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PROBABLE RAINFALL IN GDAŃSK IN VIEW OF CLIMATE CHANGE

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ABSTRACT

One of the manifestations of climate changes is the occurrence of a greater number of precipitation events, characterized by greater rain intensity that affects the economic stability of cities. Gdańsk is an example of a city in which such events have occurred since the beginning of the twenty-first century. Due to the altitude differences in the area of Gdańsk city (between –2 m and 180 m a.s.l.), the occurrence of extreme atmospheric precipitation almost immediately causes hydrological effects in the water network consisting of several streams of montane character, which flow eastwards from the plateau of the Kashubian Lakeland. Meteorological stations of the National Meteorological Service (IMGW-PIB) are located in the coastal zone (Port Północny/Northern Port, Świbno) and in the highest part of the city (the Rębiechowo airport). Because this is insufficient, the city of Gdańsk has been expanding the local rain monitoring network since 2001, currently having reliable 10-year observation data sequences. The said network is operated by the Gdańsk Water municipal company.

Climate changes resulting in different characteristics of rainfall episodes in Gdańsk naturally influence the determination of the probability of their occurrence. According to the rainfall model developed by Bogdanowicz and Stachy at the turn of the 20th and 21st centuries, at least 4 rainfall events lasting for over 8 hours in the last 17 years should be classified as a 100-year rain event. One of these extended the parameters of a 300-year rain event; whereas we asses the rain in the year 2016, when even 170 mm of rainfall was recorded on July 14, as at least a 500-year rain event. During this period, several-minute events were also recorded, which also exceeded the parameters of a 100-year rain event.

The paper presents precipitation models for the region of Gdańsk. Based on the maximum annual daily rainfall from Rębiechowo meteorological station from the years 1974–2017, an analysis of changes in precipitation values corresponding to certain probabilities of occurrence was conducted. An assessment was also made of the projected decrease in the value of precipitation in relation to hydro-technical constructions, road-engineering structures, and rainwater drainage systems in view of changing legal regulations, as well as the latest trends related to the management of rainwater.

Keywords: Rainfall, precipitation model, urbanized watershed, climate changes.

INTRODUCTION

The trends of climate change manifest themselves, above all, in the increasing tendency in air temperatures both in Europe and in Poland (Sulikowska A. et al. 2016); whereas increased daily sums of precipitation in recent years are recorded in various regions of the world, for instance, in Georgia (Egiazarowa et al. 2017). On the other hand, analyses of water surges and low-flows in minor Polish mountain rivers indicate an increase in both the extremely high and the extremely low water flows caused by higher sums of individual precipitation with a decrease in the number of episodes themselves (Wałęga et al. 2016).

Gdańsk and other cities of the Tri-City agglomeration are located on the hypsometrically varied ar-

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eas adjacent to the Bay of Gdansk. The lowest areas of the city include depression areas of the Żuławy Gdańskie, the estuary section of the Vistula, adjoining the shoreline, and Bay of Gdańsk. On the western side of Gdańsk city, the post-glacial hills of the eastern part of the Kashubian Lakeland are dominating, with hills reaching 180 m, and even 200 m above sea level, like the Donas Mountain in Gdynia. Between the zones listed above, the area of the city with the largest slopes (locally reaching 40%) is located. In the southern part, this is an area of dense residential housing, while in the northern and central parts, the moraine hills are overgrown with forests forming the Tri-City Landscape Park.

The layout of the city affects the spatial distribution and time course of atmospheric precipitation. Normal precipitation from the 1971–2000 period indicates that rainfall totals in Gdańsk range from 550 to more than 700 mm (see: Figure 1), while normal rainfall increases with the increasing ground level ordinates (Lorenc, Kowalewski 2005).

Since 2001, the Gdańskie Wody municipal water company (until 2017, Gdańskie Melioracje) has been monitoring atmospheric precipitation in Gdańsk. At the moment, it is in possession of rainfall measurement sequences, approximately 10 years in length, recorded at several outlets. After the modernization of the system in 2018, the city of Gdańsk now owns 25 rainwater stations equipped with weighing and tipping-bucket rain gauges of the latest generation. Table 1 summarizes data from the Gdańsk city station (Gdańskie Wody 2018) with normal rainfall from the multi-year period of 1971–2000 (Lorenc, 2005).

