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Original Research

Evaluating the Catastrophic Rainfall of 14 July 2016 in the Catchment Basin of the Urbanized Strzyza Stream in Gdańsk, Poland

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Abstract

We analyzed the causes, the course, and consequences of the extreme precipitation events that occurred 14 July 2016 in the watershed of Strzyza Creek in Gdańsk, Poland. Automated rain gauges located in Strzyża catchment registered a total precipitation lasting about 16 hours – from 129 to 160 mm of rain depth. More in-depth analysis based on rain data collected by Gdańsk University of Technology (GUT) rain station was done. The course of rainfall was compared with existing rain models on the national range and also with local rain formula. The results showed that, according to the Chomicz classification, the rainfall can be qualified as torrential. Its course far exceeded the theoretical values calculated for the probability of occurrence 1% (return time: 100 years). Although the analyzed rain episode was characterized by extremely high instantaneous rainfall intensities, the duration of the most intensive middle stage of about eight hours caused the highest daily rain sum registered in Gdańsk in the history of meteorological measurements. As a result, the rainfall caused two fatalities in the lower part of the Strzyza watershed. It was noted that this type of rain qualified as an extraordinary event at the turn of the XX and XXI centuries in areas located in the Mediterranean region. Rainfalls that currently occurr in this part of Europe are also characterized by proportionally higher parameters that should be considered as an indisputable effect of climate change on a global scale.

Keywords: urban flooding, extreme events, rainfall, DDF curve, IDF curve

Introduction

Extraordinary rainfall events occur in areas adjacent to sea shores all over the world. Referring to the European continent, the following events may be mentioned: 13-14 January 1994 in Crete (123 mm rainfall in five hours, daily sum of precipitation about 183 mm) [1] and 9 September 2010 on the Amalfi Coast, Italy (135 mm within six hours and maximum intensity of 90 mm per hour) [2].

The catastrophic event that occurred 14 July 2016 in Gdańsk is characterized by rain parameters similar to

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the above-mentioned rainfalls in southern Europe. The average monthly sum of precipitation in the Gdańsk area is the highest for the month of July and reaches about 75 mm [3]. However, for the second time in the Gdańsk region in the 21st century, the health and safety of residents were threatened as a result of the unforeseen rainfall. The first extraordinary rain episode occurred the 9 July 2001, when daily precipitation in the Strzyza catchment exceeded 120 mm. The second such rainfall took place on 14 July 2016 with a daily sum of precipitation exceeding 150 mm. The rainfall area in both cases was similar and contained the whole watershed of Strzyza creek and neighboring stream catchments in the Gdańsk agglomeration. The sum of total precipitation in 2016 was 20 percent higher than in 2001, but losses resulting from the rainfall were much smaller in 2016. Expenses incurred by the city authorities for flood protection in Gdańsk in the amount of €80 million protected the residents living in the southern districts of Gdańsk – especially in the neighborhood of Radunia Canal. Only in Strzyza catchment were flood losses in 2001 and 2016 similar to each other. The greatest loss was the death of two people trying to save their goods in the basement of one building situated within the flooded area of Strzyża catchment in 2016.

Material and Methods

Meteorological Causes of 14 July 2016 Rain Fall

From 10 July southeastern Poland was under the influence of tropical air masses associated with a center of high-pressure over the Balkans. Two thermal zones developed over Poland: the northwestern part of the country remained under the influence of maritime polar air mass with temperatures oscillating around 25ºC. The maximum temperature on 11 July amounted to almost 28ºC in Lębork and Szczecin and 26ºC in Koszalin [4]. In the rest of the country the maximum air temperature significantly exceeded 30ºC. On 11 July 34ºC was recorded in Opole, Legnica, Kalisz, and Płock [4]. On 13 July the tropical air mass moved away to the southeast of the country while central Poland experienced local rainfalls associated with the colder air mass transition. The short-duration rainfall with a sum of 30-40 mm caused extensive flooding of urban infrastructure in Warsaw. The measured sum of daily precipitation in Torun was almost 75 mm. The rainfall area along the eastern border on 12 and 13 July 2016 was stretched with daily values greater than 30 mm in the region of Białystok, about 50 mm in the region of Włodawa, and almost 70 mm in the Bieszczady Mountains [5].

