive measures. Therefore, it is important to conduct systematic education and develop local risk management plans that take into account social participation and the diverse needs of residents. These measures should be complemented by the development of early warning systems and the digitisation of hydrological data, enabling real-time monitoring of hazards [9–11, 17].

Based on the findings above, it's recommended to develop an adaptation strategy for the city of Bialystok that combines meteorological data, hydrological models, and local knowledge into a coherent risk management system. Its effectiveness will depend on data availability, institutional involvement, and consistent consideration of climate conditions in spatial and investment policies. A shift from a reactive to a proactive approach is now a necessity if the goal is to ensure the city's resilience to future flood threats and maintain a high quality of life for its residents [9, 11, 38].

CONCLUSIONS

The main factors increasing the risk of urban flooding in Bialystok are (i) heavy rainfalls, which increase the overload of the main rainwater receiver in the form of the Biala River, (ii) buildings in the river valley and (iii) an increase in impermeable surfaces. Studies of precipitation and air temperature conducted between 1993 and 2023 showed an upward trend in the changes occurring. The urban heat island effect exacerbates the weather phenomena. A relatively strong correlation of 0.67 was observed between the increase in average annual air temperatures and the total annual rainfall above 20 mm. Annual rainfall totals above 20 mm show an average increase in the share of total annual rainfall of 5% per decade, with a stable frequency of rainfall events.

In order to protect the city of Bialystok from the threat of flooding, it is essential to monitor the extent of predicted changes in the local climate to ensure long-term safety, while limiting the amount of work and costs involved in modernising the infrastructure in a short period of time, as financial issues are a frequent obstacle to the introduction of new technologies.

The urban drainage system in Bialystok is currently under severe pressure due to intensified development, climate change and limited possibilities for technical expansion of the sewage network. Although measures are being taken to modernise the infrastructure and implement nature-based solutions, the effectiveness of these measures will depend on their scale, the consistency of their implementation and their integration with spatial planning.

Synergistic rise in temperature and changes in the seasonal distribution of precipitation is observed because of climate change, an increase in the frequency and intensity of extreme precipitation. It is currently one of the key sources of pressure on the urban hydrological system. In the absence of appropriate adaptation measures, such as the implementation of distributed retention systems or spatial planning that takes into account infiltration zones, the risk of flooding will steadily increase.

Transformed watercourses, limited natural retention, overloaded sewage systems and loss of infiltration areas are one of the fundamental components of flood risk. Their impact is particularly evident in the context of increasingly frequent extreme rainfall events, which destabilise the water balance and increase pressure on the city's technical infrastructure. Green-blue infrastructure is a solution that should be regularly implemented in urban architecture. It is necessary to strategically transform the urban spatial structure, taking into account local hydrological conditions, retention possibilities and the need to implement nature-based systemic solutions. Efforts should be made to strengthen the functions of high and low green areas, revitalise existing biologically active spaces, and actively implement distributed retention systems such as rain gardens, infiltration basins and green roofs. These measures should be integrated into spatial planning policy and linked to climate and hydrological data in order to effectively counteract the effects of urbanisation and ensure the city's resilience to intensifying climate phenomena.

In order to adapt and protect against urban flooding, it is necessary to develop a comprehensive system of education, information and public participation, supported by modern digital tools such as warning applications, real-time hazard maps and the integration of meteorological data with the urban crisis management system. At the same time, better integration of spatial, environmental and crisis policies at the city level is needed to effectively counteract the effects of flooding and increase the city's resilience to changing climatic conditions.

