ASSESSMENT OF THE RISK OF FLOODING IN AN URBANIZED AREA IN RESPONSE TO HEAVY RAINS: CASE STUDY OF THE WARSAW CHOPIN AIRPORT

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Abstract

The paper presents the adaptation of the hydrodynamic Storm Water Management Model (SWMM) for the subcatchment area of the Służewiecki Stream in Warsaw, the major part of which is the area of the Chopin Airport. The SWMM model was used for calculating the water outflow from the studied urbanized area in response to rainfall with the probabilities of 20 and 10%, and then to assess the possibility of flooding as a result of rainwater spillage from the Airport drainage system. The scope of the work also comprised assessing the impact of the existing retention tanks at the Airport on the reduction of maximum flows in the Służewiecki Stream channel. Simulations in response to the rainfall event with a probability of 10% have shown that there are locations (sewer manholes) within the airport area where short-term rainwater overflows may potentially occur. Retention of rainwater in tanks and flow control through gate valves have a significant impact on a reduction of flows in the Słuzewiecki Stream, thus reducing the risk of flooding in the studied catchment area.

Key words: rainfall, urbanized area, risk of flooding, retention tanks, SWMM model

1. Introduction

Human activities, such as the growth of urbanized areas (impervious surfaces with stormwater systems), the reduction of the catchment retention potential, but also the climate changes, contribute to both higher outflow from a catchment in reaction to precipitation and higher urban flooding probabilities (Hall, 1986; Gutry-Korycka, 2007; Guan et al., 2015). As a result, due to the limited capacity of sewage systems and watercourses, rainwater may overflow and temporarily cause flooding on the areas that are not normally covered with water. The negative effects associated with

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flooding include damage to the natural environment and infrastructure, difficulties in communication, socio-economic loss, as well as consequences for human health (EC, 2007). In extreme cases, floods can cause deaths and casualties.

In order to effectively prevent flooding and to restrict the above mentioned consequences, one of the first necessary actions is to perform a flood risk assessment after heavy rains (EC, 2007). The basis for the assessment of such a threat, but also for the design of devices regulating rainwater runoff from catchments (e.g. retention tanks), is constituted by flow values of a specific probability of occurrence or return period. Establishing the precise values of such flows in response to rainfall is relatively difficult for urbanized areas owing to the occurrence of high variability in the land use forms, soil and topographic conditions, spatial rainfall amount, and moreover, it stems from the fact that there are numerous hydraulic structures influencing the outflow in a specific area: road culverts, tanks, valves and gates, storm water drainage systems etc. (Hsu et al., 2000; Park et al., 2008; Wu et al., 2013; Ochoa-Rodriguez et al., 2015).

Hydrological models of differing complexity are used to determine the values of flows with a specific probability of occurrence (including water runoff volume) in response to rainfall, from simple mathematical descriptions (regression formulas or relationships) to large and highly complicated models (World Meteorological Organization, 1994; Singh, 1995; Ciepielowski, Dąbkowski, 2006), which, depending on the applied criteria (model structure, time factor role, model cognitive values, operator capabilities, etc.) fall into different classes (Ozga-Zielińska, Brzeziński, 1997). Research on the validation of existing models in terms of their use in engineering practice for rainwater runoff in urbanized (urban) areas, comparing to non-urbanized (agricultural) areas, is still insufficient.

The paper presents the results of simulation of the rainfall-runoff process in the subcatchment of the Służewiecki Stream within the area of Warsaw (its main part is the Chopin Airport) using the hydrodynamic Storm Water Management Model [U.S. EPA, 2023], properly adapted to the analysed catchment. The main advantages of this model are manifested by its mostly physically measurable parameters and characteristics of the catchment, along with hydrometeorological conditions, as well as the ability to take into account the spatial variability of hydrological and hydraulic processes. The available literature provides sufficient evidence on the applications of SWMM model to urbanized areas (Warwick, Tadepalli, 1991; Krebs et al., 2013; Barszcz, 2015; Li et al., 2016; Peng et al., 2020; Yang et al., 2020).

The range of simulations in the SWMM (Storm Water Management Model) model for the analysed catchment included, among others, the forecast of maximum flows (occurring at the peak of floods) in several cross-sections of the Służewiecki Stream channel in response to rainfall of 20 and 10% probabilities. On the basis of their calculated values, an assessment of the possibility of flooding due to rainwater overflow from the Chopin Airport drainage system was carried out. The impact of existing retention tanks at the Airport area on the reduction of the determined maximum flows was also under consideration.

2. Material and methods

2.1. Analysed urbanized area

The catchment of the Służewiecki Stream, a watercourse in the Vistula basin, is located in the southern and south-western parts of Warsaw. The size of the entire catchment area to the estuary in Lake Wilanowskie is approximately 55 km^2. The total length of the Służewiecki Stream (also called the WOW channel) is ca. 15 km. Its sources are situated close to the Grójecka street, north of the Warsaw-Radom main railway.

