ACTA SCIENTIARUM POLONORUM

Acta Sci. Pol.
Formatio Circumiectus 22 (3) 2023, 59–71
ENVIRONMENTAL PROCESSES

www.acta.urk.edu.pl ISSN 1644-0765 DOI: http://dx.doi.org/10.15576/ASP.FC/2023.22.3.11

ORIGINAL PAPER Accepted: 23.10.2023

THE IMPACT OF HYDROLOGICAL RESEARCH, MUNICIPAL AUTHORITIES, AND RESIDENTS ON RAINWATER MANAGEMENT IN GDAŃSK (POLAND) IN THE PROCESS OF ADAPTING THE CITY TO CLIMATE CHANGE

Michał Szydłowski[1]✉ 0000-0003-3409-591X, Khansa Gulshad[1] 0000-0002-6984-7328, Andam Mohsin Mustafa[1] 0000-0002-7307-4786, Wojciech Szpakowski[1, 2]

[1] Gdańsk University of Technology, Faculty of Civil and Environmental Engineering, Narutowicza 11/12, 80-233 Gdańsk
[2] Gdańskie Wody (Gdańsk Water company), Kaczeńce 31, 80-614 Gdańsk

ABSTRACT

Aim of the study
The city of Gdańsk faces changing climatic conditions that result in a higher frequency of extreme weather events. In response to the increasingly frequent appearance of flash floods, scientific research was carried out to address changes in the probability of the occurrence of maximum daily precipitation in Gdańsk. The purpose of this paper is to show the role of hydrological research (science), decisions of local authorities, and the engagement of residents in the process of adapting Gdańsk to climate change.

Material and methods
The hydrological analysis was conducted using rainfall observations from the Gdańsk Rębiechowo station (1974–2021). Log-normal distribution was used as a statistical model for the precipitation probability distribution. In order to show the role of the city authorities' decisions, the methodology developed and used by Gdańsk Water company for rainwater management was presented. To emphasize the importance of city residents in climate adaptation process, the methods adopted by city authorities aimed at involving citizens in the advisory process are discussed, namely Civic Panels and the Gdańsk Climate Change Forum.

Results and conclusions
Probability distributions of maximum precipitation for different periods were developed, showing a substantial increase in precipitation with a probability of $p = 1\%$. As a result, Gdańsk Water company introduced changes to their rainwater management. Mindful of the rising flood hazard, Gdańsk City Hall has embraced a plan for adapting the city to climatic changes by 2030. The local authorities decided to involve citizens in the decision-making process. To this end, discussion panels were organized, and the Gdańsk Climate Change Forum was initiated.

Keywords: Gdańsk, climate change, extreme rainfall, urban flood, city adaptation

✉e-mail: mszyd@pg.edu.pl

INTRODUCTION

Climate change is increasingly evident (Masson-Delmotte et al., 2021), thus we must accelerate mitigation and adaptation measures simultaneously. Otherwise, the ramifications will be far worse than we can possibly imagine today. Due to climate change, flooding is one of the world's major challenges in the twenty-first century (Loudyi and Kantoush, 2020). Over the last two decades, floods have affected 2.3 billion people, or one-third of the world's population, according to the United Nations (CRED and UNISDR, 2015). Moreover, it is expected that the frequency and magnitude of extreme rainfall will increase due to global climate change (Masson-Delmotte et al., 2021). The population density in risk-prone coastal cities is projected to rise by 25% by 2050, potentially exposing more people to more frequent and increasingly stronger impacts of climate change (Aerts et al., 2014). Flooding is the focus of many scientific studies globally, with some experts attributing it to extreme weather and climate change (Skougaard Kaspersen et al., 2017; Szpakowski and Szydłowski, 2017, 2018b; Mustafa et al., 2019; Xiong et al., 2019; Ziernicka-Wojtaszek and Kopcińska, 2020). Other scholars believe it is a consequence of population growth and rapid urban development (Apollonio et al., 2016; Szwagrzyk et al., 2018; Mustafa and Szydłowski, 2020). In reality, both perspectives are valid, but the extent of their impact remains a subject of debate.

Every country is trying to find ways to address the increasing risk of flooding. A survey of urban climate action plans in both Europe and the United States reveals that majority of cities emphasize mitigation and adaptation (Aylett, 2015; Kalafatis, 2017). Subject literature seems to focus more on mitigation within climate action plans rather than adaptation plans (Papa et al., 2015; Hoppe et al., 2016). Prioritizing local adaptation strategies is essential, because they will yield quicker results, while mitigation techniques may prove effective over time and one such example is the integration of nature-based solutions.

EU Directorate-General for the Environment continues to integrate nature-based green infrastructure solutions into various policies, notably water policy. Different cities across Europe have adopted Natural Water Retention Measures (NWRM), employing a range of strategies. In Fornebu, a peninsular town in Norway, green infrastructure elements such as permeable surfaces, swales, filter strips, detention basins, and retention ponds have been utilized for sustainable stormwater management (Åstebøl et al., 2004; Backhaus and Fryd, 2013). In Leidsche Rijn, near Utrecht in the Netherlands, soakaways and infiltration basins are implemented (Strosser et al., 2015). Nottingham, England, has introduced rain gardens along residential road curbs to reduce runoff, ultimately improving water quality in the downstream river (Day Brook) (Strosser, et al., 2015).

A total of 44 Polish cities are participating in a project initiated by the Ministry of the Environment, aimed at preparing them for climate change (Masik and Gajewski, 2021). Additionally, the city of Warsaw has prepared such an adaptation plan, but as part of a separate project. For instance, like many other Polish cities, Bydgoszcz is struggling with the effects of densely populated housing, industrial growth, and service development. This trend is leading to increased occurrence of floods and droughts. Consequently, Bydgoszcz is promoting "green" or "blue-green" infrastructure (parks, rain gardens, natural water-retentive reservoirs, revitalized watercourses, and household solutions) to counteract this trend (MWiK Bydgoszcz, 2022).

In the past two decades, Gdańsk, Poland's northernmost city on the Baltic Sea, experienced two extreme rainfall events. The first occurred on July 9, 2001, and the second happened over 15 years later on July 14, 2016, (Szpakowski and Szydłowski, 2017, 2018a, 2018b). The initial floods affected around 300 families (in terms of damaged houses and/or property loss). Around 5000 individuals received special status due to suffering from natural disaster, as well as welfare support. The flood damage to the city's infrastructure amounted to €40 million (Majewski, 2016). In response to this initial disaster, Gdańsk initiated first stormwater management reforms to enhance the city's resilience.