Table 1. Mean annular precipitation totals in Gdańsk in the end of 20th and at the beginning of the 21st century

Gdańsk city rainwater station Decade of 2008–2017	Mean annual rainfall total [mm]	Normal rainfall according to the Climate Atlas of Poland IMGW-PIB, multi-year period of 1971–2000 [mm]
Oliwa	683	650–700
Matemblewo	708	650–700
Wrzeszcz – Reja	631	600–650
Dolne Miasto	562	550–600

The data collected in Table 1 does not indicate significant anomalies of normal precipitation occurring in the last decade (2008–2017) in relation to the last 30 years of the 20th century. A slight exceedance was recorded only at the Matemblewo rainwater station.

DATA AND METHODS

Among the many rainfall models at the moment, the most popular model is the one developed by Bogdanowicz and Stachy (1998), referred to as the IMGW formula. It uses collected rainfall episodes of varying

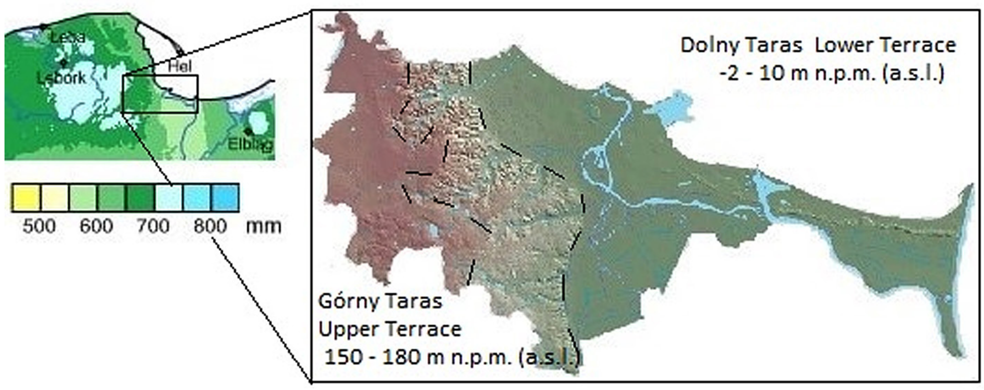

Fig. 1. Mean annual precipitations from multi-year period of 1971-2000, based on Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB) (Lorenc, Kowalewski 2005) and Numerical Terrain Model of Gdansk (mapa.gdansk.gda.pl, 2018)

duration (between 5 minutes and 72 hours) from 20 stations throughout Poland, from the period of 1961–1990. According to the authors, it can be used for the probability of occurrence $p \in (0; 1]$.

$$P_{\max,\,p} = 1.42 \cdot t^{1/3} + \alpha \cdot (-\ln\, p)^{0.584} \qquad (1)$$

The local quality of the model is evidenced by the coefficient α, which is determined by different formulas depending on the given region of Poland, and the duration of precipitation (Szpakowski, Szydłowski, 2018).

Due to the fact that the IMGW formula was based on as few as 20 Polish rainwater stations, reliable local formulas are being sought for the specific conditions of Gdańsk city. It should be noted that despite the existence of numerous rainfall stations in the city precipitation monitoring system, the City of Gdańsk is in possession of only 10-year rainfall sequences, which will ultimately be used to determine such formulas after the length of the observation period has been increased. Longer sequences were collected at the Gdańsk University of Technology. Statistical analyses of 122 precipitation episodes that occurred between 1991–2010 were prepared by Weinerowska – Bords (2015) at the Gdańsk University of Technology. On that basis, precipitation formulas valid in time intervals from 5 to 120 minutes for the minimum repetition time once every 20 years (p = 5%) were derived. The IMGW-PIB has at its disposal multi-year observations from only three stations in Gdańsk (Port Północny, Świbno, and Rębiechowo). As regards the rainfall episode, which occurred in Gdańsk on 14 July 2016, the analysis of compliance with the existing precipitation models has been conducted (Szpakowski, Szydłowski 2018).

In order to enable an analysis of probable longer-duration rainfall events in Gdańsk, the data from the IMGW-PIB Rębiechowo meteorological station was used for the analyses. An additional premise was the location of the station in the zone of the highest average rainfall, based on multiyear data. The first full observation year was 1974, when the Airport was opened in the new location. Previously, the airport station had been located by the sea, in the Zaspa district. Until now, the measurements cover the period of 27 years of the 20th century, and 17 years of the 21st century. The summary of the precipitation figures in Table 2 illustrates the visible effects of the changes in rainfall trends in terms of individual episodes.