The scope of this work concerns the upper part of the Służewiecki Stream catchment area, the range of which is limited by the P1 cross-section (Figure 1),

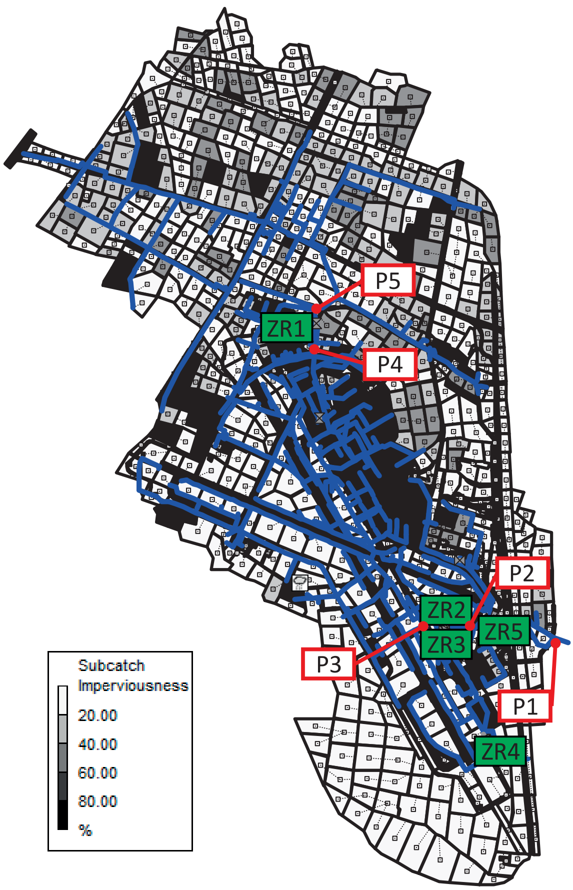

Figure 1. A schematic representation of the division of the studied part of the Służewiecki Stream catchment in the SWMM model into subcatchments with varying percentage of impervious area (indicated by different shades of grey). Designations: open channels and stormwater drainage system – lines in blue; P1-P5 – computational cross-sections; ZR1-ZR5 – retention tanks

located in the Służewiecki Stream below Kłobucka Street (approx. 450 m below the outlet from the Rainwater Treatment Plant – RTP). The size of the analysed catchment area of the Służewiecki Stream is 17.8 km^2. The part of the considered catchment includes two main areas, i.e. the area of the Chopin Airport and the city urban area, which is covered primarily by residential and industrial plots. The section of the Służewiecki Stream from the sources to the P1 cross-section is almost the entire length of a concrete collector (except for two short reaches above the Airport area), to which rainwater and snowmelt water from the catchment are drained through the sewage network. The calculation cross-section P1 corresponds to the location of the water gauging station, where the Department of Water Engineering and Applied Geology of the Warsaw University of Life Sciences systematically measures water levels and flow rates. Water levels are gauged automatically by electronic D-Diver sensors at 10-minute intervals.

Four underground retention tanks ZR1–ZR4 (their capacities are: 8,000, 11,130, 15,620 and 1,900 m^3, respectively) and two tanks at the Rainwater Treatment Plant (settling tank and retention tank ZR5 with capacities of 840 and 5,000 m^3 respectively) constitute a rainwater retention system at the Airport with a total capacity of 42,490 m^3 (Figure 1). Filling and emptying of tanks ZR1, ZR2-ZR3 and ZR5 is implemented by lowering/lifting (manually or automatically – control depends on water levels) gate valves located transversely in the channel of the Służewiecki Stream (control chambers) and/or side gate valves. ZR4 is emptied by pumping. According to the current permit required under the Water Law Act (Water Law Act permit, 2017), the maximum allowable flow rate in the Służewiecki Stream in the cross-section at the outflow from RTP may not exceed 1.53 m3/s, with rainfall of C = 5 (frequency once every 5 years; probability p = 20%) and q = 208 l/s·ha.

2.2. SWMM model for the analysed area

The SWMM (Storm Water Management Model) computer model of 5.1 version, developed by the US EPA (United States Environmental Protection Agency), was adapted for the area of the analysed subcatchment of the Służewiecki Stream for its current land use (Figure 1). Taking into account various classification criteria, SWMM belongs to the group of genetic, dynamic, nonlinear models with distributed parameters. A broad description of this model can be found, among others, in the proper reference manual (Rossman, 2015).

The adaptation of the SWMM model to the considered area involved creating objects in the model that represent the physical components of the real hydrometeorological, hydrological and hydraulic system of the catchment, and then establishing the values of their parameters (which in most cases are physically measurable characteristics). The catchment area was divided in the applied model into a set of subcatchments (Figure 1) taking into account the spatial variability of modelled hydrological processes. The following objects were considered in the model:

- Precipitation gauging station.

The simulations assumed the actual precipitation totals recorded for several events at the Okęcie meteorological station (precipitation events used in the process of model calibration and validation) and the amount of precipitation with specific probabilities and durations, calculated from empirical formulas.

- Subcatchments – 1516 objects were created.

The main criterion for the subcatchments delineation was the land use type, and the associated different share of impermeable surfaces. Twenty-six land use categories were identified, including areas for multifamily and single-family housing, commercial and industrial areas, roadways, green wasteland, runways, and airport aprons, etc. The division into subcatchments was carried out on the basis of an orthophotomap (purchased from the Head Office of Geodesy and Cartography - GUGiK), which was the background image in the model. Furthermore, the sizes of individual subcatchments adopted in the model were established through an analysis of surface runoff directions and the extent of the area covered by stormwater drainage. This analysis was conducted based on the basic map which is a large-scale cartographic study for the entire territory of Poland, containing e.g. information on the spatial location of the utilities network, cadastral parcels, buildings, data on the topography, as well as selected descriptive information regarding these facilities.

For each separated subcatchment, the values of several parameters were determined, including the size of the area, sloping of the terrain and the share of impermeable surfaces. The values of this latter parameter were determined separately for each of the adopted land use types (categories). To achieve this, an analysis of the impervious area percentage was conducted for representative subcatchments using tools of the ArcGIS platform. Meanwhile, the parameter establishing the size of subcatchment area was automatically calculated within the model as a result of georeferencing the orthophoto map. Surface slopes were determined based on elevation data obtained from the digital terrain model and the base map.