Since 2019, Arcadis and scientists from the Krakow University of Economics have been developing the Water City Index (arcadis.com). This index evaluates water management in Polish cities in four areas: life, hazard, economy and business, and culture and inhabitants. Data from water city index showed that Gdańsk consistently secured first spot in both 2021 and 2022. Gdańsk's unique location at the seaside and the riverside enables it to adapt well to the challenges of modern urbanization. Gdańsk Water (Gdańskie Wody), the municipal stormwater management company, became the first such agency in Poland to simulate severe rainfall on the city's surface. This initiative led to the construction of eight rain gardens in suitable locations in 2020.

In order to reform the operation of the city's rainwater management system and introduce new technical and administrative solutions aimed at reducing flood risk in response to climate change, the cooperation of at least three groups is necessary: scientists, local authorities with municipal services, and citizens. Scientists play crucial role in identifying and studying current problems, and to communicate the results obtained to the public. The scientific research presented here aims to demonstrate how climate change has influenced the probability distributions of maximum daily rainfall in Gdańsk. Changes in the probability distribution of exceeding the maximum daily precipitation, which occurred around the turn of the twenty-first century, were assessed for the period from 1974 to 2021.

This paper presents the city's new rainwater management system designed to adapt to the climate change. Finally, it should be noted that implementing sustainable rainwater management practices require active public participation of the local community, as the role of citizens in a modern city is beyond offering opinions on solutions proposed by decision makers. Citizens' input is essential also to the actual creation of new solutions and regulations. The paper outlines how city authorities engage communities in climate change adaptation and resilience efforts, in response to heavy rains and pluvial floods.

MATERIALS AND METHODS OF HYDROLOGICAL RESEARCH

Study area

Gdańsk is located in Central Europe, in northern Poland, and is the capital of the Pomeranian Voivodeship (Figure 1). With nearly half a million inhabitants, Gdańsk ranks sixth in Poland in terms of population, and seventh in land area, covering 263.44 km². Together with Gdynia and Sopot, Gdańsk forms the Tri-City agglomeration. Situated on the southern coast of the Baltic Sea within the Gulf of Gdańsk, the city's coastal zone encompasses the Vistula Spit, Vistula Delta Plain, and the eastern part of the Kashubian Coast.

The climate in the Gdańsk region is strongly influenced by the sea. Summer winds are predominantly from the west and northwest direction, whereas winter winds originate from the mainland. These storm winds pose a risk of lowland flooding. The mean temperature at Gdańsk Rębiechowo airport meteorological station is 7.5°C. From 1951–2018, the average annual precipitation was 572.2 mm. The highest recorded rainfall reached 924.8 mm in 2017, while the lowest was 327.7 mm in 1964 (Jakusik and Chodubska, 2020). Gdańsk's rainwater drainage system comprises numerous watercourses that flow into the Motława river or the Gulf of Gdańsk. In the early twenty-first century, Gdańsk experienced two extreme rainfall events with daily precipitation exceeding 100 mm, occurring on July 9, 2001, and on July 14, 2016 (Szpakowski and Szydłowski, 2017).

Meteorological data for maximum daily rainfall analysis

Gdańsk is equipped with two meteo stations operated by the Polish National Meteorological Service (IMGW-PIB), along with one station in the highest part of the city near Rębiechowo airport (Figure 1). Since 2001, Gdańsk has maintained a local hydrological monitoring network to scrutinise urban rainfall (Szydłowski and Mikos-Studnicka, 2015). The Gdańsk Water municipal company monitors 90 measuring points, 25 automatic rainfall stations, as well as approximately 70 water level measurement stations in retention reservoirs and watercourses (Gdańskie Wody website).

The present study utilized maximum annual daily precipitation observations to assess the impact of climate change on heavy rainfall events in Gdańsk. The dataset encompasses the longest measurement series available, starting from 1974, since Gdańsk Rębiechowo airport meteorological station opened. Additionally, precipitation observations from the Klukowo municipal rainfall station in 2017, situated just a few hundred meters from the airport, supplemented the data from 2018 to 2021. Figure 2 shows the annual maximum daily (24 h) rainfall (mm) over 48 years from 1974 to 2021.

Probability distribution of exceeding the maximum rainfall

A standard statistical analysis of annual maximum daily precipitation for the N-year period dataset has been applied in the present study. In the first stage, the