On 14 and the 15 July 2016 a shallow low-pressure area moved from southeastern to northern Poland. A wide system of atmospheric fronts was arising. The eastern part of the country was in a hot and humid tropical air mass while the rest of the country remained in a warm mass of polar air. Over the Gulf of Gdańsk, the extremely warm air from the east, initially linked with the warm atmospheric front that was transformed in an occluded front, flowed in. Precipitation lasted continuously for 14 to 17 hours (approximately from 10:30 UTC on 14 July until 03:00 on 15 July 2016) in the area of Gdańsk. From the Gulf of Gdańsk to the western part of Poland – along the line Gdańsk-Poznan-Legnica – a continuous rain zone was formed. The registered daily sum of rain did not exceed 110 mm. The only exception was Gdańsk agglomeration, when the orographic processes caused much stronger rain. The daily sum of precipitation in forests of Tri-cities Landscape Park in Gdańsk-Oliwa reached 170 mm [6]. The above recorded value exceeded twice the monthly precipitation average for July.

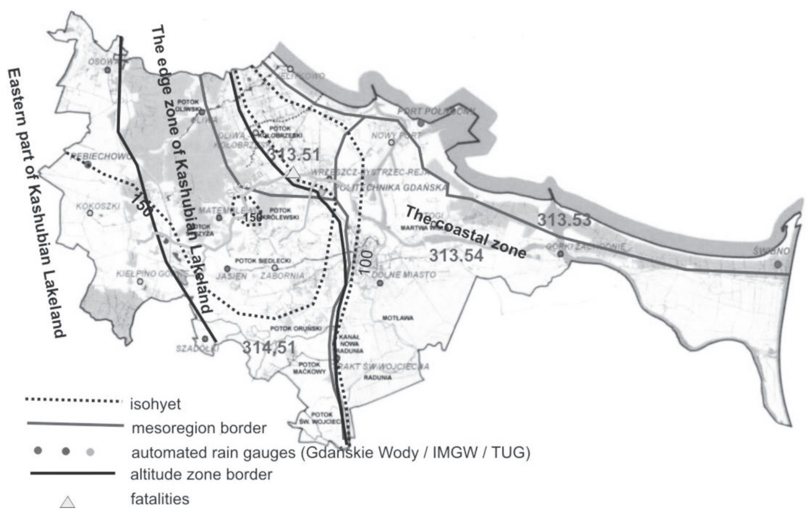

Fig. 1. Mesoregions in Gdańsk area according to Kondracki [7], and division of Gdańsk on different height zones as suggested by the network of automated rain measurement gauges [6].

14 July 2016 Rainfall Distribution in the Gdańsk Region

The Gdańsk region includes areas both adjacent to the shoreline of the Gulf of Gdańsk and the region of moraine hills of the Kaszuby Lakeland region. The entire rainfall episode in the Gdańsk agglomeration occurred during daily rainfall on 14 July 2016 (from 06:00 UTC 14 July to 06:00 15 July) and was registered by the Gdańsk rain monitoring system (12 automated rain gauges controlled, calibrated, and verified by the Gdańskie Wody Company [6]), meteorological stations of the Institute of Meteorology and Water Management, and Gdańsk University of Technology automatic rain gauge and Hellmann ombrometer. As mentioned, the warm and moist air mass flowing from the Gulf of Gdańsk to the west rose up at the same time over the moraine hills of Kaszuby. The difference in altitude between the shoreline and the highest part of western Gdańsk exceeds 160 m. As a result of adiabatic vertical lifting of air mass in the region on the edge zone of Kaszuby, rapid condensation of water vapor occurred. Consequently additional orographic precipitation processes appeared. Hence, the most intense rainfall occurred in the area between the lower terrace Tri-City and Kaszuby. Therefore, in Gdańsk three basic height zones can be distinguished due to different weather processes. Different and significant sums of rain were recorded within each zone. (Fig. 1):

– The coastal zone includes the lowest part of Gdańsk, situated adjacent to the Gulf of Gdańsk and characterized by a very gentle altitude gradient. According to the Kondracki division [7], the above zone includes mesoregions Vistula Spit (313.53), Vistula Delta Plain (313.54), and the lowest and easternmost part of the mesoregion Kaszuby Coast (313.51). Total daily rainfall in close proximity to the Gulf of Gdańsk does not exceed 100 mm.
– The edge zone of Kaszuby Lakeland is an area of steep gradient in terrain altitude, from about 10 to 150 m a.s.l. The edge zone includes the western part of the mesoregion Kaszuby Coast (313.51) with a total daily rainfall of about 150 mm and the eastern part of the Kaszuby Lakeland mesoregion (314.51), where total daily precipitation exceeded 150 mm and reached 170.2 mm in the Oliwa rain gauge [6]. Exceptional precipitation was registered in the area of Ogrodowa Street, wherein total rain depth on 14 June 2016 was only 130 mm. It should be noted, however, that this station is located in the lowest local area of Strzyża Valley surrounded by moraine hills.
– The eastern part of Kaszuby Lakeland is an area characterized by a gentle gradient of altitude compared with its edge zone. It is assumed that this area is located on the western side of National Highway S6. In the southern part of the analyzed area the total daily rainfall exceeded 100 mm, while in the northern part, Gdańsk Osowa, the amount of precipitation was about 160 mm. At the stations of the University of Gdańsk located in Kaszuby (approximately 20-30 km west of Gdańsk), the daily sum of rain on 13-15 July 2016 did not exceed 50 mm [8]. Similarly, meteorological stations located on the eastern side of the Vistula River recorded 25-40 mm daily rain, which was not exceptional.