REFERENCES

1. Yuan Y, Zhai P, Chen Y, Li J. Hourly extreme precipitation changes under the influences of regional and urbanization effects in Beijing. International Journal of Climatology. 2020; 41:1179–1189. https://doi-org.bazy.pb.edu.pl/10.1002/joc.6784
2. Gizaw MS, Thian Yew Gan. Possible impact of climate change on future extreme precipitation of the Oldman, Bow and Red Deer River Basins of Alberta. International Journal of Climatology. 2016; 36: 208–224. https://doi-org.bazy.pb.edu.pl/10.1002/joc.4338
3. Luo Z, Liu J, Zhang S, Shao W, Zhou J, Zhanga L. Impact of urbanization factors considering artificial water dissipation on extreme precipitation: A numerical simulation of rainfall in Shanghai. Quarterly Journal of the Royal Meteorological Society. 2023. https://doi-org.bazy.pb.edu.pl/10.1002/qj.4508
4. AGROMETEO Instytut Meteorologii i Gospodarki Wodnej – PIB. Słownik pojęć. Available online: https://agrometeo.imgw.pl/slownik_pojec (accessed on 20 June 2025).
5. Starostwo Powiatowe Żywiec. Natężenie opadów – klasyfikacja. Available online: https://monitoring.zywiec.powiat.pl/pliki/Natezenie_opadow-klasyfikacja.pdf (accessed on 20 June 2025)
6. Blum AG, Ferraro PJ, Archfield SA, Ryberg KR. Causal effect of impervious cover on annual flood magnitude for the United States. Geophysical Research Letters. 2020; 94–8276. https://doi.org/10.1029/2019GL086480
7. Intergovernmental Panel on Climate Change. Climate Change 2023. Synthesis Report. Summary for Policymakers. IPCC, Geneva, Switzerland, 1–34, https://doi.org/10.59327/IPCC/AR6-9789291691647.001. Available online: https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_SPM.pdf (accessed on 20 June 2025)
8. Bezak N, Raska P, Macha J, Louda J, Zupanc V, Slavíkova L. Investigating the public perception of green, hybrid and grey flood risk management measures in Europe. Progress in Disaster Science. 2024; 23: 100360.
9. Steinhausen M,Paprotny D, Dottori F, Sairam N, Mentaschi L, Alfieri L, Lüdtke S, Kreibich H, Schröter K. Drivers of future fluvial flood risk change for residential buildings in Europe. Global Environmental Change. 2022; 76: 102559. https://doi.org/10.1016/j.gloenvcha.2022.102559
10. Dyrektywa 2007/60/WE Parlamentu Europejskiego I Rady z dnia 23 października 2007 r. w sprawie oceny ryzyka powodziowego i zarządzania nim. Available online: https://eur-lex.europa.eu/legal-content/PL/TXT/HTML/?uri=CELEX:32007L0060 (accessed on 19 June 2025)
11. Sprawozdanie specjalne nr 25/2018. Dyrektywa powodziowa - nastąpiły postępy w ocenie ryzyka, jednak wymagana jest poprawa planowania i wdrażania. European Court of Auditors PL 2018. Available online: https://www.eca.europa.eu/lists/ecadocuments/sr18_25/sr_floods_pl.pdf (accessed on 21 June 2025)
12. Moody's Investors Service. P&C Insurance and Reinsurance – Global. Climate change risks outweigh opportunities for P&C (re)insurers. 14 March 2018. Available online: https://legacy-assets.eenews.net/open_files/assets/2018/03/15/document_cw_01.pdf (accessed 21 June 2025)
13. Państwowe Gospodarstwo Wodne – Wody Polskie. Raport z przeglądu i aktualizacji wstępnej oceny ryzyka powodziowego w 3 cyklu planistycznym. Załącznik nr 7. Powódź we wrześniu 2024. Ver. 1.00; 20.01.2025. Available online: https://powodz.gov.pl/www/powodz/aWORP/3W-12_Zal7_Raport_Powodz_we_wrzesniu_2024_20250124_v1.00.pdf (accessed on 21 June 2025)
14. Hammond MJ, Chen AS, Djordjević S, Butler D, Mark O. Urban flood impact assessment: A state-of-the-art review. Water Journal. 2013; 12(1): 14–29. https://doi-org.bazy.pb.edu.pl/10.1080/1573062X.2013.857421
15. Tyszewki S, Kardel I. PRO WODA. Studium hydrograficzne doliny rzeki Białej z wytycznymi do zagospodarowania rekreacyjnowypoczynkowego i elementami małej retencji oraz prace hydrologiczne niezbędne do sporządzenia dokumentacji hydrologicznej. Wrzesień 2009, Warszawa.
16. Dumieński G, Pasiecznik-Dominiak A, Tiukało A. Społeczno-ekonomiczna ocena zagrożenia powodziowego gmin w Polsce. Oficyna Wydawnicza Politechniki Wrocławskiej. 2015; 6: 110–125.
17. Strategia rozwoju Miasta Białegostoku do 2030 roku. Załącznik do Uchwały Nr XLVI/666/21 Rady Miasta Białystok z dnia 20 grudnia 2021 r. Available online: https://www.bialystok.pl/pl/dla_mieszkancow/rozwoj_miasta/strategia-rozwoju-miasta-bialegostoku-do-2030-roku.html (accessed on 22 June 2025)
18. Główny Urząd Statystyczny. Położenie i warunki naturalne. 2023. Available online: https://bialystok.stat.gov.pl/files/gfx/bialystok/pl/

defaultstronaopisowa/1102/1/1/polozenie_warunki_naturalne_8.pdf (accessed on 22 June 2025)