Table 2. Comparison of maximum daily precipitation episodes at the end of the 20th, and at the beginning of the 21st century, recorded at the Rębiechowo rainwater station – in the years 1974–2017.

The 20th century – 1974–2000 (27 years) Year – total daily rainfall	Occurrence of rainfall episodes with the largest annual daily precipitation	The 21st century – 2001–2017 (17 years) Year – total daily rainfall
0	*the three largest episodes*	3 2016 – 139.5 mm 2001 – 127.7 mm 2017 – 99.8 mm
3 1980 – 82.4 mm 1992 – 78.0 mm 1984 – 72.5 mm	*the six largest episodes*	3 2016 – 139.5 mm 2001 – 127.7 mm 2017 – 99.8 mm
4 1980 – 82.4 mm 1992 – 78.0 mm 1984 – 72.5 mm 1995 – 54.4 mm	*the nine largest episodes*	5 2016 – 139.5 mm 2001 – 127.7 mm 2017 – 99.8 mm 2010 – 71.5 mm 2009 – 57.3 mm
Year – total daily rainfall	Occurrence of precipitation episodes with the smallest annual daily rainfall	Year – total daily rainfall
7 1974 – 16.7 mm 1979 – 20.6 mm 1993 – 22.4 mm 1986 – 23.1 mm 1997 – 24.7 mm 1990 – 25.1 mm 1976 – 25,4 mm	*the nine smallest episodes*	2 2014 – 19.5 mm 2005 – 21.1 mm
4 1974 – 16.7 mm 1979 – 20.6 mm 1993 – 22.4 mm 1986 – 23.1 mm	*the six smallest episodes*	2 2014 – 19.5 mm 2005 – 21.1 mm
2 1974 – 16.7 mm 1979 – 20.6 mm	*the three smallest episodes*	1 2014 – 19.5 mm

During the analysed period of 44 years, precipitation events with the largest annual rainfall occurred in the present century: in 2001, 2016 and 2017. Out of the 9 precipitation events with the highest daily rainfall totals, as many as five occurred in the 21st century. This represents 30% of all analysed years in the present century, with only 15% of all analysed years of the twentieth century. It is worth mentioning that the rainfall of 9 July 2001, 14 July 2016 and 26–27 July 2017 were characterized by the maximum totals in the history of recorded measurements since World War II at many stations in northern Poland, while in Gdańsk itself, the precipitation totals were by far the highest (Szpakowski, Szydłowski 2018).

The maximum daily rainfall amounts in subsequent years were definitely lower in the 20th century compared to the 21st century. Among 9 such events, 7 occurred in the years 1974–2000, which corresponds to 26% of all the analysed years of the last century. In the current century, only 2 years out of 17 were recorded, in which the maximum annual daily totals were among the 9 lowest values from the entire analysed period.

The above analysis indicates that at the turn of the 20th and 21st centuries, the trend of precipitation is changing, because in recent years record-high daily sums of atmospheric precipitation have been recorded. In the whole analysed period, the largest rainfall was noted on 14 July 2016, when nearly 140 mm was recorded at the analysed station in Rębiechowo. At some Gdańsk rainfall stations, the sum of precipitation reached as much as 170 mm on that day, which qualifies this event as the largest in Poland, not including mountainous and foothill areas (Szpakowski, Szydłowski 2018).

The shortest sequence of maximum daily sums of precipitation, on the basis of which the maximum annual daily rainfall has been estimated with a determined probability of exceedance, is 25 years (in the period of 1974–1998). For the following years, the sequence of data was increased by a maximum daily sum, to reach 44 elements for the period of 1974–2017.

In the first stage, the data was verified using the Mann-Kendall Test, excluding the existence of a monotonic trend in the time series. For each data sequence, counting between 25 and 44 elements, the calculated absolute value of the given statistic turned out to be smaller than the value of the test statistic for the assumed significance level of $\alpha = 0.05$. This means that the natural mechanism of generating maximum annual rainfall is the same every year, and past values have no impact on future values (Banasik et al. 2017).

Log- and normal distribution with the distribution parameters determined using the maximum likelihood estimation was applied in the analyses in accordance with the methodology proposed by the Polish Hydrologists Association (Banasik et al. 2017).