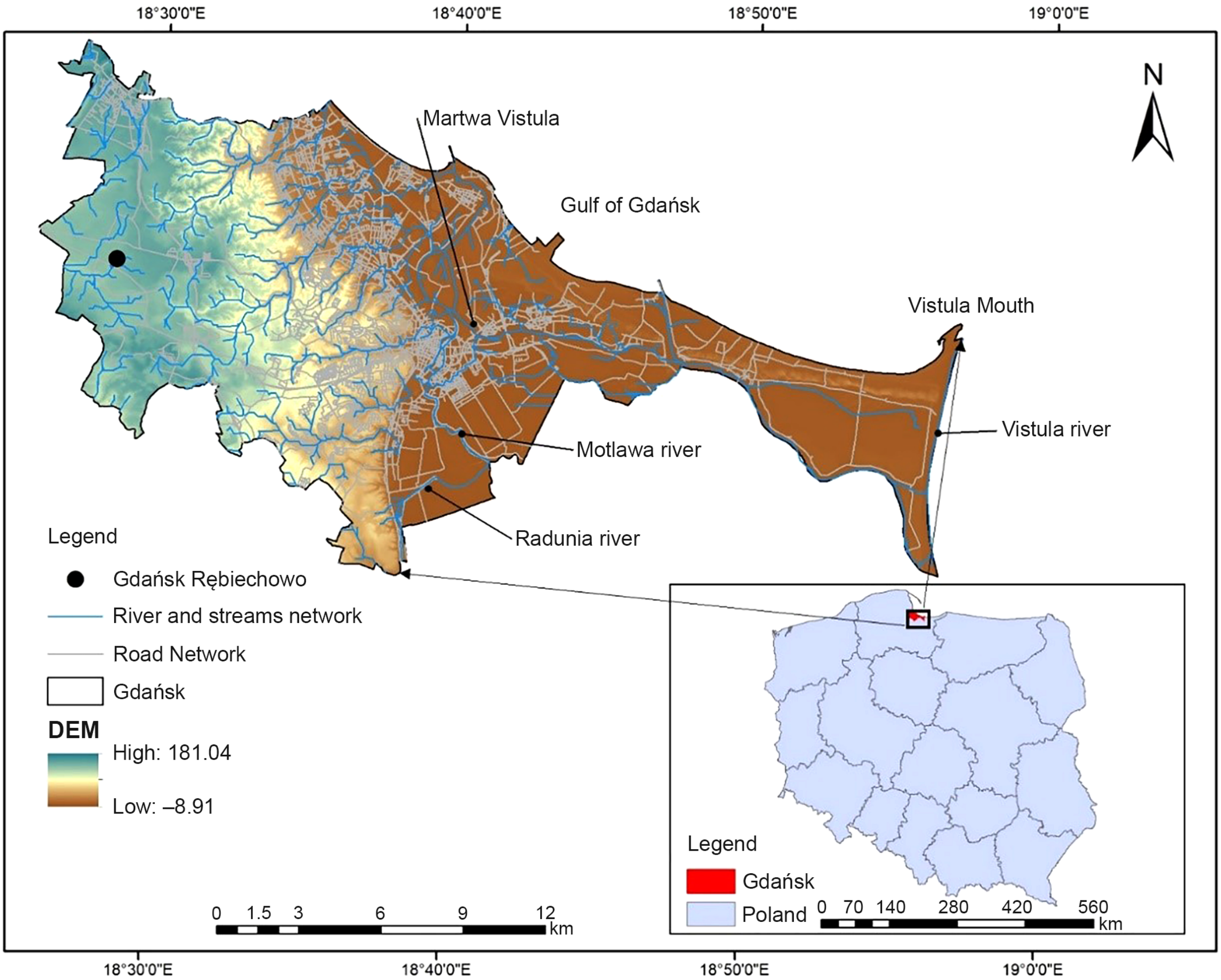

Fig. 1. The geographical location of study area: Gdańsk map showing meteorological station at Gdańsk Rębiechowo and rivers' and streams' network based on DTM without urban infrastructure (top); location map of Gdańsk in Poland (bottom right) (source: own elaboration according to GEOPORTAL data)

rainfall value sequence was ranked from the highest precipitation episode to the lowest. Then the empirical exceedance probability was calculated according to the Weibull (1951) equation:

$$p(i) = \frac{r}{N+1}$$

where p is the exceedance probability, r represents the location of a specific episode in the rainfall distribution series, and N is the length of the series.

Log-normal distribution was used as a statistical model of the precipitation probability distribution. The function parameters were estimated using the maximum likelihood method, an approach used by the Polish Hydrologists Association (Banasik et al., 2017). The values of $P_{max,\, p}$ indicating the annual maximum daily rainfall with the given theoretical probability of an excess of p were calculated using the following equation:

$$P_{\max,\, p} = \in + \exp\left(\mu + \sigma \cdot u_p\right)$$

where the lowest amount of maximum daily rainfall is denoted by $\in$; μ, σ indicate the distribution criteria determined using the maximum likelihood estimation; and u_p is the quantile of the p order in standardized

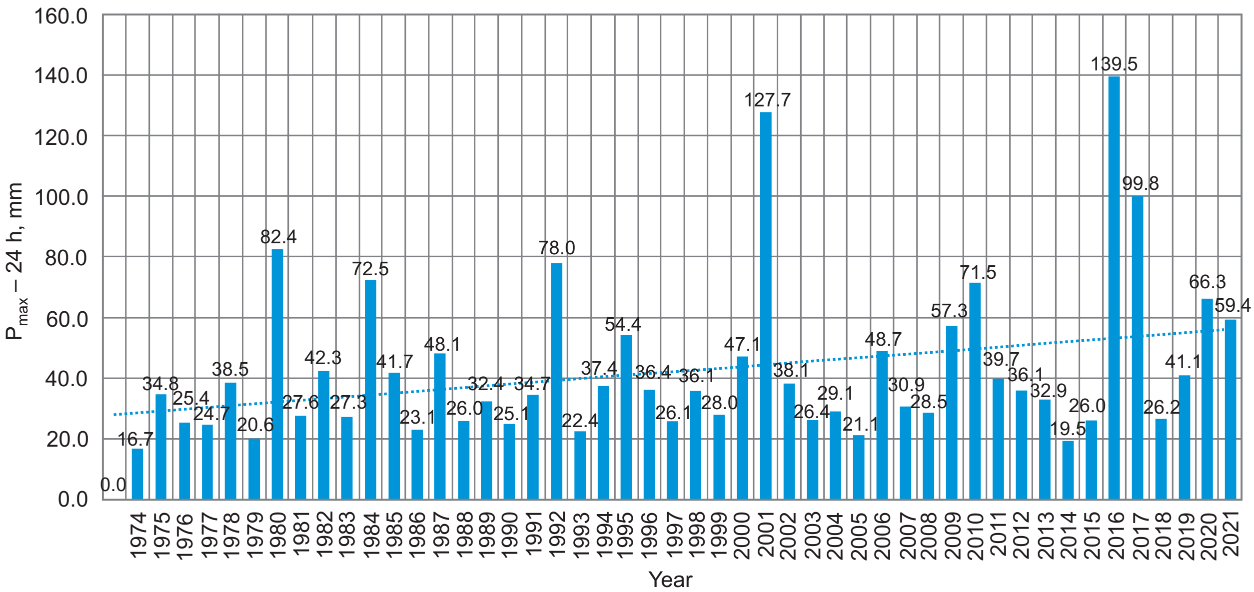

Fig. 2. Maximum daily rainfall for the period 1974–2021 with a linear trend line (source: own elaboration according to IMGW-PIB data)

normal distribution. For the series of data, the hypothesis was verified using the Kolmogorov (1933) test. The p_{value} of the test was 0.92, and there was no premise to reject the hypothesis that the distribution of maximum rainfall is a log-normal distribution.

RESULTS AND DISCUSSION OF MAXIMUM RAINFALL CHANGE

The probability distribution of exceeding the maximum daily rainfall for two periods (N = 27 years, 1974–2000) and (N = 48, 1974–2021), calculated using formula (2), is shown in Figure 3. The maximum daily precipitation for the chosen probabilities is compared in Table 1.