19. www.weatheronline.pl Białystok. Liczba dni ze śniegiem. Available online: https://www.weatheronline.pl/weather/maps/city?LANG=pl&PLZ=_____&PLZN=_____&WMO=12295&CONT=plpl&R=0&LEVEL=162&REGION=0001&LAND=RS&MOD=tab&ART=SNT&NOREGION=0 (accessed on 24 June 2025)
20. Główny Inspektorat Ochrony Środowiska. Charakterystyka strefy dla potrzeb oceny jakości powietrza. Available online: https://powietrze.gios.gov.pl/pjp/zone/characteristic/PL2002/2019/true# (accessed on 24 June 2025)
21. www.bialystok.pl file:///C:/Users/emili/Downloads/2ipolozenieelemabiotyczne33.pdf
22. Mapy.geoportal.gov – Rolnictwo. Available online: https://mapy.geoportal.gov.pl/imapnext/imap/index.html?moduleId=modulRol&mapview=53.115752%2C23.121937%2C5000s (accessed on 23 June 2025)
23. Informator Białostocki. Info.białystok.pl. Gleby. Available online: http://www.info.bialystok.pl/region/lasy/gleby/obiekt.php#:~:text=Panuj%C4%85cymi%20typami%20gleb%20s%C4%85%20gleby,gleby%20bielicowe%20i%20gleby%20rdzawe (accessed on 24 June 2025)
24. Państwowe Gospodarstwo Wodne – Wody Polskie. Karta jednolitej części wód powierzchniowych rzecznych. Rzeka Biała. Available online: http://karty.apgw.gov.pl:4200/api/v1/jcw/pdf?code=RW2000102616899 (accessed on 22 June 2025)
25. Mapy.geoportal.gov.pl - Geoportal krajowy. Available online: https://mapy.geoportal.gov.pl/imap/Imgp_2.html (accessed on 23 June 2025)
26. Urząd Statystyczny W Białymstoku. Diagnoza sytuacji społecznej, gospodarczej i przestrzennej Miasta Białystok. 2021. Available online: https://bialystok.stat.gov.pl/files/gfx/bialystok/pl/defaultstronaopisowa/85/18/1/diagnoza_strategiczna_-_wersja_ostateczna_v._23.02.2022.pdf (accessed on 23 June 2025)
27. Państwowe Gospodarstwo Wody Polskie. Available online: https://www.gov.pl/web/wody-polskie (accessed on 20 June 2025)
28. Gis-support.pl. Co to jest QGIS? Available online: https://gis-support.pl/co-to-jest-qgis/#:~:text=QGIS%20(dawna%20nazwa%20Quantum%20GIS)%20to%20darmowy%2C,jest%20jako%20projekt%20Open%20Source%20Geospatial%20Foundation (accessed on 24 June 2025)
29. Available online: https://download.qgis.org/qgisdata/2.8/pl/docs/user_manual/preamble/features.html (accessed on 24 June 2025)
30. AquaRD. Aktualizacja programu zagospodarowania wód opadowych i rozbudowy kanalizacji deszczowej w granicach administracyjnych miasta Białegostoku wraz z racjonalnym rozmieszczeniem zbiorników retencyjnych, rowów i odparowników. ETAP I. 2018.
31. Urząd Statystyczny W Białymstoku. Ludność. Available online: https://bialystok.stat.gov.pl/files/gfx/bialystok/pl/defaultstronaopisowa/1094/1/1/ludnosc_11.pdf (accessed on 23 June 2025)
32. Kundzewicz, Z., Hov, Ø., Okruszko, T. (Eds.). Zmiany klimatu i ich wpływ na wybrane sektory w Polsce. 2017.
33. IPCC, 2018: Global Warming of 1.5 °C. An IPCC Special Report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte V, Zhai P, Pörtner H-O, Skea DRJ, Shukla PR, Pirani A, Moufouma-Okia W, Péan C, Pidcock R, Connors S, Matthews JBR, Chen Y, Zhou X, Gomis MI, Lonnoy E, Maycock T, Tignor M, and Waterfield T (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 616. https://doi.org/10.1017/9781009157940
34. Biuletyn Informacji Publicznej Urzędu Miejskiego w Białymstoku. Plan Adaptacji Miasta Białystok do zmian klimatu do roku 2030. Id: 73397294-6FF2-4630-9F3E-BC9821E7AE45
35. Państwowy Instytut Geologiczny. Studium Wykonalności na potrzeby Atlasu geologiczno-inżynierskiego Białegostoku. Warszawa, 2021. http://geoportal.pgi.gov.pl/css/atlasy_gi/images/studium-bialystok.pdf
36. Instytut Meteorologii i Gospodarki Wodnej. Państwowy Instytut Badawczy. Biuletyn państwowej służby hydrologiczno-meteorologicznej. Rok 2024. Nr 13 (189). https://danepubliczne.imgw.pl/data/dane_pomiarowo_obserwacyjne/Biuletyn_PSHM/Biuletyn_PSHM_2024_ROCZNY.pdf
37. PAŃSTWOWE GOSPODARSTWO WODNE – WODY POLSKIE. Karta jednolitej części wód powierzchniowych rzecznych. Rzeka Biała. Available online: http://karty.apgw.gov.pl:4200/api/v1/jcw/pdf?code=RW2000102616899 (accessed on 22 June 2025)
38. Fu X, Xue F, Liu Y, Chen F, Yang H. Evaluation of urban flood susceptibility under the influence of urbanization based on shared socioeconomic pathways. Land 2025; 14: 621. https://doi.org/10.3390/land14030621
39. Agonafir C, Lakhankar T, Khanbilvardi R, Krakauer N, Radell D, Devineni N. A review of recent advances in urban flood research. Water Security, 2023; 19: 100141. https://doi.org/10.1016/j.