Table 1. Highest values of daily rain sums in Poland measured in the 20th and 21st centuries (until 2010), together with values measured on 14 July 2016 at Oliwa Station [6, 9-10].

Location, voivodeship	Daily rain sum (mm)	Date
Hala Gąsienicowa, małopolskie	300.0	30.06.1973
Witów, małopolskie	285.0	16.07.1934
Leskowiec	242.9	18.07.1970
Stańcowa	234.4	18.07.1970
Magurka, ślaskie	229.3	18.07.1970
Szczyrk, ślaskie	224.0	18.07.1970
Nieszawa	221.7	8.07.1955
Sienno k. Kielc	218.5	19.05.1941
Wałbrzych, dolnośląskie	206.5	18.06.1979
Jakuszyce, dolnośląskie	204.3	07.08.2006
Maków Podhalański,	190.8	25.07.2001
Zakopane,	172.3	16.07.1934
Gdańsk Oliwa,	**170.2**	**14.07.2016**
Kasprowy Wierch, małopolskie	166.1	08.07.1997
Bielsko-Biała, śląskie	162.7	16.05.2010
Kielce,	155.2	24.07.2001
Mławka k. Mławy	155.1	14.06.1999
Bielsko Biała, Śląskie	147.4	21.08.1972
Łeba, Pomorskie	141.0	24.07.1988
Pielgrzymów, opolskie	135.7	15.08.2008
Cieklin, podkarpackie	132.5	21.06.1955
Słubice, Lubuskie	132.5	08.08.1978
Ustrzyki Dolne, podkarpackie	132.0	12.06.1957
Baligród Mchawa	130.6	26.07.2005
Mosty, lubelskie	129.3	11.08.2006
Tarnów, Małopolskie	128.7	16.07.1934
Gdańsk Rębiechowo, Pomorskie	**127.7**	**09.07.2001**
Zielonki (Stare Babice)	126.5	05.08.2002
Ulszkowice, pomorskie	125.6	09.07.2001
Radostowo, pomorskie	122.2	09.07.2001
Słubice, lubuskie	121.5	04.07.2009

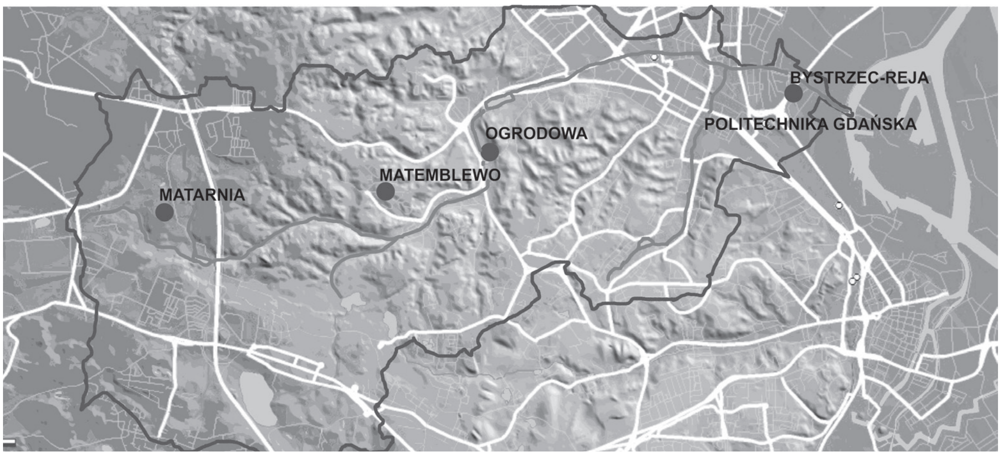

Fig. 2. Digital terrain model (DTM) of the Strzyża Stream catchment area with catchment boundary and precipitation gauges: Politechnika Gdańska - Gdańsk University of Technology - GUT (light point), Gdańskie Wody (circle) [12].