Table 1. Maximum daily rainfall P_{max} (mm) for theoretical exceedance probability (source: own elaboration)

Probability (%)	Period 1974–2000	Period 1974–2021
20	48.0	55.7
10	57.0	72.2
5	68.0	90.5
1	92.3	141.2

Figure 3 and Table 1 clearly show that the current maximum daily rainfall with specific exceedance probabilities has significantly increased compared to the values calculated only for the twentieth century. If we consider the probability of p = 1%, which is one of the reliable values for calculating flood risk and designing flood protection measures, an increase in from 92.3 mm in 2000 to 141.2 mm in 2021 can be noticed. These results confirm the already observed increase in daily precipitation with a probability of p = 1% presented in previous analysis (Szpakowski and Szydłowski, 2018b), covering the period from 2000 to 2017. The observed increase exceeds 50% of the value recorded in 2000. We should mention that the maximum daily rainfall up to the year 2000 was close to the precipitation amount calculated using the Polish theoretical model of precipitation elaborated by Bogdanowicz and Stachy (2002). The daily precipitation for the probability of p = 1% and duration of t = 24h, calculated using this model, equals 93.4 mm (Szpakowski and Szydłowski, 2018b). When we compare this value to the current maximum daily rainfall with the probability of exceeding p = 1% (141.2 mm), it becomes evident that this rainfall model is no longer reliable in the city of Gdańsk, and should no longer be employed for determining synthetic rainfall.

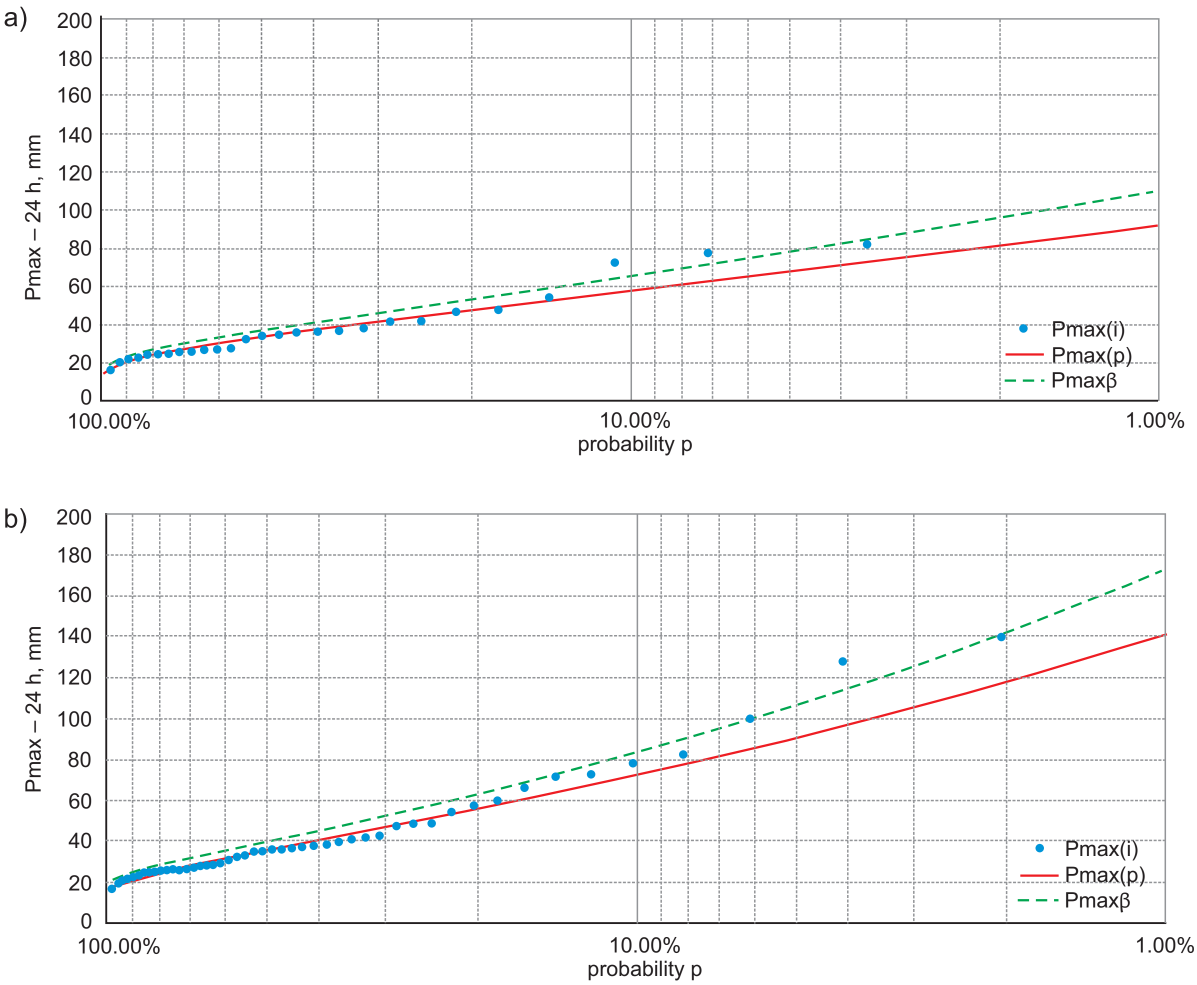

Fig. 3. The exceedance probability curves for two periods a) 1974–2000 and b) 1974–2021, according to log-normal distribution with the maximum likelihood estimation and a confidence interval limit of 85% – $P_{max\beta}$; $P_{max(i)}$ denotes the empirical probability of the exceedance of annual maximum daily rainfall, $P_{max}(p)$ denotes the theoretical probability of the exceedance of annual maximum daily rainfall (source: own elaboration)

Moreover, the analyses of maximum precipitation occurrences are also conducted by the Polish Institute of Meteorology and Water Management (IMGW-PIB) and are made available on-line (https://klimat.imgw.pl/opady-maksymalne). The results of these calculations, presented as maps form, have been prepared based on quantiles derived from maximum precipitation determined using both the Annual Maximum Precipitation (AMP) method and the Peak Over Threshold (POT) method. The maximum daily precipitation of $p = 1\%$, as read from IMGW-PIB maps, is around 99 mm and 109 mm, respectively, for these two methods. In comparison to the developed probability distribution, these values also appear to be underestimated.

To assess how the maximum daily rainfall with the exceedance probability of $p = 1\%$ changed over the years, including at the turn of the twenty-first century, calculations were additionally made for each year separately, starting from 1998 and using sequences of observations of different lengths. The variation in daily rainfall with the probability of $p = 1\%$ for the period 1998–2021 is presented in Figure 4.

