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HYDROLOGICAL EFFECTS OF URBANIZATION: THE EXPERIENCE FROM THE SOKOŁÓWKA CATCHMENT (ŁÓDŹ)

1. INTRODUCTION

The urbanization in the contemporary meaning of this word is a specific sign of the transformations that have taken place since the beginning of the 19th century and which are related with industrialization (Liszewski and Maik, 2000). It constitutes a universal process, both in terms of time and space. At the same time it is multi-directional in nature due to the changes it causes in the natural and cultural environment.

It is estimated that by the year 2030, more than 60% of the world population will have lived in urban areas (Paul and Meyer, 2001). Currently, the urban areas occupy only approximately 2% of the land surface, however, they significantly impact the natural environment. The city centres themselves generate more than 78% of all greenhouse gases (Grimm *et al.*, 2000). Modified properties of the surface of large cities cause a whole range of climatic changes. These changes affect temperature, atmospheric precipitation and cloudiness. High-rise buildings modify the flow of air and the level of its pollution, and supply of artificial heat contributes to formation of a climate with individual characteristics, which is different from the climate appropriate to rural areas.

The phenomenon of the so-called 'urban heat island', which is an effect of the city impact on climate, is most commonly discussed (Gaston, 2010). It involves

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absorption of short wave solar radiation by an increased field of the absorbing surfaces (not only flat surfaces, such as roofs and streets, but also walls of buildings), greater thermal capacity of building materials and smaller albedo of the surface. Energy absorbed by buildings is retained in the 'urban tissue' for longer periods due to the so-called 'urban canyons', i.e. streets cutting through high-rise buildings. Urban built-in areas and varied height of the buildings also impact the increase of aerodynamic roughness of the surface, which results in a reduced wind speed and additionally contributes to formation of the urban heat islands.

The urbanization also causes other climatic effects, such as greater cloudiness (by 5% to 10% greater in the cities than in other areas), greater precipitation (5–15%), increased frequency of occurrence of torrential rainfalls and storms, including storms with lightening (10–15% more) and hail, reduced frequency of snowfall and shorter time of snow cover, increasingly high frequency of fog occurrence (even by 100% during winter season) and reduced humidity of near-ground air layers (by approximately 6%).

Air pollution is a key factor in climate formation. Its impact is significant in urban areas in particular as most of the various types of emission sources are found in cities. It decreases the clarity of air, constitutes numerous condensation nuclei (up to 10 times more in urban areas than in other areas) and impacts the balance of radiation (up to 20% lower in urban areas) and heat (Gaston, 2010).

Urbanization also contributes to changes in water circulation. Replacing green areas (forests and meadows) with housing, industrial and transport development contributes to increased impervious surface, which then significantly limits absorption of rainwater and accelerates surface discharge. Consequently, during intensive precipitation, a great majority of water very quickly and directly goes into rivers, through the sewage system, which results in a shorter time of run-off concentration and increased culmination thereof. The following dependence is clearly noticeable: the more built-up areas there are in a city and the denser they are, the higher and the more frequent the flood waves are. The water that runs off from the city is very muddy and carries a huge load of various types of contamination.

A decreased recharge of water-bearing levels is another key consequence of increased impervious surfaces. Instead of getting infiltered, the rainwater gathers on the impervious surfaces, from which it is then drained by the stormwater drainage system. The water that stays in the detention zone evaporates back to the atmosphere much faster than in the areas overgrown with plants. It should also be emphasized that in case of such areas as forests an interception reservoir may be emptied due to water dripping off or being blown off by the wind from leaves, while in case of anthropogenic surfaces this phenomenon never occurs.

The phenomenon of soil settlement is equally important as decreasing ground water resources. In some cases it may reach several metres (e.g. Figueroa, 1984). This process directly affects stability of buildings. However, in some cases exfiltration of water from the city water supply network may partly balance the rainwater deficit. For instance, in an agglomeration with an area of 50 km^2 and water consumption at the level of 100,000 m^3 per day, the losses of the water supply network at the level of 20% are equivalent to 300 mm of rainwater p.a. (Marsalek *et al.*, 2008).

According to an idea that has led engineers for many years, the key task of urban rivers is to drain water from urban areas as soon as possible and in a safe manner. Due to this, the streams that have originally meandered, have been connected to the sewer system by straightening their course. Artificial deepening of the beds causes drying of the river valleys, while the sites where the sewer system ends (usually outside of the city) often suffer from overflows and inundations, as these rivers beds are not adapted to receive such large quantities of water (the problem of the so-called 'end of pipe'). Due to the lowering of the ground water level caused by sealing of the surface, rivers usually lose their hydrological connection with waters in their valley. Therefore, in order to ensure that they will function as rainwater collector, their beds are sealed, which changes their morphology and significantly affects the speed of flow. Small streams are either covered gradually, or covered completely, and larger and more important streams are sheltered with high embankments which completely isolate them from the city. Ultimately, residents only notice negative features of the rivers, while the rivers themselves being 'imprisoned' in their concrete channels very often cause flood or sanitary risks.

Transport corridors (motorway, railway etc.) constitute another consequence of the urbanization. Their construction often involves extensive ground works which significantly transform the surface and, as a result, significantly affect the characteristics of run-off and river drainage. Where a linear infrastructure is developed perpendicularly to the slope and direction of water run-off, bridges and culverts which are required in such circumstances may significantly modify water regime of the catchment. When the infrastructure is developed along the valley, river-banks are usually built over, and even special two-staged channels are established, whose upper sections may serve as river embankments or/and recreational areas.