The values of $P_{\max,p}$ denoting the maximum daily annual rainfall with a given probability of an excess of p were calculated using the following formula:

$$P_{\max,\,p} = \epsilon + \exp\left(\mu + \sigma \cdot u_p\right) \qquad (2)$$

Where – is the lower limit of the maximum daily annual rainfall; μ, σ denote the distribution parameters determined using the maximum likelihood estimation; and u_p is the quantile of the p order in the standardized normal distribution.

Atmospheric precipitation is a variable bounded from below, and not bounded from above, therefore it is considered that the logarithmic distribution shows a good fit (Węglarczyk 2010). For each series of data, the H_0 hypothesis was verified using the Kolomogorov λ test. In each case, the value of the test statistic turned out to be less than 5% of the λ_{kryt} value, and there was no basis for rejecting the hypothesis that the distribution of maximum rainfall is a log-normal distribution.

RESULTS AND DISCUSSION

The distribution of maximum rainfall totals, based on the 25-year (1974–1998) and 44-year (1974–2017) sequences, is shown in Figure 2.

The above figure (see: Figure 2) demonstrates that, taking into account the maximum annual daily rainfall totals from the period of 1999–2017, daily rainfall with the probability of exceedance increased by about half. Undoubtedly, the biggest impact on that change in value came from three precipitation events, which occurred in 2001, 2016 and 2017. This change in daily rainfall values with probabilities of exceedance by 1%, 10%, and 20%, was presented in Figure 3.

In the case of exceedance probability of more than 20%, the increase in the maximum value of the annual daily total of rainfall is small, and it remains in the

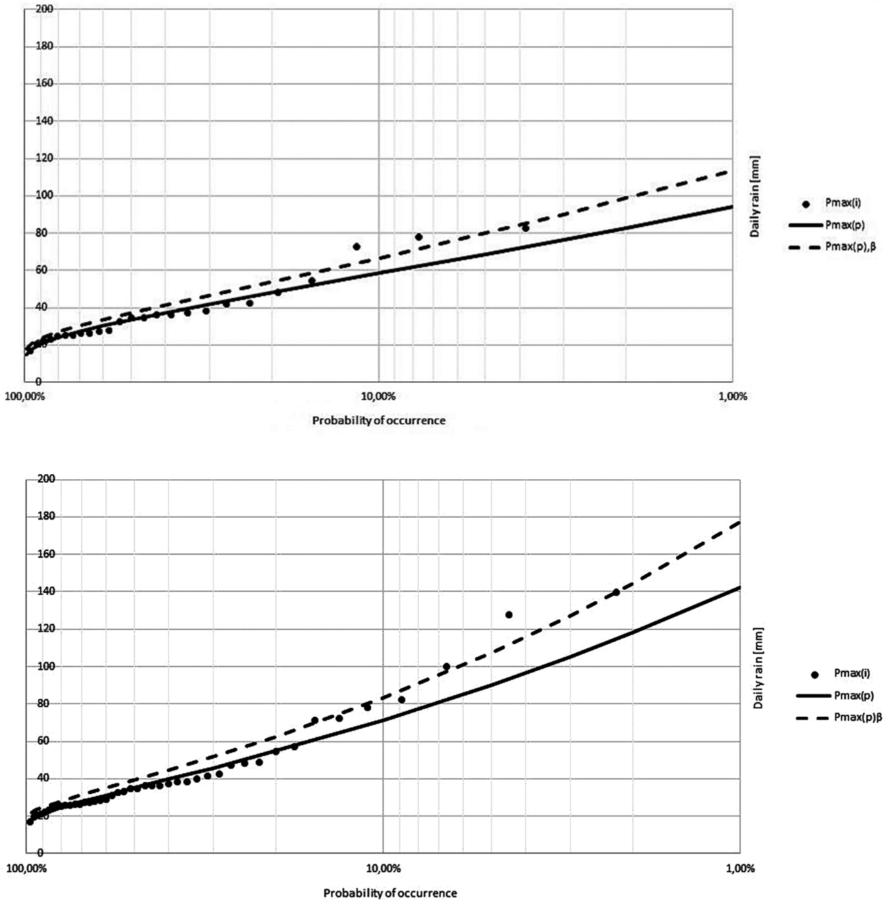

Fig. 2 The maximum annual sum of daily rainfall observed at the station of Gdańsk Rębiechowo in the periods of (1974––1998) and (1974–2017). The curve of probability of exceedance according the log-normal distribution with maximum likelihood estimation (MLE) and the limit of 85% confidence interval – $P_{max(p)B}$. $P_{max(i)}$ denoting empirical probability of the occurrence of annual maximum daily rain, $P_{max(p)}$ denoting theoretical probability of the occurrence of annual maximum daily rain