We can see the most significant increases in maximum daily precipitation values for the years 2001 and

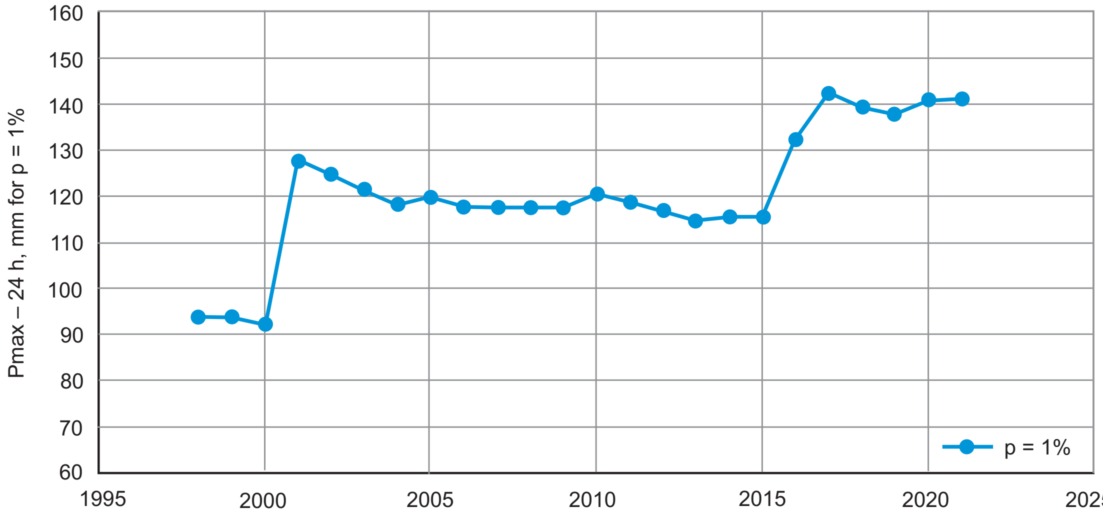

Fig. 4. Maximum theoretical daily rainfall with the probability of exceedance of p = 1%, according to the log-normal distribution with the maximum likelihood estimation (source: own elaboration)

2016–2017, when rainfalls reaching and exceeding 100 mm were recorded. Considering only the twentieth century rainfall episodes (period 1998–2000), the maximum daily precipitation for p = 1% was estimated at around 94 mm, which was consistent with the Bogdanowicz and Stachy (2022) model with 93.4 mm of rainfall. Then, in the years 2001–2015, the value of the maximum daily rainfall stabilized for the 15-year period at about 119 mm. After the last two extreme episodes, in 2016 and 2017, the daily maximum rainfall for p = 1% reached a value of 140 mm and has remained unchanged for the last 5 years (2017–2021).

Climate change in Gdańsk is shown by the increase in maximum daily rainfall (Figure 2) and the accompanying increase in the value of the maximum daily rainfall with the probability of exceeding p = 1% (Figure 3, Table 1, Figure 4). Extreme weather events, especially rainfall, are becoming common throughout the world, thereby increasing the hazard of city floods. The city of Gdańsk needed to improve its rainwater management system in connection with changes in torrential rainfall, which the local scientific community explicated and publicized during scientific conferences and thematic seminars. A new city strategy for rainwater management, adapting to the effects of climate change in the areas susceptible to pluvial flood risk, is presented in the next part of the paper.

ROLE OF LOCAL AUTHORITIES IN SHAPING RAINWATER MANAGEMENT IN THE CITY

Following the 2001 flood, Gdańsk underwent significant modifications in its approach to protect the municipal infrastructure and residents (Majewski, 2016; Cieśliński et al., 2023). The city built open retention reservoirs, which mitigated floods along natural watercourses stretching from the Kashubian Lake District plateau to the Gulf of Gdańsk. Gdansk now has 53 reservoirs with a combined capacity of nearly 800,000 m^3.

In recent years, Gdańsk has experienced torrential rainfalls, both over short periods (up to an hour) and of a longer duration, extending up to 48 hours. The rainfall in 2016 was the most extensive ever recorded in Poland (except for mountain regions). This event demonstrated the urgent need for a new stormwater policy. On January 1, 2018, Poland's new Water Law Act recognized rainwater as an environmental resource. The new Gdańsk policy rests on a three-stage rainwater management strategy, which include: i) water management within the land property whether a single building (structure) or a complex of buildings (one architectural design), ii) water management within the municipal stormwater system and retention reservoirs, and iii) crisis management. This strategy can be described as follows:

- First, rainfall should be retained at the point of origin. Blue-green infrastructure drains rainfall from impervious surfaces. By lowering green areas below impermeable roads and parking zones and implementing nature-based solutions like bioretention swales, rain gardens, ditches, moguls, etc., the desired outcomes can be achieved. In this system, the gray stormwater system comes into play to manage any excess rainwater. Each property is responsible for managing 30 mm of impermeable runoff with blue-green infrastructure and redirecting excess water to the municipal stormwater system. In cases where draining into the rainwater system is not possible, 60 mm of impervious surface runoff must be effectively handled. Furthermore, rainwater from public roads should be directed into the municipal stormwater network through green retention areas. Rainwater from public roads should be discharged into the municipal stormwater network through green retention areas. Additionally, nature-based methods attempt to improve rainwater quality, with woodland areas within the Tri-City Landscape Park serving as rainwater collection point.

- In Gdańsk's second stage of rainwater management, excess water is retained within municipal reservoirs featuring vegetation. These reservoirs consider the future land use and land cover of urban catchments and as well as rainfall durations with a probability of 1%.
- Third stage of rainwater management is dedicated to disaster (crisis) management, designed to address rainfall events exceeding 100-year return period. The emergency actions are based on the Pomeranian Voivodeship's Crisis Response Plan and Gdańsk's Crisis Management Plan.

To facilitate the adoption of rainwater management policy changes, Gdańsk Water and other municipal units developed blue-green demonstration facilities aimed at persuading property owners, designers, and investors to apply these solutions (Kasprzyk et al., 2022). Thirty municipal facilities have been designated to manage rainwater in the green retention areas (Figure 5). Gdańsk Water also accepted many individual facilities into the investment process.