In view of the presented daily sum of precipitation distribution on 14 July 2016, the variability of altitude shows that an additional 60-70 mm of rain in the region of the edge zone of Kaszuby has the origin in the orographic processes provoked by moving air masses.

Compared to precipitation events in Europe, the analyzed rainfall was not a unique episode. When hills or mountains in the neighborhood of the coastline are higher than hills surrounding the Gdańsk agglomeration, the orographic effect of rainfall may be much more intense. On 3 October 2015 in France, a pressure system provoked the inflow of hot and humid air mass into the Côte d'Azur area. Air rising up to 1,000 m caused dramatic rainfall 20 km from the coast of the Mediterranean sea onto land. 106 mm of rain was noted in Cannes within one hour and 175 mm in two hours. The total sum of precipitation was 196 mm. The rainfall was accompanied by strong lightning due to storm clouds that developed in the upper troposphere. Twenty people were killed in the flooding and the calculated initial losses exceeded €500 million [9].

The rain episode of 14 July 2016 in Gdańsk is one of the most intensive daily precipitation events recorded in Poland [10-11] (Table 1). Higher daily rain sums have been registered mainly in the mountains, where normal precipitation is twice higher compared to Gdańsk.

As mentioned, the greatest losses due to the rain which covered the region on 14 July occurred in Strzyza Creek Watershed. Therefore, the rainfall event and its effects in the largest catchment of Gdańsk stream have been analyzed in more detail.

Characteristics of Strzyza Catchment

At 13.2 km long, the Strzyza flows from the source region at a height of about 140 m a.s.l. Its catchment area includes wooded upland moraine, industrial zones, and sites of dense urban development. Longitudinal declines in the stream are in the range 0.5-5%, and the mean catchment slope in the eastern direction is approximately 1%. The total area of Strzyza catchment is equal to 33.9 km^2 (Fig. 2). Nine reservoirs with a total area of 13.46 hectares and the retention capacity of approximately 215,000 m^3 operate in the catchment. The biggest of them are Kielpinek and Jasien, located in the upper part of the watershed with total retention capacity of 108,000 m^3, and Srebrniki Reservoir with a water storage capacity of 64,500 m^3, located on the border of the edge zone of Kaszuby and the lower terrace of the city [6].

Normal rainfall in Strzyza catchment varies from 550 (lower part) to 700 (upper part) mm. The annual sum of precipitation in subsequent years differs significantly, depending on location details. For example, for 2009 the rain height variation between stations was 82 mm, and for 2010 up to 171 mm. This indicates a significant spatial variation of rainfall in this part of Gdańsk [12].

In the closing cross-section of Strzyza Basin, the average annual flow rate SSQ in the period 2000-14 amounted to 0.175 m^3/s. The highest average annual flow rate of the mentioned interval WSQ occurred in 2001 and amounted to 0.222 m^3/s. On the contrary, the smallest average annual flow rate NSQ occurred a year earlier at 0.137 m^3/s. Maximum flow rate corresponding the bankfull stage is about 22 m^3/s [13].

Total precipitation on 14 July 2016 in Strzyza Catchment ranged from 129.9 mm at Ogrodowa station to 162.1 mm at Matemblewo station. The results of precipitation were recorded on an automatic tipping-bucket rain gauge Davis Vantage Pro 2 at the weather station located at Gdańsk University of Technology (GUT) and were taken into account for detailed analysis. An automatic station was installed in 2008 in the weather garden of the Faculty of Civil and Environmental Engineering of GUT, and records of meteorological parameters with a time step of 10 minutes and measurement accuracy of 0.2 mm were realized. In the daily rain 14 July the rain gauge registered 150.8 mm of rain. The control rain gauge (Hellmann instrument) indicated 152.2 mm at the same time.

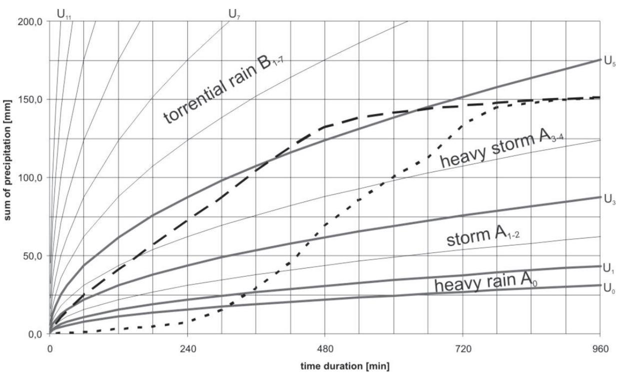

Fig. 3. Sum rain curve of the 14 July 2016 rainfall event (dotted line) and maximum precipitation totals at predetermined time curve (dashed line) against Chomicz scale curves $U_{0\text{-}11}$ [13].