- Open channels and storm water drainage pipes, nodal points (located in the place of sewage manholes/chambers or determining the change in the characteristics of the sewers) – 1029 reaches of canals and 1021 nodes were created.

The parameters of the sewage system, included in the model, rely on data from the principal map. The channel routing created in the model reflects the location of the actual channels in the catchment. For each channel and node, the values of several parameters were determined in the SWMM model, including the shape and diameter of the sewer, the roughness coefficient, the elevation of the bottom of the sewer manholes and the height from its bottom to the terrain level.

- Retention tanks – five such elements were incorporated, marked by ZR1 to ZR5 symbols, as well as the rainwater settling tank. Tanks ZR1 and ZR5 are located at the highest and lowest point, respectively, within the retention

system of the catchment. Retention tank ZR5 and the rainwater settling tank are situated within the Rainwater Treatment Plant area.
- Gate valves in flow control chambers (gate valves transverse to the direction of flow in the Służewiecki Stream), which interact with retention tanks at the Airport; weirs and side gate valves in control chambers and/or tanks.
- Pumps co-existing with retention tanks ZR4 and ZR5.

2.3. Model calibration and validation

In order to determine the characteristics and parameters for the drainage system elements in the area of the analysed part of the Służewiecki Stream catchment, which were then retrieved in the SWMM model, the real characteristics measured in the field or identified on the basis of available materials (documentation, studies) were used, as well as parameter values recommended in the tables of the manual (Rossman, 2015). Model calibration involved simulations in response to actual rainfall rates, recorded by the Institute of Meteorology and Water Management at the Okęcie meteorological station (located in the area of the Chopin Airport). Measured and simulated values of water levels in the drainage system of the Airport area (in channels in front of/behind gate valves in flow control chambers and retention tanks) were compared, as well as peak flows of the generated hydrograph and outflow volumes at P1 cross-section of the Służewiecki Stream (Figure 1). The correspondence of the graphs of both flow hydrographs during the events was also analysed based on visual assessment. The values of flows in the P1 cross-section of the Służewiecki Stream were measured by the Department of Water Engineering and Applied Geology of the Warsaw University of Life Sciences as part of the COST/210/2006 research project, carried out in 2006-2009 with the support of the National Science Centre in Poland (Banasik et al., 2007). The compliance assessment of the above-mentioned hydrograph parameters at the P1 cross-section was executed with the use of the relative error, which was calculated from the equation:

$$\delta = \frac{x - x_0}{x_0} \cdot 100\% \tag{1}$$

where:
δ – relative error [%], x – calculated (simulated) value, x_0 – measured value

In order to achieve agreement between the values of peak flows of the hydrographs and outflow volumes, obtained from measurements and simulated in the model, the parameters of various objects and structures in rainwater management system in the catchment area were optimised relating to subcatchments (such as: depth of depression storage, surface roughness coefficient, width of overland flow path, fraction of effective impervious area), rainwater drainage channels (roughness coefficient, amount of energy losses) and gate valves in flow control chambers (in certain cases, a constant or time-varying gate lifting height was applied). Additionally, it was necessary to incorporate in the model the operating range and performance of pumps that transported rainwater from retention tanks ZR4 and ZR5 to specific sewers.

The conducted analysis showed that there are no high-sensitive parameters for peak flow and outflow volumes, associated with subcatchments and sewers. Similar conclusions were obtained in studies conducted using SWMM model for Tianjin Binhai International Airport in China [Peng et al., 2023]. The parameters of the objects in the model for the Służewiecki Stream catchment were corrected only to a small extent, and their final values were within the ranges recommended in the tables of the manual for the SWMM model (Rossman, 2015).

However, it was found that the sensitivity of the parameter of width of the overland flow path is slightly more significant than other parameters. The values of this parameter significantly varied for individual subcatchments, which were assigned different types of land use (any of the twenty-six accepted types). They ranged from 7 to 200 m, in this case, respectively, for catchment areas used as roads and arable land. Furthermore in this study, the Manning`s "n" surface roughness coefficient for pervious overland flow is predominantly pre-set as 0.13 (0.25 for forest areas) and 0.013 for overland flow over an impervious sub-area (0.011 for flows over sewers), depth of depression storage for pervious sub-area mostly is 2.5 mm (5.0 mm for forest areas) and for impervious portion of the catchment - 1.3 mm, whereas the percentage of impervious area with no depression storage is assumed to be 25%. Average surface slopes in subcatchments ranged from 0.1 to 2%. The percentages of impervious area parameter, established according to the methodology outlined in the previous chapter were slightly adjusted, but only for subcatchments located outside the airport area and used for residential purposes.

The calibration of the model for the studied catchment heavily relies on optimizing the operation of gate valves located in flow control chambers at retention tanks ZR1, ZR2/ZR3, and ZR5. This optimization involved determining the variability of gate valve openings height during the duration of events (simulations). Within the Warsaw Chopin Airport area, the control of gate valve opening height, which affects the filling and emptying of existing retention tanks, depends on the flow rates and/or water levels in specific stormwater channels and retention tanks. It is programmed in such a way that the flow in the channel below a certain gate valve is less than 1.53 $m^3 \cdot s^{-1}$, while simultaneously keeping the water level in the stormwater channels or retention tanks below permissible levels. As a result of calibration, which has taken these conditions into consideration, for each gate valve in the model "Control Curves" were established.