Apart from the above-mentioned factors, the consequences of urbanization for the processes of erosion, transport and sedimentation of substances in the lower stretches of rivers are also of importance. The soil erosion is increased, in urban areas in particular, due to removing the topsoil. Intensified urbanization processes increase production of sediments by 100-times in comparison to natural areas (Wolman and Schick, 1962). Excessive erosion contributes to an increased concentration of material suspended in water, which subsequently results in less light reaching plants, filling up the bed where organisms live, and damaging fish gills (Horner *et al.*, 1994; Marsalek *et al.*, 2008).

Urban environment also significantly impacts the temperature of water discharged. Its increase is particularly noticeable during summer months, when precipitation water becomes significantly warmer following its contact with heated surfaces (roofs and pavements) (van Buren *et al.*, 2000). As a result, water running off from these areas may be warmer even by 10°C (Schueler, 1987). When the heated precipitation water gets into a river, in many cases it may contribute to occurrence of irreversible changes in aquatic ecosystems which house organisms of a specific thermal tolerance. In consequence, this phenomenon may contribute to a complete change in the species living in a given habitat (Galli, 1991).

Hydrochemical consequences of urbanization constitute a separate category. They include an increased mobility of heavy metals, a significant share of chlorides, eutrophic processes caused by compounds of nitrogen and phosphorus, increased deficiency of dissolved oxygen accompanied by biomass accumulation, increased concentration of ammonia, chlorine, cyanides, sulphides, phenols and surfactants that impact the general toxicity of sewage drained to urban rivers (Chambers *et al.*, 1997; Marsalek *et al.*, 2008).

Microbiological contamination of urban water is one of the key consequences of metropolitan development, as it directly affects health of city inhabitants. Four groups of aquatic organisms that affect human health have been identified: viruses, bacteria, protozoans and parasites (Marsalek *et al.*, 2008). The type and size of contamination are often related with the standard of waste management and sanitary conditions in a given area. Nevertheless, the microbiological contamination may occur even in highly developed areas following torrential rains, on beaches by city swimming pools in particular.

Anthropogenic effects are so large now that they may be compared to the changes caused by large-scale natural processes. In case of urban areas, interference in the natural environment is to improve the quality of human life, while it often leads to undesired, incidental and irreversible changes. In the context of water circulation, sealing of surfaces is of the greatest importance. It controls movement of precipitation water through the routes that are different from the natural ones. It seems that we partly know how to deal with this issue. Development of technologies and innovation have enabled us to manufacture permeable materials and construct local automatic systems that pre-treat this water, however, their implementation and control by integrated management, which covers not only engineering elements but also the processes that recognize capacity of the environment and control it, will become the greatest challenge in the near future.

2. METHODOLOGICAL BACKGROUND

The investigations included two small river beds draining the western part of the Wzniesienia Łódzkie (Łódź Hills): Sokołówka and Dzierżązna (figure 1). The catchments of both rivers are built of drift tills and fluvioglacial deposits, however, they differ in land uses and bed characteristics. To the cross-section in Sokołów, the

Sokołówka river basin has an elongated shape and is almost fully located within administrative boundaries of Łódź, in the north of the city. It covers an area of 19.2 km^2 and it is a typical urban basin. The Sokołówka river valley is visibly incised, the average basin slope equals to 17.5‰, while its denivelation exceeds 80 m. Poorly permeable deposits are mainly in its central and upper parts, while in the lower part predominate sand deposits. The length of the main course is 11.8 km and its average slope is equal to 6.01‰. The Sokołówka river bed of average water table width of 1.4 m was strengthened and concretened at substantial length and its embankments have a regular shape (slope 1:1.5) (Bartnik and Moniewski, 2010).

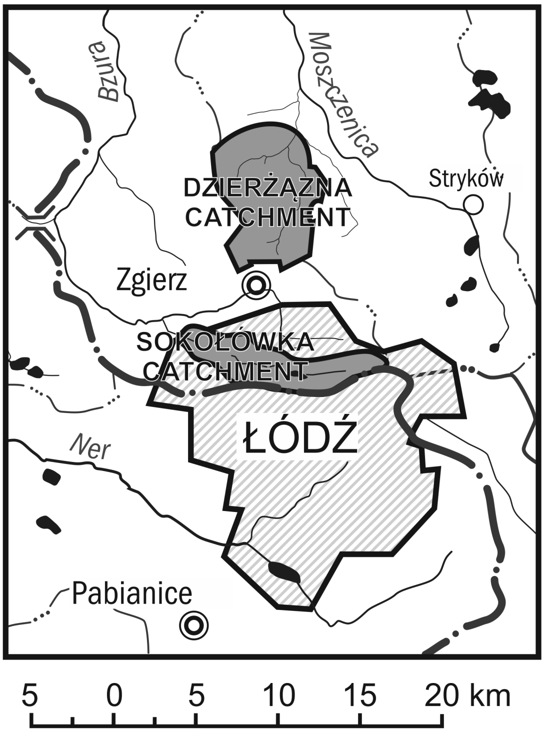


Fig. 1. Localization of the investigated catchments
Source: own elaboration

Establishing a reference catchment was also required. The Dzierżązna river, which is located several kilometres away, was selected for this purpose. Originally, both the hydrographic units located in the basin of the Bzura were characterized by similar physic-geographical conditions. Today, however, they differ significantly due to the way of using their surface, i.e. due to the intensity of anthropopressure.

Dzierżązna catchment (A = 25.1 km^2), located in the north of Zgierz, may be regarded as a suburban basin. Its area is formed mainly by arable lands and forests.