Characteristics of Used Rain Models

The basic classification of storm selection for a single rainfall episode is adopted based on the Chomicz rainfall intensity scale, which is popular in Poland [14].

$$U_k = \alpha_k \sqrt{t} \text{ . where } \alpha_k = \sqrt{2^k} \tag{1}$$

…where U_k is the upper limit value of rainfall depth for kth grade of Chomicz scale (mm) and t is the time of rain duration (min). The boundary between storms and torrential rains is grade $k = 5$ on that scale. Area A_0 means heavy rains, $A_{1\text{-}2}$ storms, $A_{3\text{-}4}$ heavy storms, and B torrential rains (Fig. 3).

In the analyses of randomly occurring single rainfalls, nationwide rain models (Reinhold, Lambor and Bogdanowicz-Stachy) [15] and a local rain model (Weinerowska-Bords) [3] were used. The obtained results were compared with Rozanski analysis based on the rainfall data of Polish meteorological stations until 1929, which was prepared in 1930 [16]. The Reinhold equation is based on the knowledge of precipitation intensity for the time duration of 15 minutes and return period of C = 1 year (which corresponds to the probability occurrence p = 100%), which is designated as q_{15}. Rain intensity q in function of q_{15} and also time duration t and return period for rainfall C is described by Eq. 2 [17]:

$$q = q_{15} \frac{38}{t+9}\left(\sqrt[4]{C} - 0{,}369\right) \text{ [dm}^3\text{ /(s ha)]} \tag{2}$$

The values of annual rainfall intensity q_{15}, initially established in 1940 for the historic territory of Germany, is for Gdańsk 93 dm³/(s ha). In Germany these values are determined currently individually for each catchment and gathered in the KOSTRA atlas as guidelines for environmental design purposes in Germany [15].

Lambor proposed a rain intensity formula with the probability of occurrence p and duration time t in function of normal annual rain [18]:

$$J = \frac{(38 - 12 \cdot \log p) H^{0,28}}{(t+c)^n} + d \tag{3}$$

The parameters in the above equation – c, d, n – are defined for the Gdańsk region as follows:

$$c = \frac{1}{1000}\left(20.92 \cdot H \cdot p^{0,345} - 0{,}15 \cdot p - 2.0\right) \tag{4a}$$

$$d = \frac{1}{1000}\left(47.3 - 0.023 p\right) \tag{4b}$$

$$n = 0.779 - 0.164 \cdot H \tag{4c}$$

…where J is precipitation intensity (mm/h), H is the value of normal rain (mean annual value) for selected localization (m). The Lambor formula was widely used in the 1950s, but now this model is less often used [17].

The rain model proposed by Bogdanowicz and Stachy, commonly called the IMGW formula, was published at the end of the last century. It was established on the basis of maximum annual precipitation data registered by 20 meteorological station in 1960-90. According to the authors, the formula can be used for establishing the probability of exceedance of rainfall episodes $p \in (0;1]$ [15]. The maximal precipitation depth P (mm) with the probability of exceedance p (-) depending on the duration time t (min) is as follows [19]:

$$P_{\max,p} = 1{,}42 \cdot t^{1/3} + \alpha \cdot (-\ln p)^{0{,}584} \tag{5}$$

Parameter α, which consists of the location and the scale for the northwestern part of Poland, is defined as:

$$\alpha = 3{,}92 \cdot \ln(t_m + 1) - 1{,}662$$

for the duration time 5≤t≤30 min (6a)

$$\alpha = 9{,}16 \cdot \ln(t_m + 1) - 19{,}6$$

for the duration time 30≤t≤60 min (6b)

$$\alpha = 2{,}223 \cdot \ln(t_m + 1) + 10{,}639$$

for the duration time 120≤t≤720 min (6c)

$$\alpha = 9{,}472 \cdot \ln(t_m + 1) - 37{,}032$$

for the duration time 720<t≤4320 min (6d)

Local rain models are based on local precipitation data. It is worth mentioning the results obtained for Kraków [20-21] and Wrocław [22-23]. For the Gdańsk region Weinerowska-Bords established the local rain formula based on 122 rain episodes collected by the GUT meteorological station in the period 1991-2010 [3]. All rain episodes that passed the criterion $2/3U_0$ on the Chomicz scale were selected as a source data to be used in global optimization with computational procedure