range of between 45–55 mm. The most significant increases in value can be noted for the probability of an exceedance by 1%. The maximum daily annual amount of rainfall thus calculated increased from about 95 mm at the end of the 20th century to 140 mm after two wet years of 2016 and 2017. It should be mentioned that the values up to the year 2000 are close to the values calculated using the theoretical model of precipitation by Bogdanowicz and Stachy (1998), which determines daily rainfall in the amount of 93.4 mm as precipitation event occurring once every 100 years.

Climate change, which over the last two decades in Gdańsk resulted in the occurrence of several extreme rainfall events, should affect design solutions of drainage systems. In relation to road engineering structures, such as bridges, tunnels, culverts and retaining structures, the provisions of the Ordinance of the Minister of Transport and Maritime Economy of 30 May 2000 on technical conditions to be met by road facilities, engineering structures, and their location, also apply to the passage of rainwater (Journal of Laws of 2000, No. 63, item 735, as amended). (r.w.t.d.o.i.). Pursuant to §18 passage 3 regarding the bridges, and §40 passage 2 regarding the culverts, of the r.w.t.d.o.i. regulation, reliable flow capacity for bridges should be designed depending on the road class, and in relation to the probability of exceeding the maximum annual flow (see: Table 3).

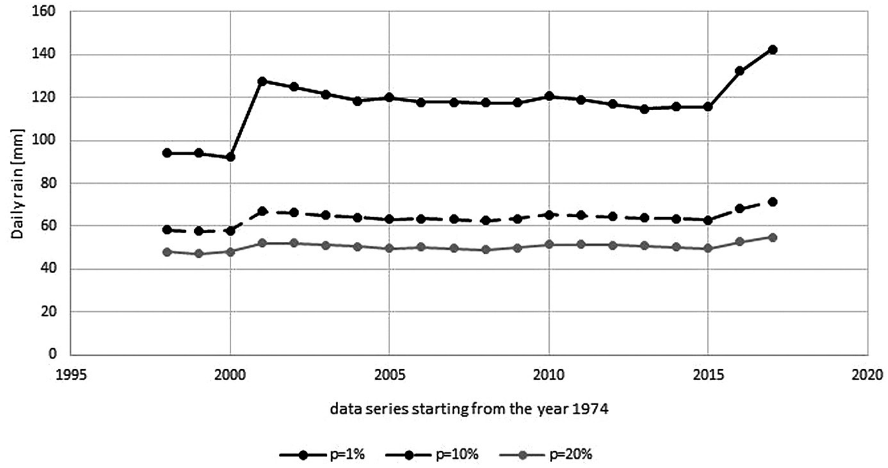

Fig. 3. Maximum theoretical daily rain sum with the probability of exceedance of 1%, 10% and 20% according to the log-normal distribution with maximum likelihood estimation (MLE)

Table 3. Criteria for determining standard rain for which road engineering structures are designed according to the Regulation of the Minister of Transport and Maritime Economy of 30 May 2000 on technical conditions to be met by road engineering facilities and their location (Dz. U. / Journal of Laws z r. 2000 nr 63 poz. 735 ze zm./as amended)

Road class	Road description	Probability of occurrence of excess flows (Repetition period of normal flow (years])	
	§18 passage 3	bridge	temporary bridge
A, S, GP	highway, expressway, major trunk road	0,3% (333)	2% (50)
G, Z	main road, collecting road	0,5% (200)	3% (33)
L, D	local road, access road	1% (100)	3% (33)
	§40 passage 2	culvert	temporary culvert
A, S, GP	highway, expressway, major trunk road	1% (100)	3% (33)
G, Z	main road, collecting road	1% (100)	5% (20)
L, D	local road, access road	2% (50)	5% (20)

The discharge of rainwater in sewage systems, aimed at achieving the appropriate standard of drainage, is regulated by the provisions of the European harmonized standard PN-EN 752: 2008 - External sewage systems. The standard distinguishes two basic hydraulic situations:

– system operation without any temporary occurrences of water - determined due to the appropriate frequency of measurable rainfall;
– reaching the water level higher than the level of street curbs and pouring it onto adjacent areas, in a socially acceptable time of recurrence. This time depends on the type and land use of the flooded area.