The area of Dzierżązna basin is relatively slightly transformed by humans and to a great extent it preserved its natural characteristics strictly combined with the physiogeographical features of the region. Very permeable sand-gravel deposits of Grotnicki-Lućmierski sandur are of great importance for infiltration conditions. Low permeable deposits and anthropogenic surfaces are relatively rare. The average slope of the main river course is 7.1‰ with length of 9.5 km. Some sections of the Dzierżązna river bed are straightened and strengthened with fascines, while others have preserved their natural meandering pattern. The river's average width is 2 m. Few retention reservoirs were built on the river; they play the role of fish or recreation ponds. Rain gutters draining water from A2 railway and an interceptor sewer carrying rainfall water from Zgierz area (Jokiel ed., 2002) should be included into the artificial drainage network.

In the Sokołówka catchment, human interference with the environment extensively transformed its original features in a short time. The basins of the Sokołówka and of its single tributary, i.e. Brzoza, were turned into concrete troughs, which were partly closed and connected with the rainwater drainage system. Within this area, the river is more than three times longer than the length of a natural river network. In the upper part of the catchment, there is a dense residential estate of single-family buildings, and industrial development dominates in its middle section. Natural sediments, which are usually characterized by good infiltration, were covered by a layer of anthropogenic cover (such as debris, slag, asphalt and concrete) of variable filtration conditions. Only the lower part of the catchment has maintained a suburban character, with a significant share of arable land (figure 2).

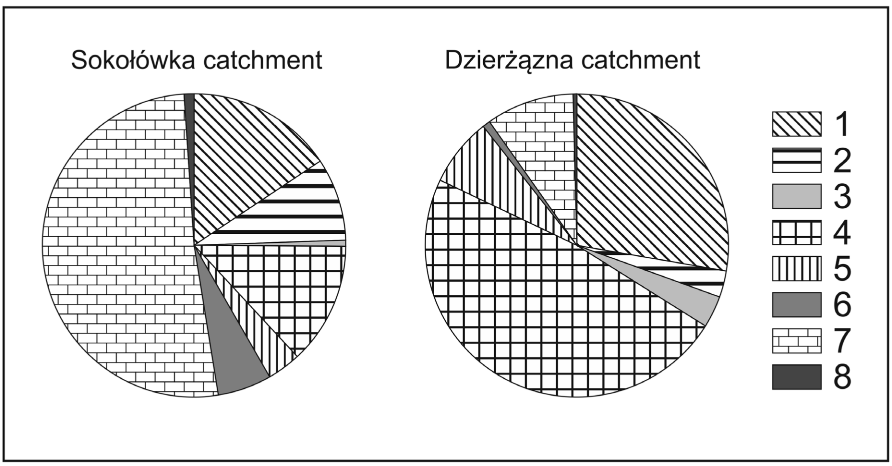


Fig. 2. The structure of the use of the areas in the catchments studied
1 – forests, 2 – green areas, 3 – orchards, allotment gardens, 4 – arable land, 5 – meadows, pastures, 6 – wasteland, 7 – housing and industrial development, 8 – water resources
Sources: own elaboration

3. ASSESSMENT OF THE EXTENT OF THE SOKOŁÓWKA CATCHMENT TRANSFORMATION

The project objective was to identify the impacts of urbanization of the Sokołówka river catchment on the course of various types of flood waves. In order to compare the conditions of shaping the run-off in both catchments, a SCS (Soil Conservation Service) method has been used (Ozga-Zielińska and Brzeziński, 1994; Jaworski and Szkutnicki, 1999; Viessman and Lewis, 2003). This method was developed in the USA and it enables calculation of effective precipitation in uncontrolled catchments. According to this method, the effective precipitation depends on the type of soil, type of land use and characteristics of forested areas. Tabular values provide the basis to calculate a non-dimensional CN parameter, which adopts theoretical values from 0 (for the catchment with unlimited absorptive capacity) to 100 (for the catchment which has been saturated with water to the maximum level).

Discrete maps of the catchments were used to present the results (figures 3 and 4). The area of both catchments was covered with grids of 250 m^2 whose colour indicates a weighted average value of the CN parameter (Bartnik *et al.*, 2008). A share of a given form of the land use in the surface of the relevant square constitutes the weight.

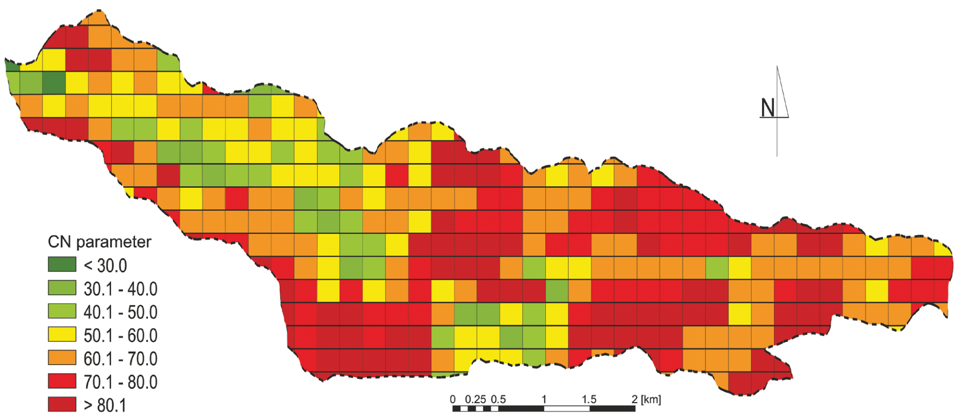


Fig. 3. Spatial distribution of the CN parameter in the Sokołówka catchment. Noticeable strong transformation of this area caused by urbanization
Source: own elaboration