CRS (controlled random research). The formula for precipitation intensity q [$dm^3/(s\ ha)$] for the duration time $t<60$ minutes is written as:

$$q = -a \cdot \ln p + b \quad (6)$$

$$a = 0.011306 \cdot t^2 - 1.500482 \cdot t + 69.2635 \quad (6a)$$

$$b = 0.075719 \cdot t^2 - 9.04707 \cdot t + 374.845 \quad (6b)$$

… and for the duration time $t \geq 60$ min.:

$$q = a \cdot p^{-b} \quad (7)$$

$$a = 0.017767 \cdot t^2 - 2.756281 \cdot t + 247.28426 \quad (7a)$$

$$b = 0.002902 \cdot t + 0.271315 \quad (7b)$$

Because of the duration time of analyzed rain episodes and their lasting period not exceeding 120 minutes, the practical use of equations 6 and 7 is limited by the probability of exceedance greater than $p = 5\%$ and the rain duration time $t \leq 120$ min.

Using data concerning the torrential rains that occurred in Polish lands until 1929, Rozanski proposed a formula based on the Hellman equation, which represents the upper limit of total precipitation, depending on the rain duration time. The use of the formula is limited to the rain duration of 360 minutes. With regional coefficients for northern Poland (Pomerania) it can be written as follows [16]:

$$I = a + \frac{b}{\sqrt[3]{t}} \quad (8)$$

$$a = -0{,}512 \quad (8a)$$

$$b = +5{,}640 \quad (8b)$$

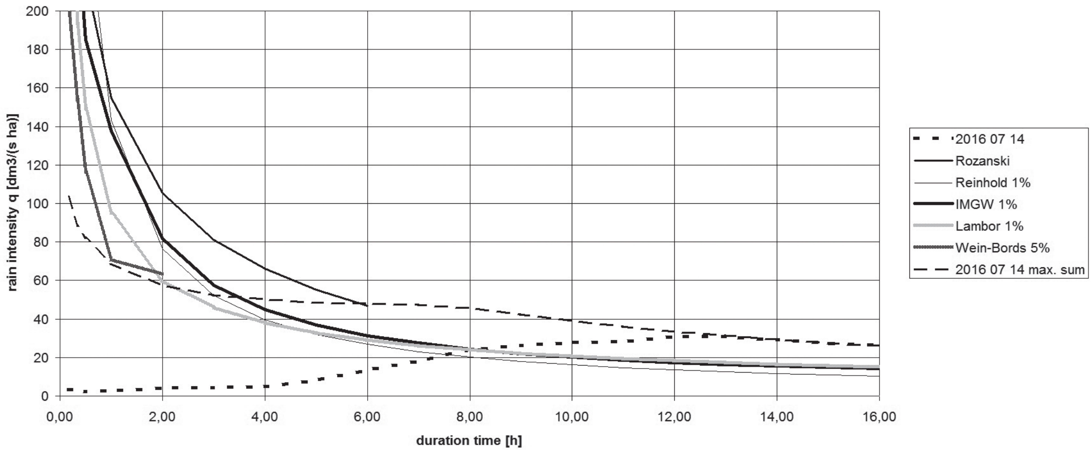

Fig. 4. Maximum rain intensity at predetermined time curve (2016 07 14 max. sum) and rain intensity curve from the beginning of the 14 July 2016 (2016 07 14) event together with IDF curves of rain models.