Recommended projected rainfall frequencies, and acceptable flooding frequencies are summarized in Table 4 below:

One of the elements of the rainwater management system in Gdańsk is reservoir retention. Generally, we are aiming at the situation where, within the real estate property, rainfall resulting from the European standard PN-EN 752: 2008 can be managed. Excess water arising during the precipitation event with the probability of 1% exceedance should be safely captured by the municipal retention reservoirs, creating a unique reservoir retention system within the city of Gdańsk, which currently includes 51 objects. Guidelines for retention reservoirs such as hydro-technical construc-

Table 4. The frequency of rainfall and the frequency of flood for different types of land development, according to PN -EN 752:2008 Drain and sewer systems outside buildings

The frequency of rainfall (once every C years]	Type of land development	The frequency of flood (once every C years]
once every 1 year	Rural areas	once every 10 years
1 x every 2 years	Residential areas	once every 20 years
1 x every 5 years	City centres, service areas and industry	once every 30 years
once every 10 years	Underground communication facilities, transitions and crossings under the streets	once every 50 years

tions are regulated by the Ordinance of the Minister of the Environment of 20 April 2007 on technical conditions for hydro-technical structures and their location (Journal of Laws of 2007, No. 86, item 579/ Dz. U z r. 2007 nr 86 poz. 579).

The calculation results presented above indicate the need to predict and safeguard larger retention volumes in the designed tanks, and to increase the size of other retention devices, because precipitation with the characteristics recognized at the end of the 20th century as precipitation with a 1% probability of exceedance after the rainfall in 2018 can be considered as a once-in-22-years event, in other words, a phenomenon with a 4.5% probability of exceedance (see: Figure 4).

CONCLUSIONS

Gdańsk is among those cities in Poland, which are particularly severely hit by meteorological events resulting from the changing climate. The very location of the city, characterized by the hypsometric diversity of the terrain surface (from -2 m to 180 m above sea level) affects the high variability of atmospheric precipitation. According to the Polish Climate Atlas, normal precipitation from the 1971–2000 period amounted to from about 550 mm (in the area of Żuławy Gdańskie and the coastal zone of the Bay of Gdańsk) to about 700 mm (in the eastern part of the moraine plateau of the Kashubian Lakeland).

The largest daily rainfall total in the analysed 27 years of the 20th century did not exceed 80 mm. Meanwhile, in the last 17 years, the daily rainfall has already exceeded 100 mm four times, to reach 170 mm in one of the stations of the local rainfall monitoring network in 2016. This particular precipitation event was classified as the largest in the lowland and highland part of Poland. At the same time, a general increase in rainfall was observed in Gdańsk. In 2017, the highest totals of atmospheric precipitation were recorded, because in several rainfall stations the sum of precipitation exceeded 900, or even 950 mm.

The analysis of the maximum daily rainfall sequences for the Rębiechowo station in the years 1974–2017 shows that rainfall events recognized at the end of the 20th century as 100-year rainfall became much more common. The observed climate changes indicate the desirability of a different approach to the design of new objects of city drainage systems, and the need

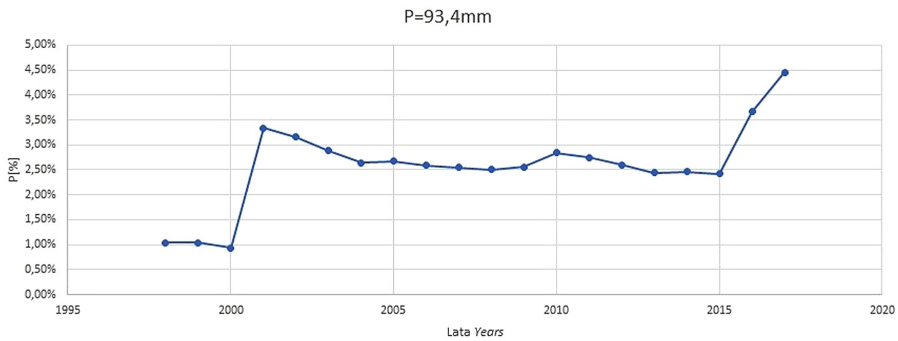

Fig. 4. Probability of occurrence of 1% daily rain equal 93.4 mm calculated by Bogdanowicz and Stachy (1998) based on maximum annual daily rainfall totals, starting from the year 1974, for the meteorological station in Rębiechowo

to increase the residents' awareness about responsible property development, including water storage activities. It is equally important to start a discussion on the modernization of existing facilities that were designed 20 years ago with the 100-year rain in mind; namely, whether they are currently able to safely contain water resulting from the precipitation occurring four times more often, with the qualification of a single event including both the higher intensity of shorter precipitation, and longer duration of rainfall with lower intensity.