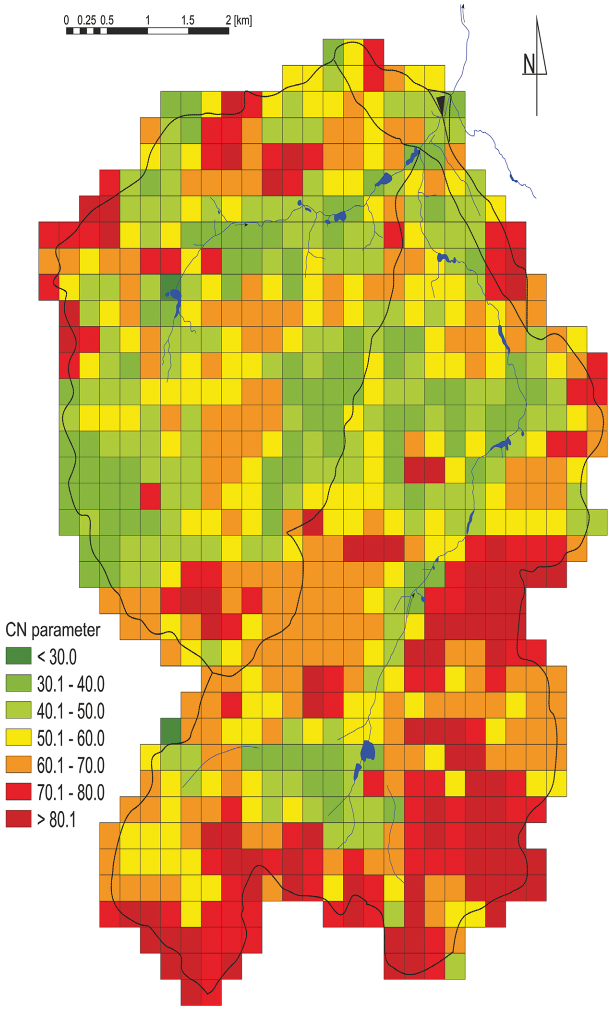


Fig. 4. Spatial distribution of the CN parameter in the Dzierżązna catchment. Urban areas are only found in the southern borders of the catchment (the area of the city of Zgierz and a large village of Dąbrówka)
Source: own elaboration

The spatial distribution of the CN parameter indicates significant differences in the area of two catchments. Low CN values characterize the sand and gravel bed of the river valley in the Sokołówka catchment, in the stretches where it has not been sealed (figure 3). High CN values, which clearly dominate in comparison to the reference catchment, overlap with the areas that have undergone the strongest urbanization, industrial areas in particular, where the degree of imperviousness of the bed is very high, and a significant share of precipitation water is intercepted by the rainwater drainage system. The upper catchment of the Sokołówka, which is made of drift clay, also holds a high CN value.

The average value of the CN parameter calculated for the Sokołówka catchment reaches 67 and it is only slightly higher than in the case of the Dzierżązna catchment, which reaches 59. Major differences may be found in the structure of this parameter (figure 5). Although in both these cases most raster cells hold the values within the range of 60 to 70, the Sokołówka catchment is characterized by a higher number of high CN and a smaller number of low CN. The variability coefficient c_v of the CN parameter reaches 0.21. In the Dzierżązna catchment, the size of intervals is more even, the CN values > 90 are rare (in 3 cases) and they do not impact the average value. In the case of the Dzierżązna, differentiation of this parameter is slightly greater: $c_v = 0.26$. The analysis of the CN parameter values indicates that, although the two catchments are close to each other, a potential capacity of forming direct run-off is greater in the Sokołówka catchment than in the Dzierżązna catchment.

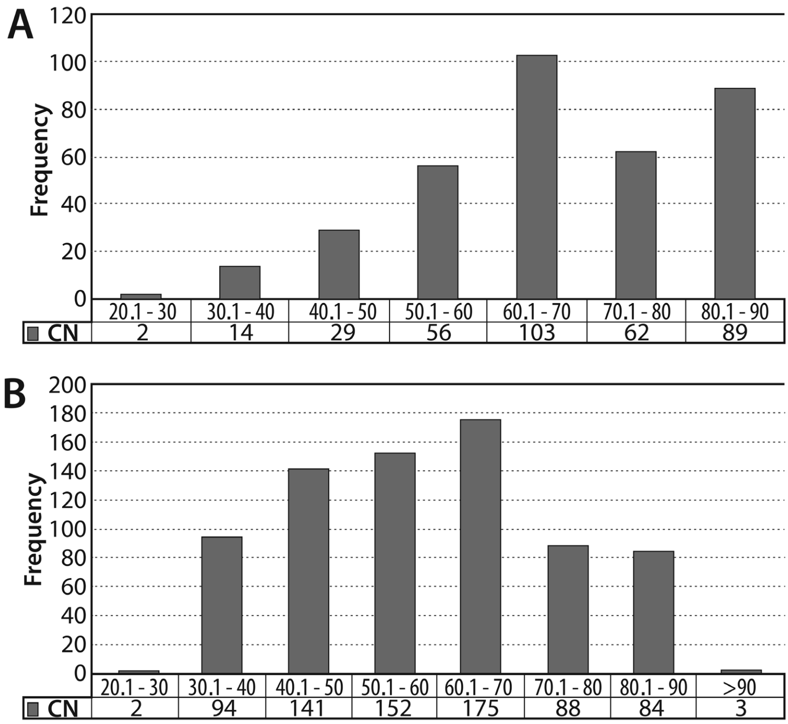


Fig. 5. The structure of the size of CN parameter:
A – in the Sokołówka catchment; B – in the Dzierżązna catchment
Source: own elaboration

It is confirmed by the value of effective precipitation in both catchments (figure 6). The difference in the P_e value is already noticeable at the average daily totals of precipitation that are higher than approximately 20 mm and it grows with their increase. However, the SCS method used in this case does not take into account formation of flood waves, so the indicators obtained should be perceived as indicative.