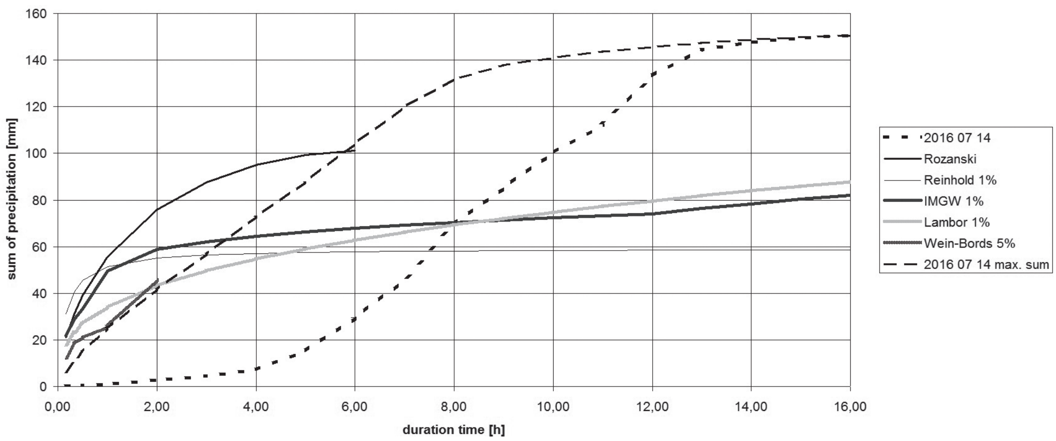

Fig. 5. Maximum rain sum at predetermined time curve (2016 07 14 max. sum) and rain sum curve from the beginning of the 14 of July 2016 (2016 07 14) together with DDF curves of rain models.

Results and Discussion

The duration of the14 July 2016 rain at the GUT station was approximately 16 hours. According to the Chomicz scale, three stages of temporal distribution can be distinguished:

1. 260 minutes, from about 10:40 to about 15:00 UTC. This stage is characterized by low intensity of precipitation, below the curve U_1, which indicates a normal rain. The sum of precipitation at this stage was 8.4 mm.
2. 480 minutes, from about 15:00 to about 23:00 UTC, characterized by high intensity of precipitation. After 390 minutes above curve U_5, which indicates torrential rain. The sum of precipitation at this stage was 130.4 mm, and mean rainfall intensity was greater than 0.27 mm/min.
3. 220 minutes, from about 23:00 UTC to the end of the rain. This stage is characterized by low intensity of precipitation, below curve U_1, which indicates a normal rain. The sum of precipitation at this stage was 12.0 mm.

Taking into account the course of the rain sum curve (Fig. 3), the analyzed rain did not exceed the U_5 curve of the Chomicz scale and can be categorized as a heavy storm. However, due to the course of the middle stage expressed as the curve of maximum totals of precipitation at a predetermined time, the rainfall is undoubtedly classified as a torrential rain. It should be noted that the Chomicz criterion is considered a preliminary indicative criterion and has a mainly descriptive significance [15].

Different rain durations (from 10 minutes to 16 hours) were assumed in analysis. For the predetermined time the duration was the highest total sum of precipitation (curves 2016 07 14 max. sum in Figs 4-5) from the entire event. The values calculated from the rainfall histogram were also represented in Figs 4-5 (curves 2016 07 14).

Taking into account equations 2-8 for different rain models, intensity-duration-frequency (IDF) and depth-duration-frequency (DDF) curves were elaborated upon. IDF curve (Fig. 4) presents the calculated rain intensity q[dm^3/(s ha)] in function of its frequency of coincidental occurrence and rain duration t(min). The value of rain intensity for the rain duration time from 5 minutes to 16 hours were calculated. The probability of rain occurrence of $p = 1\%$ for the Reinhold (Eq. 2) Lambor (Eq. 3) and IMGW (Eq. 5) rain models was supposed in the calculations. For the local rain model (Eqs. 6 and 7) a value of $p = 5\%$ was assumed due to the limitation of the model. The upper limit of total precipitation proposed by Rozanski (Eq. 8) and curves representing the real event of 14 of July 2016 (2014 07 14 and 2014 07 14 max.sum) are also presented in Fig. 4.

On the basis of rainfall intensity q, expressed in dm^3/(s ha), the intensity of precipitation can be determined in mm/min or mm/h using the transformation:

$$1\frac{dm^3}{s \cdot ha} = \frac{60}{10000}\frac{mm}{\min} = \frac{3600}{10000}\frac{mm}{h} \qquad (9)$$

After multiplying by time the intensity of rainfall in mm/min or mm/h, a total sum of precipitation in a determined time can be found. The dependence of total precipitation sum in function of rain time duration and the probability of rainfall occurrence is described by the DDF curve, which is shown in Fig. 5 for the same curves as in Fig. 4.

Calculations show that the course of rainfall recorded on 14 July 2016 at the Gdańsk University of Technology rain station exceeded the probability of the rain occurrence of 1% calculated for all rain models after eight hours of rain. During this time 76 mm of rain were collected, which is quite close to the 70 mm collected during the 3.5 hours of the middle stage of rain. Taking into account the maximum total sum of precipitation for a predetermined time, already in the interval of 3.5 hours all theoretical values of rainfall intensity for 100 years return time were exceeded. The maximal sum of rain for the predetermined time of 360 minutes was below the upper limit of total precipitation proposed by Rozanski [16], who collected rain data in the first three decades of the 20th century.