Figure 5. The system of rainwater management in Gdańsk: a) in Gdańsk Stogi, 1.8 ha residential area, green retention area 0.2 ha, volume 284 m^3, year of establishment 2019; b) in Gdańsk Main Town-Lastadia 0.8 ha municipal office building area, green retention area 0.03 ha, volume 108 m^3, year of establishment 2020; and c) in Gdańsk Central City – crossroad 3 Maja Str., green retention area 0.08 ha, volume 100 m^3, year of establishment 2020 (source: Gdańsk Water company)

The effectiveness of the implemented policy has been primary confirmed by heavy rainfall episodes that occurred several times in various parts of the city in the period 2018–2021. As a result of the expansion of the rainfall monitoring system (26 rainfall stations in Gdańsk), notable rainfall events were recorded, including 28 mm in 10 minutes, 38 mm in 30 minutes (May 2018), 45 mm in 30 minutes, and 52 mm in 60 minutes (August 2018). Moreover, heavy rainfall of up to 60 mm within 2–3 hours, covering almost the whole city was also observed (June 2019). Local rainwater management challenges have been resolved in places where blue-green infrastructure has been implemented. However, for heavy rainfall events of this magnitude, only a combination of surface retention (natural green areas and blue-green infrastructure), along with municipal retention reservoirs, gives a chance to mitigate pluvial flood risk in Gdańsk (Figure 6).

As a consequence of climate change, which results in the occurrence of hazardous rainfall episodes, we need to consider inevitable that inundations and floods in Gdańsk will occur despite the work done by the city. Therefore, special operating procedures have been introduced in the city by the Gdańsk Water company to be enacted during flood events (3rd stage of rainwater management). Within the city, the locations most sensitive to rainfall and torrential rainfall were selected and designated as so-called black spots. Upon the announcement of flood risk, operational brigades are mobilized to drain water from these locations. These operations are supported by units of the Fire Brigade. After each rainfall event that requires emergency action, Gdańsk Water develops operational reports on the precipitation event, in which the causes and necessary actions to limit the future flooding risk are analyzed. Additionally, regular flood defense training is also organized at these black spots to improve the actual rescue operations.

CITIZENS IN BUILDING THE CITY'S RESILIENCE TO URBAN FLOODS

In addition to Gdańsk's new rainwater management policy, community participation is crucial to the city's resilience to climate change. Gdańsk City Hall took the initiative to organize a citizens' panel in 2016, to address climate change concerns (Gerwin et al., 2016). The citizens' panel enables arriving at munici-

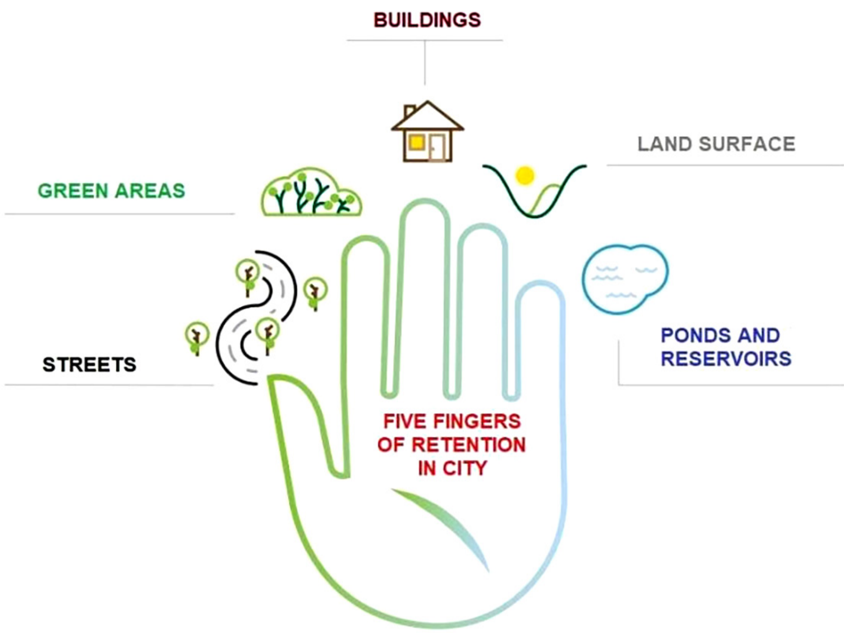

Fig. 6. Multilevel urban retention in Gdańsk: street, large scale urban greenery (forest), property scale, district scale, urban reservoir (source: Gdańsk Water company)

pal, regional, or state decisions democratically, while involving residents from diverse demographics to discuss the issues. Panel activities entail debates, where panelists analyze the problem and offer potential solutions. The debate and participation of diverse groups and professionals allow panelists to view alternative perspectives and make community-best recommendations. Tri-City citizen and expert meetings sought answers to questions like:

- How can the Tri-City Landscape Park retain rainwater?
- What measures should be taken to assist Gdańsk residents after a heavy rain?
- When constructing new reservoirs, should they be partially filled or left empty?

Both the citizen panel and experts proposed a range of recommendations, including measures to reduce rainwater surface runoff:

- Implementation of natural dikes in forest's valleys, promotion of micro-retention, stream meandering, and wetlands restoration.
- Construction of new retention reservoirs on the city's upper terrace.
- Encouraging the creation of private green spaces and restriction on sales in public areas on the upper terrace to optimize rainwater retention.
- Limitation of deforestation activities in the landscape park.

The city made these recommendations mandatory and used them to amend local spatial development plans, to publicize the prospect of residents aiding in a disaster (e.g., flood), and to create a subsidy program for private rainwater retention.

Another form of citizen participation in ongoing efforts to adapt the city to climate change is the Gdańsk Climate Change Forum. In August 2019, Gdańsk approved a 2030 climate change adaptation plan (PUACC, 2019), which encompasses a strategy and proposed actions for mitigating the consequences of climate change. This plan incorporates various measures including the use of green infrastructure, permeable surfaces, and limiting and delaying rainwater runoff to sewer systems.

However, the plan is not intended to be a final document, but is subject to assessment and evaluation, with active involvement of citizens. The first public consultations of the plan were conducted as part of the Gdańsk Climate Change Forum on November 25, 2020. This forum is based on an open planning process, serving as a platform for participants to identify climate related issues and engage in a constructive debate regarding solutions. During the initial meeting, the most important problems of the city regarding climate policy were selected. As a result of the discussions, a catalog of threats, challenges and problems related to the ongoing climate emergency was compiled. Of particular concern was the problem of water management and retention. Gdańsk's unique geomorphology, division into two terraces separated by the Tri-City Landscape Park forests, and situation in the low-lying areas of Żuławy Wiślane, makes it susceptible to threats from rainwater and rising sea levels. Among the potential solutions, the most commonly proposed included the expansion of biologically active areas, removing paved surfaces, building rain gardens, or extending and reconstructing storage reservoirs. The authorities and inhabitants assigned a special role to green areas in Gdańsk's climate resilience.