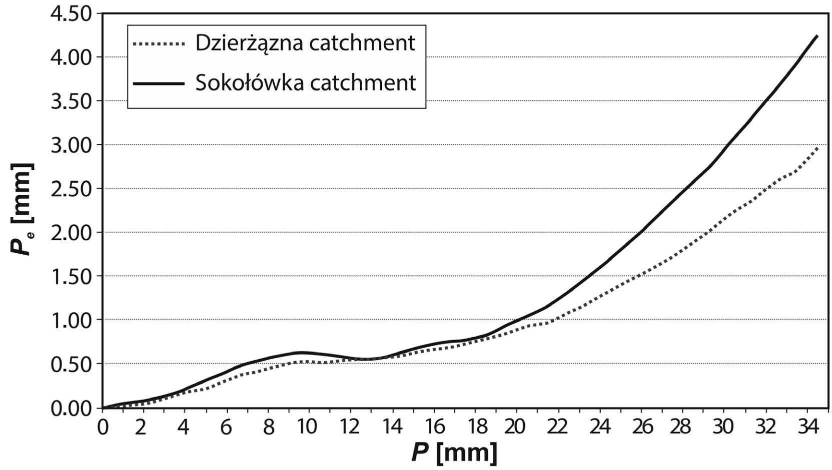


Fig. 6. Effective precipitation (P_e) in the function of the total precipitation (P)
The average humidity level has been adopted
Source: own elaboration

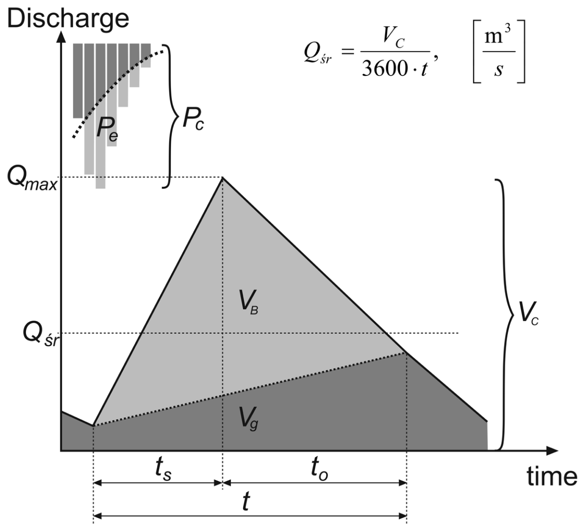
It is worth emphasising that the surface of the Sokołówka catchment facilitates infiltration to a lesser extent than the Dzierżązna catchment, and that is why it may absorb less precipitation or snow-melt water. On the basis of the dependence (Pociask-Karteczka ed., 2003):

$$RS = 24.5 \bullet \frac{1000}{CN} - 10$$

in both catchments it is possible to calculate a theoretical value of the so-called potential retention, i.e. the maximum layer of water that may be retained in the conditions of a given catchment, with an assumption that the precipitation will last for unlimited time. According to this formula, the quantity of the precipitation retained in the Sokołówka catchment may be estimated to reach the level of approximately 356 mm, while for the Dzierżązna catchment, on average, it could reach as much as approximately 405 mm.

The actual conditions of water circulation will cause a different response to the alimentation by the catchment, which is indicated by the measurement data derived.

The analysis of flood waves enables identification of these elements of the geographical environment of the catchment that determine the conditions of the run-off formation. Next to meteorological factors, the shape and size of the catchment, its inclination, a degree of ground permeability and land cover are also of importance to the course of flood. They impact both the flood duration, its volume, peak discharge and the time needed to reach it. Parameters of the theoretical run-off hydrograph and the method of establishing or calculating them are presented in figure 7.



$$Q_{śr} = \frac{V_C}{3600 \cdot t}, \quad \left[\frac{m^3}{s}\right]$$

$$q_{\max} = \frac{1000 \cdot Q_{\max}}{A}, \quad \left[\frac{dm^3}{s \cdot km^2}\right]$$

$$q_{śr} = \frac{1000 \cdot Q_{śr}}{A}, \quad \left[\frac{dm^3}{s \cdot km^2}\right]$$

$$C_B = \frac{V_B}{1000 \cdot A \cdot P_C} \cdot 100, \quad [\%]$$

$$C_C = \frac{V_C}{1000 \cdot A \cdot P_C} \cdot 100, \quad [\%]$$

$$W_g = \left(1 - \frac{V_B}{V_C}\right) \cdot 100, \quad [\%]$$

Fig. 7. Characteristics of the flood waves
A – catchment surface [km^2]; P_c – total precipitation prior to the flood waves (including snow coverage); P_e – effective precipitation; t – duration of the flood waves; t_s – wave rising time; t_o – wave falling time; Q_{max} – peak discharge; $Q_{śr}$ – average discharge of the flood wave; q_{max} – maximum unit discharge of the flood wave; $q_{śr}$ – average unit discharge of the flood wave; V_B – direct discharge volume; C_B – coefficient of the quick discharge of the flood wave; V_C – total run-off volume; C_C – coefficient of the total run-off of the flood wave; W_g – coefficient of the underground flood wave recharge
Source: Ciepielowski (1987), Ozga-Zielińska and Brzeziński (1994), Byczkowski (1996)

4. ASSESSMENT OF THE IMPACTS OF URBANIZATION ON THE COURSE OF RIVER FLOOD WAVES

In order to assess the impact of urbanization on the river run-off, a comparative analysis of several flood waves that simultaneously occurred in the two catchments in 2009 has been conducted. Intensity and duration of precipitation plays an important part in flood wave formation. That is why only these flood wave episodes have been selected that were characterized by clearly identified genesis and similar total precipitation (figure 8 illustrates intensity of precipitation in the Sokołówka catchment). The key parameters of the flood waves calculated for each episode are compiled in table 1. Maximum and average unit precipitation, direct and total run-off coefficient and baseflow index in the course of flood waves have also been derived.