wasec.2023.100141

40. Wibig J. Klimat i bioklimat miast. Łódzkie Towarzystwo Naukowe, Łódź 2016.
41. Millán M. Millán, Extreme hydrometeorological events and climate change predictions in Europe, Journal of Hydrology, 2014; 518B: 206–224. https://doi.org/10.1016/j.jhydrol.2013.12.041
42. Hanson S., Nicholls R, Ranger N, Hallegatte S, Corfee-Morlot J, Herweijer C, Chateau J. A global ranking of port cities with high exposure to climate extremes. Climatic Change. 2011; 104: 89–111. https://doi.org/10.1007/s10584-010-9977-4
43. Richards DR, Edwards PJ. Using water management infrastructure to address both flood risk and the urban heat island. International Journal of Water Resources Development, 2017; 34(4), 490–498. https://doi.org/10.1080/07900627.2017.1357538
44. Yang L, Yang Y, Shen Y. et al. Urban development pattern's influence on extreme rainfall occurrences. Nature Communications. 2024; 15(1), 3997. https://doi.org/10.1038/s41467-024-48533-5
45. Saddiqi MM, Zhao W, Cotterill S, Dereli RK. Smart management of combined sewer overflows: From an ancient technology to artificial intelligence, WiresWater 2023, https://doi.org/10.1002/wat2.1635
46. Observer. Characteristics of selected climate elements in Poland in February 2025. Institute of Meteorology and Water Management. Available online: https://obserwator.imgw.pl/2025/03/24/charakterystyka-wybranych-elementow-klimatu-w-polsce-w-lutym-2025-roku/ (access on 8 May 2025)
47. Piniewski M, Szcześniak M, Kardel I, Berezowski T, Okruszko T, Srinivasan R, Kundzewicz ZW. Hydrological modelling of the Vistula and Odra river basins using SWAT. Hydrological Sciences Journal. 2017; 62(8): 1266–1289.
48. Miejski System Informacji Przestrzennej. Miasto Białystok. Available online: https://bialystok.maps.arcgis.com/apps/webappviewer/index.html?id=04c49a13c25942ad92158e10507c6a88 (accessed on 24 June 2025)
49. Lu S, Huang J, Wu J. Knowledge domain and development trend of urban flood vulnerability research: A bibliometric analysis. Water, 2023; 15: 1865. https://doi.org/10.3390/w15101865
50. Utsumi N, Seto S, Kanae S, Maeda EE, Oki T. Does higher Surface temperature intensify extreme precipitation? Geophysical Research Letters. 2011; 38, L16708. https://doi-org.bazy.pb.edu.pl/10.1029/2011GL048426
51. Faccini F, Luino F, Paliaga G, Roccati A, Turconi L. Flash flood events along the west mediterranean coasts: inundations of urbanized areas conditioned by anthropic impacts. Land. 2021; 10(6): 620. https://doi.org/10.3390/land10060620
52. Stavropoulos S, Zaimes GN, Filippidis E, Diaconu DC, Emmanouloudis D. Mitigating flash floods with the use of new technologies: a μulti-criteria decision analysis to map flood susceptibility for Zakynthos Island, Greece. Journal of Urban and Regional Analysis. 2020; XII(2): 233–248. https://doi.org/10.37043/JURA.2020.12.2.7
53. Hydrology. The resources and circulation of water in nature. Environmental Engineering. 2023, https://inzynieriasrodowiska.com.pl/encyklopedia/zasoby-i-krazenie-wody-w-przyrodzie (accessed on 7 May 2025).
54. Luís C, Pierfranco C. Flood risk in urban areas: Modelling, management and adaptation to climate change. A review. Hydrology, 2022; 9(3): 50. https://doi.org/10.3390/hydrology9030050
55. Walczykiewicz T, Woźniak Ł. Współczesne problemy retencji wód. Warszawa: Instytut Meteorologii i Gospodarki Wodnej - Państwowy Instytut Badawczy; 2018; 198.
56. Jorgensen SE. Applications in Ecological Engineering, Copenhagen University Ed. Amsterdam, 2009.
57. Barbier EB. Wetlands as natural assets. Hydrological Sciences Journal, 2011; 56(8): 1360–1373. https://doi.org/10.1080/02626667.2011.629787
58. Yazdanfar Z, Sharma A. Urban drainage system planning and design–challenges with climate change and urbanization: a review. Water Science and Technology, 2015; 72(2): 165–179. https://doi.org/10.2166/wst.2015.207
59. Aronica GT, Lanza LG. Drainage efficiency in urban areas: a case study. Hydrological Processes: An International Journal, 2005; 19(5): 1105–1119. https://doi.org/10.1002/hyp.5648
60. Hamdi R, Duchêne F, Berckmans J, Delcloo A, Vanpoucke C, Termonia P. Evolution of urban heat wave intensity for the Brussels Capital Region in the ARPEGE-Climat A1B scenario. Urban Climate. 2016; 17: 176–195. https://doi.org/10.1016/j.uclim.2016.08.001Get rights and content
61. Berg P, Moseley Ch, Haerter JO. Strong increase in convective precipitation in response to higher temperatures. Nature Geoscience. 2013; 6: 181–185.
62. Ward K, Lauf S, Kleinschmit B, Endlicher W. Heat waves and urban heat islands in Europe: A review of relevant drivers. Science of The Total Environment. 2016; 569–570: 527–539. https://doi.org/10.1016/j.scitotenv.2016.06.119
63. Czubaszek R, Wysocka-Czubaszek A. Urban heat island in Białystok. Journal of Ecological Engineering. 2016; 17(3): 60–65. https://doi.org/10.12911/22998993/63323
64. Sauter Ch, Fowler HJ, Westra S, Ali H, Peleg N, White ChJ. Compound extreme hourly rainfall