The next stage of model development was its validation on the basis of the values of peak flows of the hydrographs and outflow volumes recorded in the studied catchment at P1 cross-section for four rainfall-runoff events (primarily as part of the COST/210/2006 project). The assessment of agreement between the mentioned hydrograph parameters obtained from measurements and simulated in the model was performed using the relative error (Equation 1).

The rain events adopted for model verification were characterized by precipitation range from 7.1 to 24.2 mm and duration from 30 to 180 minutes. The relative error values, determined in the model validation process, using the values of peak flows and outflow volumes for four rainfall-runoff events, ranged from -8.4 to 19.9% and from -7.1 to 23.7%, respectively. The largest relative error value was less than 25%, which was considered to be the limit of model acceptance, as explained in the work of Ozga-Zielińska and Brzezinski (1997). The mean model errors, calculated on the basis of absolute values of the simulation error (minus signs were neglected) were 11.0 and 14.7% with respect to peak flows and outflow volumes, respectively. Positive results of the SWMM model validation for the Służewiecki Stream catchment under consideration allowed further exploitation of the model in consistency with the scope of this work.

2.4. Scope and methodology of computer simulations

Simulations were performed of rainwater runoff in the SWMM model, assuming that the totals of precipitation for specific events are spatially uniform throughout the catchment area of the Służewiecki Stream. Three precipitation events were considered in simulations using the model:

- Event no. 1: duration $t = 15$ minutes, occurrence probability $p = 20\%$ (frequency $C = 5$ years, e.g. once in 5 years), precipitation total $P = 11,9$ mm and unit precipitation intensity $q = 132$ l/s·ha – according to Błaszczyk formula (Błaszczyk et al., 1983).

The parameters of this event correspond to the rainfall, which was adopted to design the existing drainage system of the Chopin Airport area.

- Event no. 2: $t = 15$ minutes, $p = 20\%$ ($C = 5$ years), $P = 19.0$ mm and $q = 211$ l/s·ha – according to the formula by Bogdanowicz-Stachý (1998).

The existing permit under the Water Law Act for the disposal of rainwater and snowmelt water from the area of Chopin Airport to the Służewiecki Stream was granted, including that the maximum water flow rate in the Służewiecki Stream in the cross-section at the outflow from the Rainwater Treatment Plant does not exceed 1.53 m^3/s in case of $C = 5$ years and $q = 208$ l/s·ha rainfall. The value of this unit precipitation intensity corresponds approximately to the value calculated by the Bogdanowicz-Stachý formula ($q = 211$ l/s·ha).

- Event no. 3: $t = 15$ minutes, $p = 10\%$ ($C = 10$ years), $P = 22.6$ mm and $q = 251$ l/s·ha – also calculated using the formula of Bogdanowicz-Stachý.

According to current recommendations, for the dimensioning of rainwater retention tanks, given their significance for land drainage systems reliability, the values of rainfall frequencies for tanks should be increased according to the recommended design frequencies of the sewage networks (Kotowski et al., 2010). Therefore, the current simulations also involved $C = 10$ years rain frequency.

Simulations of rainwater runoff in response to the above-described rainfall events were performed by the SWMM maintaining the already mentioned condition of the permit under the Water Law Act that the flow in the Służewiecki Stream below the Chopin Airport area will not exceed 1.53 m^3/s. With this in mind, the simulations took into account the regulation of flows using gate valves located in the Służewiecki Stream (flow control chambers), which stimulated the processes of filling and emptying retention tanks at Chopin Airport with rainwater, and the flows in the Służewiecki Stream at the same time.

The results of some simulations were used to prepare maps showing the relative depth of channels H/D (the ratio of the calculated maximum water level in channels *H* to diameter *D*) and the location of places (sewer inspection manholes) where rainwater outflows from canals at the Airport may potentially occur. Additionally, water level profiles in the Służewiecki Stream at a critical moment of the simulation were prepared. Such profiles embrace two selected reaches of the Służewiecki Stream – its main stormwater channel (following markings are consistent with Figure 1):

- Profile no. 1: from P1 cross-section (downstream of the Airport) to the inspection manhole of the sewer system, located about 200 m upstream of ZR2/ZR3 retention tanks.
- Profile no. 2: from the above mentioned sewage manhole to P5 cross-section (upstream of the Airport).

3. Results and discussion

The SWMM model, properly adapted for the analysed Służewiecki Stream subcatchment (Figure 1), was utilized to simulate rainwater runoff in response to three rainfall events (described in the previous section). The scope of these analyses comprised the determination of the maximum flow rates and volume of floods in selected cross-sections of the Służewiecki Stream (main stormwater channel), caused by precipitation of 20 and 10% probabilities, as well as the assessment of the flooding possibility in the area of Chopin Airport.

Table 1 contains the characteristics of simulated floods in computational cross-sections of the Służewiecki Stream (P1-P5) in response to three different parameters of rainfall events. Figure 2 presents flow hydrographs (limited in the figure to 6 hours of their duration) caused by the rain-flood event no. 2 (C = 5 years, q = 211 l/s·ha). Those simulations in the model involved basically the regulation of flows by gate valves located in the Służewiecki Stream, which determined the course of filling and emptying of retention tanks at the Airport, and also regulated the flows in the main channel. Rainfall event no. 2 served also for additional simulation (it has a reference no. 1 in Table 1) with the gate valves fully open in the Służewiecki Stream.