Due to the fact that the middle stage with the highest rain intensity lasted up to eight hours, the total sum of precipitation over 130 mm nearly doubled the theoretical values of IMGW and Lambor rain models for the probability of occurrence of 1%. The intensity of precipitation in this phase varied from 12 to 22 mm/hour. Therefore, the duration time of the middle stage with an average intensity of more than 16 mm/hour (45 dm^3/(s ha)) was the major anomaly with respect to the course of historical rainfall episodes. Additionally, the sum of the rain, which was registered at Gdańsk University of Technology within 16 hours of rainfall, exceeds by 30% the rain characterized by the return time of 500 years as calculated by Twardosz for Kraków conditions [20].

To estimate the effects of catastrophic precipitation in the Strzyza Catchment, the commonly known SCS method was used [24-25]. In order to evaluate the curve number of SCS method (CN) for the entire catchment, the whole basin was divided into 43 sub-areas with estimated constant value of the CN parameter for each sub-area. This parameter depends on the surface development, soil conditions, and land slopes. The mean CN coefficient for the mean moisture level was established as 78.64 [26], which corresponds to CN = 61 for the dry humidity level and was adopted for the effective rainfall estimation. Finally, for the 14 July 2016 episode the effective precipitation and in consequence the Strzyza outflow was estimated at 63.8 mm, which constitutes 42.3% of total precipitation (Table 2).

The results show that in the middle stage of the rain (from the 7th to the 13th hours of rain) the outflow volume at the mouth of Strzyza Stream is far beyond the estimated channel capacity corresponding to the shoreline water level as 22 m^3/s [13].

The recommendations of the German Association for Water, Wastewater, and Waste Management DWA-A118: 2006 [27] indicate that in order to determine the rain

Table 2. Estimating the effective rain in successive rain hours based on Gdańsk University of Technology automated rain gauge data regarding 14 July 2016 using the SCS method [24].

Time	Rain	Effective rain	
hour	mm	mm	m^3/s
1	1	0.0	0.0
2	2	0.0	0.0
3	1.6	0.0	0.0
4	2.8	0.0	0.0
5	7.8	0.1	0.5
6	14	1.6	14.7
7	16.6	4.2	39.1
8	23.6	9.1	86.1
9	15.8	7.7	72.9
10	15.2	8.4	79.2
11	12	7.2	67.7
12	21	13.6	127.7
13	11.2	7.7	72.2
14	3.2	2.2	21.1
15	1.8	1.3	11.9
16	1.2	0.8	8.0
Total:	150.8	63.8	

probability occurrence of 10%, there should be at least 30 years of rain courses data of both short and long episodes. Taking these guidelines into account, some authors have suggested that in urban conditions the intensity duration frequency curve can be calculated only for a return time of 20 years (p = 5%) in the present state of knowledge [28].

Conclusions

The rainfall on 14 July 2016 in Gdańsk was exceptional. The analysis of the data was based on a comparison with existing rain models for a 1% probability of occurrence corresponding to a return time of 100 years. Analyses showed that the rain course and its parameters do not correspond to the Polish models of precipitation as described by the IDF and DDF curves. The main reason is the course of the middle rainfall stage, with an average intensity of 45 $dm^3/(s\ ha)$ and having a long duration time of about eight hours. This catastrophic rainfall was classified as torrential characterized by number B_1 of the Chomicz scale.

During eight hours of the most intense rainfall, about 130 mm of rain fell into the Strzyża Catchment. Assuming the maximal safety water outflow of 22 m^3/s in Strzyza Estuary, the excess of water created for at least seven hours an additional ground retention in subterranean areas (e.g., cellars, underground garages, underground commercial buildings) or outflowed from Strzyza Watershed in a different way (in disagreement with sanitary sewage system laws).

The rainfall event that took place in Gdańsk Strzyza Basin on 14 July 2016 was catastrophic. The total sum of precipitation for the 16-hour rainfall episode in Gdańsk University of Technology (150.8 mm) was one of the highest daily precipitation rates ever recorded in northern Poland. However, there was no extreme rain intensity in its course, but due to the duration of the rain, the total amount of precipitation was that high. It is important to note that the health and safety hazards of inhabitants due to torrential rains can occur more frequently because of the change in the causes of such events (e.g., climate change). This confirms only a 15-year interval of "calm" between rainfall catastrophes in Strzyza Catchment between 2001 and 2016.

Extreme rainy episodes observed both in Poland and Europe should convince the authorities to renew guidelines for a safer dimensioning of stormwater management systems.

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