Another meeting of the Forum took place on October 22, 2021. During this meeting, the mayor of the city appointed the Advisory Board of the Gdańsk Climate Change Forum. This Advisory Board consists of scientists specializing in climate and urban matters. The most recent meeting of the city residents participating in the Forum was held on October 11, 2022. During this meeting, the participants' task was to search for solutions to the priority problems and challenges identified two years earlier. The Advisory Board verifies the Forum's proposed solutions for legality and municipal competences. Subsequently, the Advisory Board will submit the final list of tasks to update Gdańsk's climate change plan. The Advisory Board will propose developed ideas and recommendations for particular initiatives in 2023. In the next step, citizens can reengage in the forum to review the experts' solutions, and submit their comments. Any modifications to the plan must be approved by Gdańsk City Hall.

CONCLUSIONS

The study discusses the impact of climate change on Gdańsk's rainwater management policy. The authors have confirmed the effects of climate change, including an increase in extreme rainfall events, through an analysis of changes in the probability of exceeding the daily maximum rainfall. In the twenty-first century, daily rainfall with a probability of p = 1% exceeds 141 mm, compared to 92 mm towards the end of the twentieth century. Consequently, researchers have proposed revisions to Gdańsk's stormwater system design criteria, which have been presented to the local authorities.

Recognizing the limited capacity of the rainwater drainage system, city authorities initiated new rainwater management laws in urbanized catchments. The principal feature of this new system is a three-stage urban retention system that utilizes the city's blue-green infrastructure (first-level retention).

The study illustrates natural rainwater management options that incorporate green retention areas such as rain gardens and squares. Recent rainstorms have demonstrated their retention efficiency. However, it is worth noting that solutions involving the creation of new natural (blue-green) retention in the city have their limitations, primarily due to the existing urban development. Planning and designing retention for new developments is more straightforward, as is the case in Gdańsk, where retaining 30 mm of rainwater is a requirement for all new projects. When limitations in implementing blue-green infrastructure exist or when rainfall exceeds 30 mm, excess water is channeled to municipal retention ponds, where it can be utilized as a water resource. Climate change now indicates greater amount of rainfall in the autumn and winter periods (often instead of snow). Therefore, the City of Gdańsk is expanding the urban rainwater management system in areas that can't drain excess water. Crisis management and rescue activities come into play at the third level if reservoirs overflow, leading to flood hazards. As part of the city's climate change adaptation efforts, municipal services are also educated on flooding.

The observed increase in pluvial flood risk led city authorities to consider urban floods as inevitable challenge. In response, they began collaborating with residents on climate change adaptation measures. The city has established social platforms for individuals to share experiences and gain knowledge about pluvial flood mitigation. A citizens' panel was organized to discuss new strategies for reducing urban flooding. Additionally, the Gdańsk Climate Change Forum was created to educate the public and seek input on recommended adaption strategies. This is a noteworthy example of how citizen science can be developed by engaging citizens in climate change adaptation alongside expert science.

In summary, it can be affirmed that the cooperation between the scientific community, local authorities and city residents presents an opportunity for effective climate change adaptation, particularly in the field of rainwater management in Gdańsk.

REFERENCES

Aerts, J.C.J.H., Botzen, W.J.W., Emanuel, K., Lin, N., de Moel, H., Michel-Kerjan, E.O. (2014). Evaluating flood resilience strategies for coastal megacities. Science, 344, 473–475.

Apollonio, C., Balacco, G., Novelli, A., Tarantino, E., Piccinni, A.F. (2016). Land use change impact on flooding areas: The case study of Cervaro basin (Italy). Sustainability, 8, 996.

Åstebøl, S.O., Hvitved-Jacobsen, T., Simonsen, Ø. (2004). Sustainable stormwater management at Fornebu – From an airport to an industrial and residential area of the city of Oslo, Norway. Science of the Total Environment, 334, 239–249.

Aylett, A. (2015). Institutionalizing the urban governance of climate change adaptation: Results of an international survey. Urban Climate, 14, 4–16.

Backhaus, A., Fryd, O. (2013). The aesthetic performance of urban landscape-based stormwater management systems: A review of twenty projects in Northern Europe. Journal of Landscape Architecture, 8, 52–63.

Banasik, K., Wałęga, A., Węglarczyk, S., Więzik, B. (2017). Aktualizacja metodyki obliczania przepływów i opadów maksymalnych o określonym prawdopodobieństwie przewyższenia dla zlewni kontrolowanych i niekontrolowanych oraz identyfikacji modeli transformacji opadu w odpływ. Warszawa: Stowarzyszenie Hydrologów Polskich.

Bogdanowicz, E., Stachy, J. (2002). Maximum rainfall in Poland – A design approach. IAHS Publication, 15–18.

Cieśliński, R., Szydłowski, M., Chlost, I., Mikos-Studnicka, P. (2023). Hazards of a flooding event in the city of Gdansk and possible forms of preventing the phenomenon – Case study. Urban Water Journal. DOI: 10.1080/1573062X.2023.2254745

CRED, UNISDR (2015). The human cost of weather-related disasters 1995–2015. United Nations: Geneva, Switzerland.

Gdańskie Wody website System pomiarów meteorologicznych i hydrologicznych aglomeracji gdańskiej. https://pomiary.gdanskiewody.pl (access: July 7, 2023).

Gerwin, M., Pancewicz, Ł., Haas, M. (2016). Summary report of the 'First Citizens' Panel. In: Gdańsk City Hall Report.

Hoppe, T., Van der Vegt, A., Stegmaier, P. (2016). Presenting a framework to analyze local climate policy and action in small and medium-sized cities. Sustainability, 8, 847.

Jakusik, E., Chodubska, A. (2020). Charakterystyka warunków opadowych w Gdańsku w latach 1951–2018. In: T. Walczykiewicz (ed.), Współczesne problemy gospodarki wodnej w kontekście zagospodarowania przestrzennego, 41–54. Poland: IMGW-PIB.

Kalafatis, S.E. (2017). Identifying the potential for climate compatible development efforts and the missing links. Sustainability, 9, 1642.

Kasprzyk, M., Szpakowski, W., Poznańska, E., Boogaard, F., Bobkowska, K., Gajewska, M. (2022). Technical solutions and benefits of introducing rain gardens – Gdańsk case study. Science of the Total Environment, 835, 155487.

Kolmogorov, A.N. (1933). Sulla deterrninazione empirica di una legge di distribuzione. Giornde1l'Inst. Ital. degli. Art., 4, 89–91.

Loudyi, D., Kantoush, S.A. (2020). Flood risk management in the Middle East and North Africa (MENA) region. Urban Water Journal, 17, 379–380.