preconditioned by heatwaves most likely in the mid-latitudes, Weather and Climate Extremes, 2023; 40: 100563. https://doi.org/10.1016/j.wace.2023.100563

65. Liu S, Shi K, Wu Y, Cui Y. Suburban greening and suburbanization changing surface urban heat island intensity in China. Building and Environment, 2023; 228: 109906. https://doi.org/10.1016/j.buildenv.2022.109906
66. Bailey DJ, Baumann PR. An urban heat island under flood conditions. Middle States Geographer. 2019; 52: 14–23.
67. Richards DR, Edwards PJ. Using water management infrastructure to address both flood risk and the urban heat island. International Journal of Water Resources Development. 2017; 34(4): 490–498a. https://doi.org/10.1080/07900627.2017.1357538
68. Li C, Sun N, Lu Y, Guo B, Wang Y, Sun X, Yao Y. Review on urban flood risk assessment. Sustainability. 2023; 15(1): 765. https://doi.org/10.3390/su15010765
69. Zang Y, Meng Y, Guan X, Lv H, Yan D. Study on urban flood early warning system considering flood loss. International Journal of Disaster Risk Reduction. 2022; 77(1–2): 103042. https://doi.org/10.1016/j.ijdrr.2022.103042
70. Wartalska K., Grzegorzek M., Bełcik M., Wdowikowski M., Kolanek A., Niemierka E., Kaźmierczak B. The potential of rainwater harvesting systems in Europe–Current state of Art and future perspectives. Water Resources Management. 2024; 38(12): 4657–4683. https://doi.org/10.1007/s11269-024-03882-0
71. Kaźmierczak B, Kotowski A. The influence of precipitation intensity growth on the urban drainage systems designing. Theoretical and Applied Climatology. 2014; 118(1): 285–296. https://doi.org/10.1007/s00704-013-1067-x
72. Derkzen ML, Teeffelen AJ, Verburg PH. Green infrastructure for urban climate adaptation: How do residents' views on climate impacts and green infrastructure shape adaptation preferences?. Landscape and Urban Planning. 2017; 157: 106–130. https://doi.org/10.1016/j.landurbplan.2016.05.027