The results of simulations of maximum flow rates and flood volumes by SWMM model, presented in the Table 1, indicate that their values differ significantly between individual cross-sections, as well as in a single cross-section for the assumed precipitation events with different parameters. The highest values of maximum flood flows were noted in the P3 calculation cross-section (located upstream of ZR2/ZR3 retention tanks), which ranged from 7.678 to 14.113 m^3/s for the assumed precipitation events. Such high values are the result of rainwater outflow primarily from the Airport area to the Służewiecki Stream through the rainwater sewage system. On the other hand, the lowest flow values were observed in the P1 cross-section (located downstream of the Airport area), varying from 0.389 to 1.329 m^3/s for the basic simulations. These values are considerably lower than in both P3 and P5 cross-section (located upstream of the Airport). In respect of the precipitation event no. 2 simulations, considering fully open gate valves, the value of the maximum flow in the cross-section closing the analysed catchment was equal to 4.526 m^3/s. Therefore, it significantly exceeded the values obtained for other simulation scenarios, which involved the regulation of flows in the main stormwater channel by means of gate valves, as well as the permitted flow (1.53 m^3/s) in the Służewiecki Stream in the cross-section downstream of the Airport area according to the applicable water permit.

With regard to flood volumes, their simulated values in the P1 cross-section become more than twice as high as in the P5 cross-section. The increase in volume between those cross-sections is the effect of supplying the Służewiecki Stream with rainwater from the Airport area. Total rainwater runoff volumes from the area of the considered catchment – in the P1 cross-section, ranged from 40.776 to 65.934 $10^3 \cdot m^3$ for the previously described precipitation events.

Table 1. Simulated flood characteristics for the computational cross-sections and flow reduction by the tanks

Event number	Rain intensity [l/s·ha]	Maximum flow rate [m^3/s]					Volume [$10^3 \cdot m^3$]		Flow reduction*[2] [%]		
		P5	P4	P3	P2	P1	P5	P1	ZR1	ZR2/ ZR3	P5/ P1
1	132	4.951	1.903	7.678	0.435	0.389	15.804	40.776	61.6	94.3	92.1
2*[1]	211	7.439	4.462	12.181	4.186	4.526	25.161	65.934	40.0	65.6	39.2
2	211	7.455	2.607	11.850	1.559	1.235	24.936	61.453	65.0	86.8	83.4
3	251	8.793	2.900	14.113	1.507	1.329	30.373	65.638	67.0	89.3	84.9

[1] simulation of fully open gates in flow regulation chambers; [2] flow reduction in the main channel by retention tanks ZR1 and ZR2/ZR3 and between P5 and P1 cross-sections.

Simulations performed for a rainfall of 20% probability (events 1 and 2) showed the significance of two applied methods for calculating the unit intensity of precipitation, i.e. according to the formulas of Błaszczyk and Bogdanowicz-Stachý, conditioning the resultant values of the analysed flood characteristics. It is

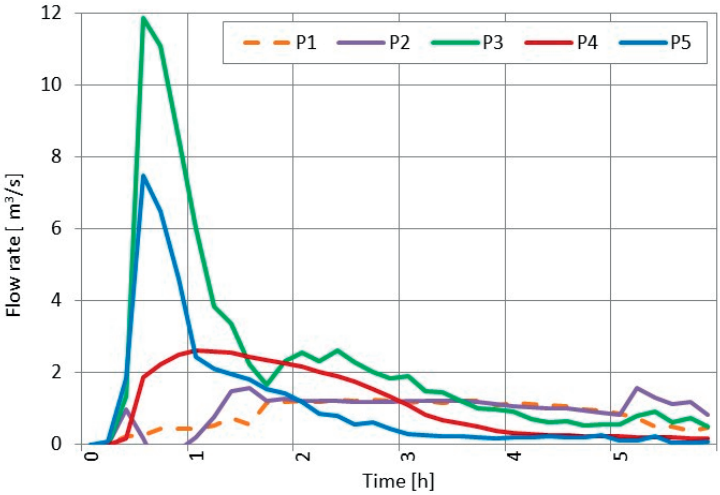

Figure 2. Simulated floods in calculation cross-sections P1-P5 for rain no. 2

currently assumed that the precipitation model according to Bogdanowicz-Stachý is more precise for establishing the reliable rain intensity, while the Błaszczyk model underestimates the results by the order of 40% (Kotowski, 2011). In consequence, the consideration of precipitation intensity by the Bogdanowicz-Stachý formula (211 l/s·ha) in the simulation had an impact on the increase of stream flow rates in the rainwater drainage channels, and thus their higher filling, leading to potential flooding from sewer inspection manholes.

The largest differences in the maximum flood flow values occurred between P3 and P2 cross-sections, i.e. upstream and downstream of the ZR2/ZR3 tanks. Considerably lower flow values in the P2 cross-section are the result of flow control by means of a gate valve located in the Służewiecki Stream channel and rainwater retention in the above-mentioned tanks. The estimated reductions of flows between P3 and P2 sections, resulting from the above-described measures, ranged from 86.8% to 94.3% for the three analysed precipitation events (Table 1). However, the reduction of flows between sections P5 and P4, located upstream and downstream of the gate valve controlling the processes of filling and emptying the ZR1 tank (situated in the upper part of the Airport area), ranged from 61.6 to 67.0% for the three basic scenarios of simulation. Those scenarios assumed that the gate valves lifting in the main stormwater channel in tanks ZR1 and ZR2/ZR3 are constant 5 and 35 cm above the channel bottom in the flow control chambers, respectively. On the other hand, the lifting height of the gate valves in the channels within the Rainwater Treatment Plant (at the ZR5 tank and the rainwater settling tank) is controlled automatically and variable in time, causing a reduction of the maximum flow rate in the Służewiecki Stream in the cross-section downstream the Airport area to a value not exceeding the permitted - 1.53 m^3/s. The lowest obtained values of flow reduction as an effect of rainwater retention in tanks ZR1 and ZR2/ZR3 (40.0 and 65.6%) referred to simulations with fully open gate valves in flow control chambers.