Majewski, W. (2016). Urban flash flood in Gdańsk – 2001. Case study. Meteorology Hydrology and Water Management. Research and Operational Applications, 4, 41–49.

Masik, G., Gajewski, R. (2021). Working towards urban capacity and resilience strategy implementation: Adaptation plans and strategies in Polish cities. Cities, 119, 103381.

Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S., Péan, C., Berger, S., Zhou, B. (2021). Climate change 2021: The physical science basis. Working Group I contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

Mustafa, A., Szydłowski, M. (2020). The impact of spatiotemporal changes in land development (1984–2019) on the increase in the runoff coefficient in Erbil, Kurdistan Region of Iraq. Remote Sensing, 12, 1302.

Mustafa, A.M., Muhammed, H., Szydłowski, M. (2019). Extreme rainfalls as a cause of urban flash floods: A case study of the Erbil – Kurdistan region of Iraq. Acta Scientiarum Polonorum. Formatio Circumiectus, 18, 113–132.

MWiK Bydgoszcz (2022). Wykorzystajmy siłę deszczu z nieba! Bydgoszcz.

Natural Water Retention Measures (NWRM). Case studies. http://nwrm.eu/list-of-all-case-studies. http://nwrm.eu/list-of-all-case-studies (accessed: August 20, 2023).

Papa, R., Galderisi, A., Saretta, E., Vigo Majello, M.C. (2015). European cities dealing with climate issues: Ideas and tools for a better framing of current practices. TeMA Journal of Land Use, Mobility and Environment, 63–80.

PUACC, 2019. Plan of Adaptation of the City of Gdańsk to Climate Change by 2030. https://download.cloudgdansk.pl/gdansk-pl/d/201811117491/mpa_projekt_gdansk.pdf (access: August 20, 2023). (in Polish).

Skougaard Kaspersen, P., Høegh Ravn, N., Arnbjerg-Nielsen, K., Madsen, H., Drews, M. (2017). Comparison of the impacts of urban development and climate change on exposing European cities to pluvial flooding. Hydrol. Earth Syst. Sci., 21, 4131–4147.

Strosser, P., Delacámara, G., Hanus, H., Williams, H. (2015). A guide to support the selection, design and implementation of Natural Water Retention Measures in Europe. Capturing the multiple benefits of nature-based solutions.

Szpakowski, W., Szydłowski, M. (2017). Extraordinary rainfalls in Gdansk (Northern Poland) in the 21st century. 15th International Symposium Water Management and Hydraulics Engineering, 2–11). University of Zagreb, Croatia.

Szpakowski, W., Szydłowski, M. (2018a). Evaluating the catastrophic rainfall of 14 july 2016 in the catchment basin of the urbanized Strzyza stream in Gdańsk, Poland. Polish Journal of Environmental Studies, 27, 861–869.

Szpakowski, W., Szydłowski, M. (2018b). Probable rainfall in Gdańsk in view of climate change. Acta Scientiarum Polonorum. Formatio Circumiectus, 3, 175–183.

Szwagrzyk, M., Kaim, D., Price, B., Wypych, A., Grabska, E., Kozak, J. (2018). Impact of forecasted land use changes on flood risk in the Polish Carpathians. Natural Hazards, 94, 227–240.

Szydłowski, M., Mikos-Studnicka, P. (2015). The influence of hydrological data quality on estimating the runoff from city catchment on the example of Strzyża stream in Gdańsk. Inżynieria Ekologiczna, 44, 139–153.

Weibull, W. (1951). A statistical distribution function of wide applicability. ASME Journal of Applied Mechanics, 18(3), 293–297.

Xiong, L., Yan, L., Du, T., Yan, P., Li, L., Xu, W. (2019). Impacts of climate change on urban extreme rainfall and drainage infrastructure performance: A case study in Wuhan City, China. Irrigation and Drainage, 68, 152–164.

Ziernicka-Wojtaszek, A., Kopcińska, J. (2020). Variation in atmospheric precipitation in Poland in the years 2001–2018. Atmosphere, 11, 794.

WPŁYW BADAŃ HYDROLOGICZNYCH, WŁADZ MIEJSKICH I MIESZKAŃCÓW NA GOSPODARKĘ WODAMI OPADOWYMI W GDAŃSKU (POLSKA) W PROCESIE ADAPTACJI MIASTA DO ZMIANY KLIMATU

ABSTRAKT

Cel pracy

Miasto Gdańsk boryka się ze zmieniającymi się warunkami klimatycznymi, które skutkują większą częstotliwością występowania ekstremalnych zjawisk pogodowych. W odpowiedzi na coraz częstsze występowanie gwałtownych powodzi przeprowadzono badania nad zmianami prawdopodobieństwa wystąpienia maksymalnych opadów dobowych w Gdańsku. Celem artykułu jest ukazanie roli badań hydrologicznych (nauki), decyzji władz lokalnych oraz zaangażowania mieszkańców w proces adaptacji Gdańska do zmiany klimatu.

Materiał i metody

Analizę hydrologiczną przeprowadzono na podstawie obserwacji opadów ze stacji Gdańsk Rębiechowo (1974–2021). Jako model statystyczny rozkładu prawdopodobieństwa opadów wykorzystano rozkład logarytmiczno-normalny. Aby pokazać rolę decyzji władz miasta, przedstawiono metodologię opracowaną i stosowaną przez Przedsiębiorstwo Gdańskie Wody w zakresie zagospodarowania wód opadowych. Aby podkreślić znaczenie mieszkańców w procesie adaptacji klimatycznej, omówiono przyjęte przez władze miasta metody włączania obywateli w proces doradczy, czyli Panele Obywatelskie i Gdańskie Forum Zmian Klimatu.

Wyniki i wnioski

Opracowano rozkłady prawdopodobieństwa opadów maksymalnych dla różnych okresów, wykazujące znaczny wzrost opadów z prawdopodobieństwem $p = 1\%$. Z tego powodu spółka Gdańskie Wody wprowadziła zmiany w praktykach gospodarowania wodami opadowymi. Mając świadomość rosnącego zagrożenia powodziowego, Urząd Miasta Gdańska przyjął plan przystosowania miasta do zmiany klimatu do 2030 roku. Władze lokalne zdecydowały się włączyć obywateli w proces decyzyjny. W tym celu zorganizowano panele dyskusyjne i zainicjowano Gdańskie Forum Zmian Klimatu.

Słowa kluczowe: Gdańsk, zmiana klimatu, powódź miejska, opady ekstremalne, adaptacja miasta