In order to identify similarities and differences in the response of both catchments to alimentation, four cases of flood wave have been analyzed. An example of a winter flood wave covers two consecutive episodes that took place in mid-February (figure 8A). The first one occurred between 22nd and 25th February and it was a snow-melt flood wave (OR) caused by fast temperature rise above zero, which initiated reduction of almost a twenty centimetre thick snow cover. Precipitation that took place during the night of 22nd and 23rd February accelerated this process even more. The snow-melt arrival was synchronous in nature, however, the flood wave occurrence was different in each catchment. In the Sokołów section, two waves whose culminations were moved by approximately 10 hours in relation to the daily maximum temperature were observed. The concentration time of the first one was very brief and took just over an hour, while in the Dzierżązna catchment the increase in discharge was slow and lasted 75 hours. The temperature rose, which took place on 26th February, stimulated another spell of small rain and the other snow-melt and precipitation flood wave (RO). It is worth noting that in the Sokołówka catchment it was a separate flood wave, while in the Dzierżązna catchment both flood waves overlapped. Their total duration was twice as long as the time of the flood wave in the Sokołówka catchment and it took 8.5 days.

The snow-melt and precipitation flood wave (RO) was characterized by the highest volume and the greatest average discharge ($Q_{śr}$) of all the flood waves covered by the study. The average Sokołówka's discharge reached 0.259 $m^3 \cdot s^{-1}$, while the Dzierżązna's 0.387 $m^3 \cdot s^{-1}$. Due to a large share of snow-melt water in the total run-off, the direct run-off coefficient (C_B) also reached maximum values and in the two catchments it reached 70% and 38% respectively. At that time, the total discharge coefficient (C_C) in the Sokołówka catchment exceeded 137% (table 1).

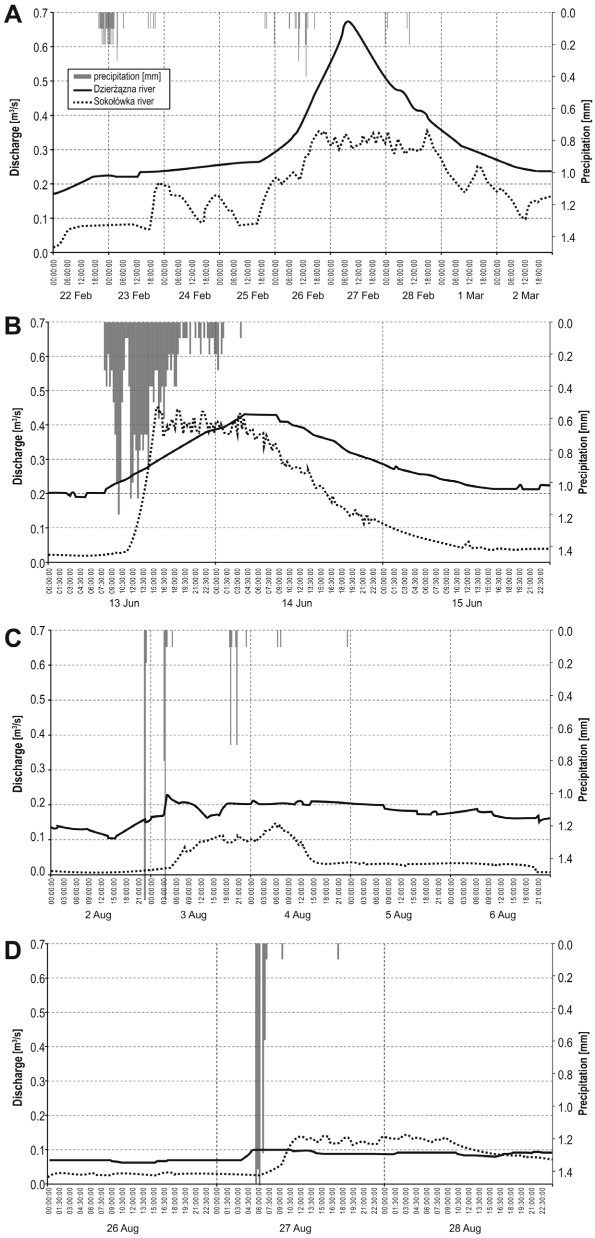


Fig. 8. The examples of various types of flood waves that occurred in the Sokołówka and the Dzierżązna in 2009

A – snow-melt precipitation; B – related with the passage of warm front; C – induced by torrential rain; D – related with the passage of cold front

Source: own elaboration

Table 1. The parameters of selected flood waves in the catchments of the Sokołówka and Dzierżązna in the hydrological year of 2009