However, the calculated values of reductions of flows between P5 and P1 sections (located upstream and downstream of the Airport area respectively), amounting to 83.4 to 92.1% for the three basic simulation scenarios, resulted from rainwater retention in the existing airport drainage system and flow control through gate valves in the Służewiecki Stream. The lowest value of flow reduction (39.2%) was computed for simulations involving fully open gate valves.

For one of the rainfall events - event no. 3, graphs were devised of the time variability of water levels (rainwater filling) in five tanks located at the Airport (Figure 3). Event no. 3 is characterized by a unit intensity of precipitation q = 251 l/s·ha (C = 10 years frequency), higher than the reliable design value for the drainage system of the Airport area (equal to q = 132 l/s·ha). Detailed parameters of these precipitation events were given in the previous section. The resultant water level courses in the ZR1 tank (which retains rainwater from the subcatchment upstream of the Airport) and the ZR4 tank, have proven that the emptying times of these tanks (for technological reasons it is not possible to empty them completely) were much shorter than for ZR2/ZR3 and ZR5 tanks. Moreover, the volume of retained rainwater in the ZR1 and ZR4 tanks was much smaller than in the other tanks. Fundamental importance for the reduction of maximum flows in the Służewiecki Stream was attributable to ZR2 and ZR3 tanks, offering the largest retention capacities in the rainwater management system of the Airport, equalling to 11,130 and 15,620 m^3, respectively. For precipitation event no. 3, the maximum simulated values of water levels in these tanks were 2.3 m, and the time of their emptying reached more or less two days. On the other hand, the ZR5 tank, which has the lowest topographical location (altitude) at the Airport, was filled to a level

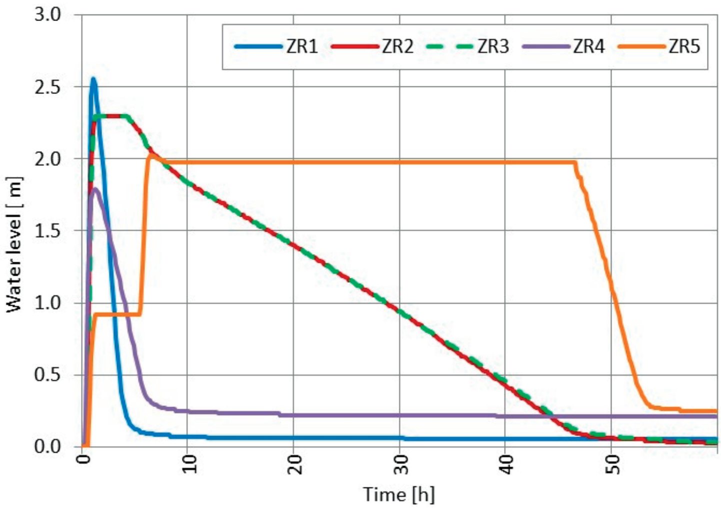

Figure 3. Simulated water levels in the ZR1-ZR5 tanks for rain no. 3

of approx. 2.0 m. The process of emptying this reservoir began already after two days approximately, when the water stage in the Służewiecki Stream downstream of the Airport reached a low value.

In the existing retention tanks on the Chopin Airport premises, large quantities of rainwater are collected during rainfall events, which subsequently flow into the Służewiecki Stream. According to Carvalho et al. (2013), rainwater can serve as alternative sources to meet various non-potable water needs in airport areas, such as fire protection, aircraft washing and irrigation of landscape elements. Studies conducted by Kuller et al. (2015) demonstrated that collecting rainwater runoff from paved surfaces at Amsterdam`s Schiphol Airport (the fourth-largest airport in Europe) could meet the entire demand for non-potable water. The Copenhagen Airport in Denmark serves as an example of successful implementation of a sustainable water management strategy, where an extensive drainage system and large rainwater pools have been constructed to prevent flooding of the area. The airport has two separate drainage systems for the disposal of wastewater and rainwater, which significantly reduced the amount of water requiring treatment in external water treatment water processing plants (Baxter et al., 2019). Implementing similar solutions at the Warsaw Chopin Airport could enhance the existing rainwater management system.

The results of simulations in the SWMM model, after considering the rainfall of $C = 10$ years frequency and unit intensity of $q = 251$ l/s·ha (precipitation event no. 3), were used to prepare maps showing the risk of flooding (Figure 4A) and the capacity of canals in the Airport area (Figure 4B). The analysis proved that there are locations (sewage manholes/chambers) at the Airport where short-term rainwater floods from canals may potentially occur (points marked in red in Figure 4A). Moreover, simulations indicate that usually after a few minutes from the moment of flooding in a particular place, rainwater tends to flow from the surface to the storm water drainage system.

The analysis for rainfall event 3 has also clearly shown that alues of the relative channels depth of H/D may be higher than recommended in the literature – a value of 0.75, as well as equalling to 1.00 (indicating the total filling of the stormwater channel) for some sections of rainwater drainage (marked with yellow and red respectively in Figure 4B). However, for other reaches, the relative water depths in channels did not exceed the limit value of 0.75 (channels marked in green). At the critical point of the simulation, a vital number of stormwater channels were completely filled with rainwater so they operated under pressure. However, for most channels, this situation occurred for a short time span.

It should be noted, however, that the discussed simulation results refer to a precipitation event characterized by almost twice the unit intensity than the reliable precipitation – event no. 1 ($q = 132$ l/s·ha), which was used to design the existing drainage system of the Airport. Lastly, the computation for rainfall event no. 1 showed that only a few sewer manholes may be subject to small and short-term rainwater overflows.