The presented results of calculations indicate that climate changes affect individual cities, which are forced to spend more and more funds in order to adapt to the new situation. In the case of Gdańsk, these activities began after the first flood resulting from the occurrence of extraordinary rainfall in 2001. Retention reservoirs are being built, of which there are now more than 50. Guidelines and provisions in local spatial development plans are modified with better rainwater management in mind. Also, various initiatives are implemented, aimed at developing small-scale water retention systems. The owners of individual properties, who minimize potential flood losses through various activities, have a significant share in adapting the city to climate change.

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Rozporządzenie Ministra Transportu i Gospodarki Morskiej z dnia 30 maja 2000 r. w sprawie warunków technicznych, jakim powinny odpowiadać drogowe obiekty inżynierskie i ich usytuowanie. (Dz. U. z r. 2000 nr 63 poz. 735 ze zm.).

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OPADY PRAWDOPODOBNE W GDAŃSKU W ŚWIETLE ZMIAN KLIMATYCZNYCH

ABSTRAKT

Zmiany klimatu objawiające się m.in. występowaniem większej liczby epizodów opadowych, cechujących się większą intensywnością, wpływają na stabilność ekonomiczną miast. Takim przykładem jest Gdańsk, miasto w którym od początku XXI wieku występują tego typu zdarzenia. Ze względu na wysokościowe zróż-

nicowanie miasta pojawienie się ekstremalnego opadu atmosferycznego praktycznie natychmiast powoduje skutki hydrologiczne w sieci hydrograficznej, składającej się z kilkunastu potoków o charakterze górskim, spływającym w kierunku wschodnim z wysoczyzny Pojezierza Kaszubskiego. Stacje meteorologiczne Państwowej Służby Hydrologiczno Meteorologicznej IMGW-PIB znajdują się w pasie nadmorskim (Port Płn., Świbno) oraz w najwyżej położonej części miasta (Rębiechowo). Ponieważ jest to niewystarczające, miasto Gdańsk od roku 2001 rozbudowuje lokalną sieć monitoringu opadów, dysponując obecnie wiarygodnymi ciągami 10-cio letnich obserwacji. Sieć tą eksploatuje spółka miejska Gdańskie Wody.

Zmiany klimatu, skutkujące inną charakterystyką występujących w Gdańsku zjawisk opadowych, w sposób naturalny wpływają na określanie prawdopodobieństwa ich wystąpienia. Według modelu opadowego opracowanego przez Bogdanowicz i Stachy (1998) na przełomie XX i XXI wieku w ostatnich 17 latach co najmniej 4 zdarzenia opadowe o czasie trwania powyżej 8 godzin, należy zakwalifikować jako deszcz 100-letni. Jeden epizod spośród nich przekroczył parametry deszczu 300-letniego, zaś opad z roku 2016 w którym 14 lipca zanotowano nawet 170 mm opadu, autorzy kwalifikują na co najmniej deszcz 500-letni. W tym okresie wystąpiły również zdarzenia kilkunastominutowe, które również przekraczały parametry deszczu 100-letniego.

W pracy przedstawiono modele opadowe dla rejonu Gdańska, a na podstawie maksymalnych rocznych sum dobowych opadów ze stacji Rębiechowo z wielolecia 1974–2017 dokonano analizy zmian wartości opadu odpowiadających określonym prawdopodobieństwom wystąpienia. Dokonano również oceny wzrostu wartości projektowych opadów w stosunku do budowli hydrotechnicznych, drogowych obiektów inżynierskich oraz systemów kanalizacji deszczowej w świetle zmieniających się przepisów prawnych, a także najnowszych trendów związanych z zagospodarowywaniem wód opadowych.

Słowa kluczowe: opad atmosferyczny, model opadowy, zlewnia zurbanizowana, zmiany klimatu