River – section	Sokołówka – Sokołów (19.21 km²)					Dzierżązna – Swoboda (42.9 km²)				
Date	23–24.02	25.02–1.03	13–15.06	2–4.08	27–28.08	22–25.02	25.02–2.03	13–15.06	2–5.08	27–28.08
Type of flood wave	OR	RO	O-c	ON	O-ch	OR[a]	RO	O-c	ON	O-ch
P_c [mm]	18.1	3.0	25.8	13.3	15.9	29.5	4.6	13.9	13.4	15.9
P_e [mm]	0.41	2.10	1.82	0.46	0.67	0.32	1.75	0.53	0.31	0.09
t [h]	21.50	84.75	58.50	44.25	34.75	82.75	122.50	56.25	72.75	36.00
t_s [h]	4.25	27.00	6.75	32.75	18.75	75.00	42.50	20.25	13.00	3.00
t_O [h]	17.25	57.75	51.75	11.50	16.00	7.75	80.00	36.00	59.75	33.00
Q_{max} [$m^3 \cdot s^{-1}$]	0.195	0.337	0.441	0.147	0.243	0.261	0.656	0.420	0.231	0.174
$Q_{śr}$ [$m^3 \cdot s^{-1}$]	0.137	0.259	0.189	0.075	0.186	0.232	0.387	0.310	0.188	0.153
q_{max} [$dm^3 \cdot s^{-1} \cdot km^{-2}$]	10.17	17.55	22.94	7.66	12.64	6.08	15.29	9.79	5.38	4.07
$q_{śr}$ [$dm^3 \cdot s^{-1} \cdot km^{-2}$]	7.13	13.48	9.82	3.89	9.70	5.41	9.03	7.23	4.38	3.58
V_B [thousand m^3]	7.95	40.37	34.93	8.81	12.83	13.91	75.20	22.57	13.38	3.78
C_B [%]	2.29	70.05	7.05	3.45	4.20	1.10	38.10	3.78	2.33	0.55
V_C [thousand m^3]	10.60	79.02	39.73	11.91	23.31	68.99	170.76	62.78	49.26	19.89
C_C [%]	3.05	137.12	8.02	4.66	7.63	5.45	86.53	10.53	8.57	2.92
W_g [%]	25.03	48.91	12.08	26.01	44.97	79.83	55.96	64.06	72.83	81.00

Explanations: OR – precipitation and snow-melt flood wave; RO – snow-melt and precipitation flood wave; O-c – precipitation flood wave (warm front); ON – precipitation and torrential rain flood wave; O-ch – precipitation flood wave (cool front); symbols of flood wave characteristics are the same as in figure 7.

[a] Estimated parameters due to overlapping of a subsequent flood wave in the Dzierżązna catchment.

Source: own elaboration.

The next flood wave studied took place in mid-June 2009, and was caused by the passing of a warm front (O-c) (figure 8B). Frontal precipitation occurred simultaneously in both catchments, however, its total in the Sokołówka catchment (25.8 mm) was almost twice as high as it was in the Dzierżązna catchment (13.9 mm). In the Sokołów section, the highest culmination discharge (*Qmax*) – 0.441 $m^3 \cdot s^{-1}$ was recorded at that time, which was even higher than the Dzierżązna discharge. Its duration (*ts*) was short and lasted less than 7 hours, while in the Dzierżązna catchment

– over 20 hours. The maximum unit run-off (*qmax*) from the Sokołówka catchment reached 22.94 $dm^3 \cdot s^{-1} \cdot km^{-2}$ at that time and was twice as high as discharge in the Dzierżązna catchment.

A precipitation and torrential flood wave (ON) took place in early August. It was induced by convection rain exceeding 13 mm. This is illustrated in the hydrograph of the discharge in the form of two overlapping flood waves (figure 8C). On that occasion, the time necessary to reach the flood culmination point (*ts*) in the Sokołówka catchment was much longer than in the case of the Dzierżązna and reached almost 33 hours. The duration of the flood wave falling (*to*) was only 11.5 hours and was over 5 times shorter than its equivalent in the Dzierżązna catchment.

The last of the flood waves presented (O-ch) was due to precipitation that accompanied the arrival of cool front. The total of short but intensive torrential rains reached just under 16 mm in two catchments. In the Sokołówka catchment, the volume of direct run-off (*VB*) was significantly larger during this flood wave (12.8 thousand m^3) than in the Dzierżązna catchment (3.8 thousand m^3). The discharges: the culmination ($Qmax = 0.243\ m^3 \cdot s^{-1}$) and the average one ($Qśr = 0.186\ m^3 \cdot s^{-1}$) were higher than the respective discharges of the Dzierżązna. Although the Dzierżązna flood wave rising time demonstrated in table 1 was short (*ts* = 3 h), the dynamics of increase in the Sokołówka discharges was clearly higher (figure 7D). The average unit run-off of this catchment during the flood wave (*qśr*) was significantly higher and it reached 9.7 $dm^3 \cdot s^{-1} \cdot km^{-2}$.

These hydrographs and characteristics derived indicate a different course of flood waves in each river. Only precipitation flood waves induced by arrival of atmospheric fronts: warm (O-c) and cool (O-ch) were characterized by similar duration as precipitation of similar intensity occurred synchronously in the two catchments. The remaining flood wave parameters indicate significant differences between these catchments.

The different course of the flood waves recorded to a certain extent resulted from different shapes and sizes of the catchments, however, their response to alimentation was mainly due to the structure of land use. It has been observed that during the culmination waves the unit discharges in the section closing the Sokołówka urbanized catchments were always higher (even 3 times) than in the Swoboda section, which closes the Dzierżązna catchment. The difference also covers average unit discharges during the flood waves. In the Sokołówka catchment they reached 13.5 $dm^3 \cdot s^{-1} \cdot km^{-2}$, while in the Dzierżązna catchment they hardly ever exceeded 9 $dm^3 \cdot s^{-1} \cdot km^{-2}$. It is worth reminding that the rainwater drainage system, which drains rainwater from in-built areas that occupy more than half of its surface, plays a key role in the increase of the Sokołówka flood discharges (figure 2). A large share of impervious surfaces and sealing of the bed that covered a long stretch contributed to the fact that the infiltration coefficient calculated for the Sokołówka catchment reached only 31.4% on average, while for the Dzierżązna catchment 70.7%.