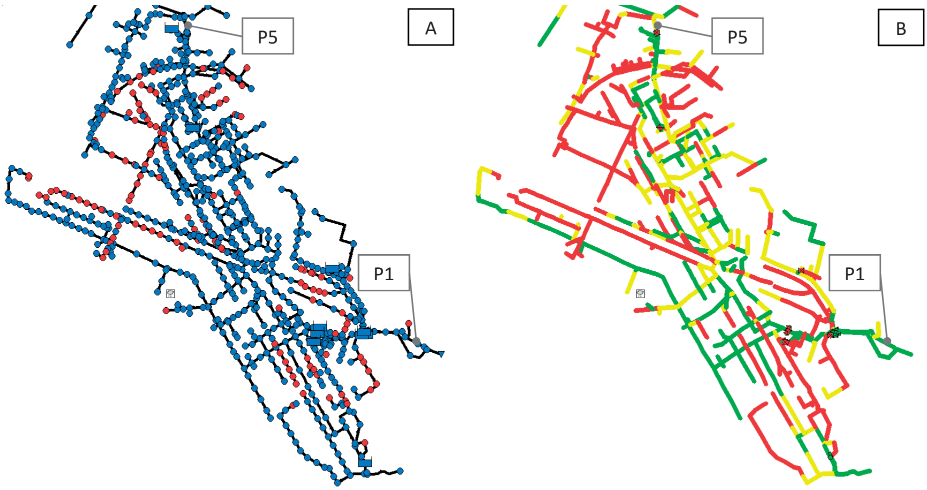

Figure 4. Potential storm water overflow sites for the analysed canal system (A) and relative rainwater depth in stormwater channels at the Airport site (B) at the critical moment of the simulation for rain no. 3. Markings: P5 and P1 – computational cross-sections upstream and downstream of the Airport; points (sewer manholes) in blue and red stand for no overflow and potential overflow respectively; green, yellow and red channels indicate relative water depths in channels with $H/D < 0.75$ (less than 75% of the total diameter of the channel), $0.75 \le H/D < 1.00$, $H/D \ge 1.00$ (total canal fill) respectively

Even temporary accumulation of rainwater on airport runways can lead to aquaplaning and aircraft skidding during landing and take-off (Li et al., 2018). Predicting the risk of flooding and issuing alerts based on measured data regarding water film height is an effective way to reduce aircraft accidents caused by the accumulation of rainwater on runways (Ling et al., 2023). The risk of flooding can be reduced, among other measures, by implementing green-blue infrastructure elements within airport areas, which increase the retention of rainwater. The above statement is supported by results of research conducted using the SWMM model for Beijing Daxing International Airport in China in response to a 100-year return period rainfall event (Peng et al., 2020). Simulations for the current state of the airport`s use revealed that many sections of the rainwater drainage are completely filled with water, leading to rainwater overflow from sewer manholes. On the other hand, simulations that incorporated green-blue infrastructure (such as green roofs, infiltration trenches, rain barrels, vegetative swales, and permeable paved surfaces) demonstrated that implementation of such infrastructure effectively reduced the risk of flooding in the studied area. In other studies, it has been determined that the implementation of green-blue objects on the mentioned airport premises can lead to a reduction of rainwater runoff by 18% during heavy rainfall events (Peng et al., 2022).

Simulations in the model for rainfall event no. 2 ($q = 211$ l/s·ha) served to create two profiles of the maximum water level in the Służewiecki Stream (Figure 5), covering the stormwater channel reach from the P1 cross-section downstream of the Airport area to the P5 section. The flow conditions in the drainage system of the studied catchment were calculated using the Dynamic Wave model, which involves solving full Saint-Venant equations (Laouacheria et al., 2019) at several points in sewer pipes/open channels and manholes (nodes). The analysis showed that during critical moments of the simulation (temporally differentiated for two created profiles), rainwater completely filled certain sections of the Służewiecki Stream, which are mainly closed channels, primarily with a circular cross-section (the sewer diameters range from 1.8 to 2.5 m). The Służewiecki Stream has an artificial open channel character with a trapezoidal cross-section only in the sections of the channel located upstream from retention tank ZR1 and downstream from tank ZR5. The simulations did not indicate a direct threat of rainwater flooding from the Służewiecki Stream at the Chopin Airport. Respective analyses for precipitation events no. 1 (q = 132 l/s·ha) and 3 (q = 251 l/s·ha) lead to comparable conclusions, namely in both cases there may occur short-time span overflow at some reaches of the main canal, but there is no flooding risk indicated.

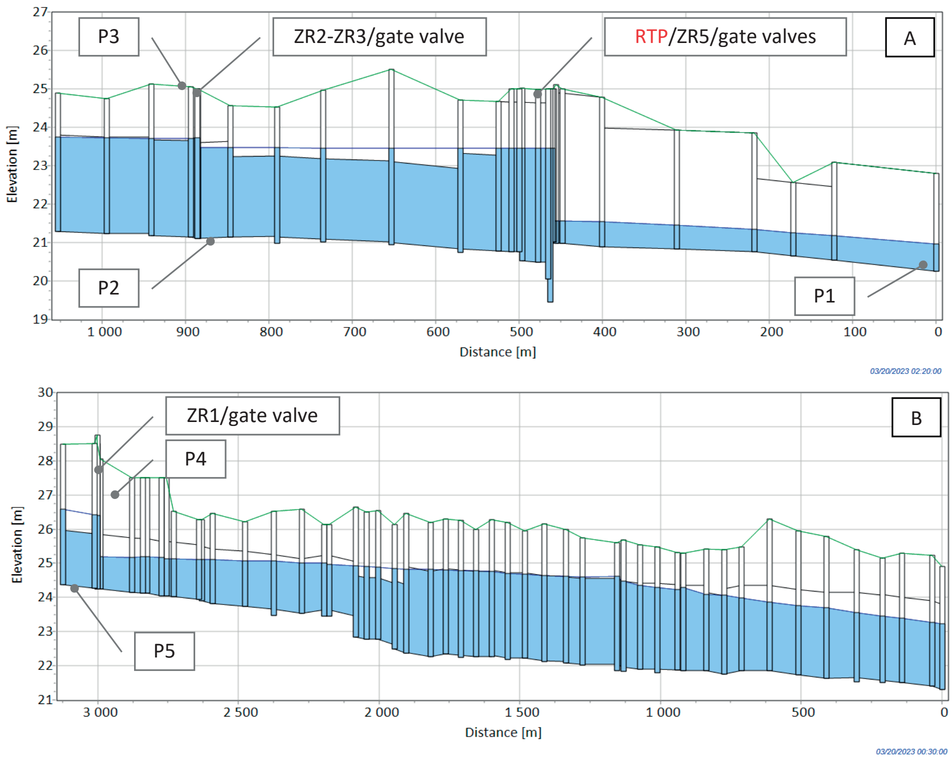

Figure 5. Maximum water level profiles in the Służewiecki Stream for event no. 2 – profiles no. 1 (A) and 2 (B). Markings: water levels in stormwater channels and manholes (nodes) - lines in blue; P1-P5 - calculation cross-sections; ZR1-ZR3, ZR5 - retention tanks; RTP - Rainwater Treatment Plant

4. Conclusions

The SWMM (Storm Water Management Model) computer model was used to simulate rainwater runoff from the area of the urbanized subcatchment of the Służewiecki Stream in response to 20 and 10% probability precipitation (frequencies once every 5 and 10 years) and then to estimate the risk of flooding within Warsaw Chopin Airport compounds. The performed calculations enabled the formulation of the following conclusions and statements:

- The SWMM model enables the spatial and temporal variability assessment of modelled hydrological processes in response to rainfall of any type, as well as the calculation of reliable values of water level, flow and volume of rainwater in each device of the urbanized area drainage system (in rivers and open channels, tanks, storm water manholes and drainage pipes, etc.).
- Values of water flows in the computational cross-section of the Służewiecki Stream downstream of the Airport area, simulated in the model assuming the control of flows by gate valves and rainwater retention in existing tanks, in response to 20 and 10% probability precipitation events, in both cases were lower than the permitted flow (according to the permit under the Water Law Act, its value was 1.53 m^3/s for rainfall of a 20% probability). The functioning of the above-mentioned hydraulic structures shows a vital impact on the flow rate reduction in the Służewiecki Stream, and, in the same way restricts the risk of flooding in the analysed urban catchment. Optimising the operation of gate valves located in the Służewiecki Stream (flow control chambers) could improve the filling and emptying retention tanks efficiency at the Airport, and guarantee greater reduction of water flows.
- Computer simulations for rainfall of a 10% probability have indicated that the magnitude of relative water depth in the stormwater channels may in short periods of time exceed the value of 0.75 (recommended in the literature), as well equal to 1.00 (meaning the complete filling of the channel with rainwater and its operation under pressure) in relation to some stormwater channels at the Airport. They also pointed at certain locations (sewage manholes) at the Airport where short-term rainwater floods from canals can potentially occur. The obtained results of calculations could serve as a basis for assessing the negative effects related to potential overflows and the necessary actions intended to reduce the possibilities of their occurrence, coupled with anticipated environmental, infrastructure and socio-economic impacts. The suitability of SWMM model can be found for similar simulations in other urbanized areas.

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OCENA ZAGROŻENIA WYSTĘPOWANIA PODTOPIEŃ NA OBSZARZE ZURBANIZOWANYM W REAKCJI NA NAWALNE DESZCZE: STUDIUM PRZYPADKU LOTNISKA CHOPINA W WARSZAWIE

Abstrakt

W artykule przedstawiono adaptację hydrodynamicznego modelu *Storm Water Management Model* (SWMM) dla zlewni cząstkowej Potoku Służewieckiego w Warszawie, której przeważającą część stanowi teren Lotniska im. Chopina. Model SWMM zastosowano do obliczania odpływu wód z badanego obszaru zurbanizowanego w reakcji na opady deszczu o prawdopodobieństwach wystąpienia 20% i 10%, a następnie do oceny możliwości występowania podtopień w wyniku wylewania się wód deszczowych z systemu odwodnienia Lotniska. Zakres pracy obejmował również ocenę wpływu istniejących zbiorników retencyjnych na terenie lotniska na redukcję przepływów maksymalnych w kanale Potoku Służewieckiego. Symulacje dla opadu o prawdopodobieństwie 10% wykazały, że na terenie lotniska są miejsca (studzienki kanalizacyjne), w których potencjalnie mogą występować krótkotrwałe wylewy wód deszczowych. Retencjonowanie wód deszczowych w zbiornikach i sterowanie przepływami za pomocą zasuw ma duży wpływ na redukcję przepływów w Potoku Służewieckim, a tym samym na zmniejszenie zagrożenia występowania podtopień na obszarze badanej zlewni.

Słowa kluczowe: opady deszczu, obszar zurbanizowany, zagrożenie podtopieniami, zbiorniki retencyjne, model SWMM