The other indicators also determine the scale of anthropogenic transformations of run-off of the Sokołówka catchment. The effective precipitation (*Pe*) calculated for three summer flood waves covered by the analysis of this catchment reached 4.9% of the total precipitation (*Pc*) on average. Thus, it was twice as high as the value recorded for the Dzierżązna catchment (2.2%). These values correspond with the relation identified by Ciupa (2009) in the urbanized catchment of the Silnica (Kielce region). The total precipitation was the same, however, the effective precipitation in the urbanized catchment was twice as high as in the catchments that have been covered by anthropopressure to a lesser extent. The direct discharge coefficient calculated for the flood waves analyzed was larger by 1.5 to 7.6 times in the Sokołówka catchment than in the Dzierżązna.

According to Ciepielowski (1987), the shape of flood wave hydrographs for small catchments may be determined by anthropogenic factors. It is a well-known fact that hydrographs of catchments covered with forests or arable land are flatter than the hydrographs of urban catchments. Nevertheless, the urbanization effects in the Sokołówka catchment also result from meteorological factors, which determine the course of snow-melt flood waves, too. Duration of these waves was also shorter due to a thinner snow cover in the city and higher air temperature than the temperature in the Dzierżązna catchment, which was due to increased albedo and higher emission of artificial heat.

5. CONCLUSIONS

The run-off process is more dynamic in urban catchments than in the ones that are less transformed due to anthropopressure, as transformation of precipitation into run-off occurs much faster in the urban catchments. Increased dynamics of discharge in small urban streams is due to two reasons. Concrete reinforcement of the river bed and banks results in an almost complete separation of the stream from groundwater alimentation, which then causes decreasing of low discharges. Sealing of a large part of the catchment surface also leads to the situation where only small quantities of water permeate to supply ground water reservoirs. As a result, during dry periods, the groundwater level falls down fast within its drainage, which causes long periods without run-off. The Sokołówka, which from a constantly flowing river turned into a periodical stream within the period of several decades, is a clear example. During dry periods and winter, the run-off of the upper part of the catchment ceases completely, and the unit run-off for the whole surface of the catchment (Sokołów section) does not exceed 0.5 $dm^3 \cdot s^{-1} \cdot km^{-2}$.

On the other hand, reconstruction of beds of urban streams is designed to adapt them to episodic drainage of water from the rainwater drainage system, as small streams have to collect water from vast impervious land whose surface increases as a result of urban spatial development or intensification of other urban processes. A very small retention capacity of urban catchment contributes to the situation where the run-off dynamics in urban conditions may be compared to the regime of a mountain stream. As a result, the maximum unit run-offs reaching 103 $dm^3 \cdot s^{-1} \cdot km^{-2}$ and 176 $dm^3 \cdot s^{-1} \cdot km^{-2}$ were recorded in the upper and most urbanized section of the Sokołówka catchment during the above summer flood waves taken into account of this analysis. In this context, it is worth emphasizing that these values were not the highest, as within Łódź territory there had already been precipitation reaching several dozen millimetres within several hours, which contributed to much higher flood waves and even flash floods (recently on three occasions in May and June 2007). Straightening and concrete reinforcement of the Łódź stream beds have not significantly impacted the size of the culmination discharge, however, it accelerated the arrival of the culmination wave. That is why flood waves in the Sokołówka catchment occasionally are very violent in nature (discharge may increase even to 1.5 $m^3 \cdot s^{-1}$ in 15 minutes). It leads to inundations of large areas holding dense road infrastructure, which also constitute a risk to residential buildings. Sudden snowmelt flood waves that supply surface water with a large load of contamination are equally dangerous.

In peripheral districts of Łódź, also in the Sokołówka catchment, large-scale development of sanitary and rainwater drainage system is taking place. If this investment does not include systemic solutions and the integrated rainwater management which uses the BMPs solutions, it will induce vast modifications that will impact the directions and dynamics of this catchment's discharge in long-term perspective, such as increased maximum discharges, intensified erosion processes in the river beds and further modifications in the underground retention. Such problems are particularly severe in small catchments, as they have a limited capacity to compensate negative effects of anthropopressure. That is why it is necessary to change rainwater management policy to adopt decentralized solutions that will improve retention capacity in the catchment and slow down its run-off.

A fast progressing development in Łódź, in Bałuty, its northern district in particular, has already facilitated a drastic change of conditions of the river run-off in the watershed zone. Similar phenomena occur in all urban river catchments whose natural streams are turned into rainwater collectors. Due to the specificity of urban space, including a large share of isolating surfaces, changes in the run-off formation are unavoidable. In the future, however, such solutions should be applied that will compensate for the limited infiltration, slower run-off and increased retention. The run-off from large impervious surfaces (hypermarkets, industrial facilities, car parks and residential estates) should be retained for the sake of landscape and treated with the aid of ecosystem-based biotechnologies instead of being directly drained through stormwater drainage system, and where possible, the surfaces should be unsealed with the aid of the BMPs under the rainwater management. Appropriate management of river valleys as urban green areas and ecological corridors may also impact the shape and speed of the flood wave movement. Construction of retention reservoirs and polders will contribute to decreasing the height of the wave, and de-sealing of the beds and urban surfaces will favourably impact low discharges.

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