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# HYDRODYNAMIC MODELLING OF THE COMBINED SEWAGE SYSTEM FOR THE CITY OF PRZEMYŚL

The paper presents results of studies on hydraulic parameters characterizing various variants of modernization of sewage system serving the city of Przemyśl. In the research work, a hydrodynamic model of urban catchment area with its sewage network cooperating with a sewage pumping station, storm overflow and retention reservoirs was developed with the use of Storm Water Management Model (SWMM) software. In the analysis, actual pluviometer records were used as input data.

## 1. INTRODUCTION

Intensive development of urban areas observed in recent years and connecting new catchments to the existing sewage systems cause more and more frequent occurrences of clogging in sewage systems resulting in hydraulic overloads of sewage networks and facilities, inundation of catchment areas, and damage to urban infrastructure. This forces the operators to undertake positive preventive actions. Many of the existing sewage systems, constructed typically several decades ago, require currently an immediate modernization as their technical condition and flow parameters can no longer meet neither hydraulic requirements nor regulations applicable to their effect on the natural environment.

According to recommendations of the European standard EN 752 [1], all modernization undertakings, especially those consisting in extension of a sewage system, should be preceded with studies on and detailed examination of the system's actual condition from both technical and hydraulic point of view. This can involve the necessity to make use of hydrodynamic models that, apart from the need of feeding them with actual measurement data, will require precise calibration [2]. In the case of

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existing sewage systems, simulation programs turn out to be particularly suitable tools as they allow one to carry out hydrodynamic simulations of wastewater flow both in existing sewage systems and networks extended by adding new facilities. The issue of increasing the throughput capacity of combined sewage systems with the use of a hydrodynamic model was presented, e.g. in [3–5]; further, [6] contains discussion on issues related to modelling design parameters of retention reservoirs with the use of hydrodynamic models of urban catchment areas and sewage networks.

This paper presents results of simulation tests carried out for the existing combined sewage system of the city of Przemyśl. The fundamental research problem consisted in determination of possibility to counteract the phenomenon of hydraulic overloading occurring in the city's sewage network cooperating with the left-bank sewage pumping station located in Zasanie district and the storm overflow discharging sewage to the river San that turned out to have insufficient hydraulic throughput capacity.

## 2. SOFTWARE TOOL

In the studies presented in this paper, a software package made available by the United States Environmental Protection Agency (EPA) was used. To simulate processes of surface runoff, soaking, retention and evapotranspiration of precipitation water in the catchment area as well as flows in the combined sewage system, the Storm Water Management Model was used. The mathematical model implemented in the software environment offers the possibility to create a complete description of the precipitation water runoff phenomenon reproducing the actual conditions with a high degree of accuracy [7].

The program is typically used for analyzing operation of existing sewage systems and modelling wastewater flows in storm and combined sewage networks extended by adding new facilities [8, 9]. It is also a useful tool in comparative analysis of wastewater runoff for surfaces of various types [10] and examination of hydrologic conditions and their evolution occurring along with development of the catchment [3, 11].

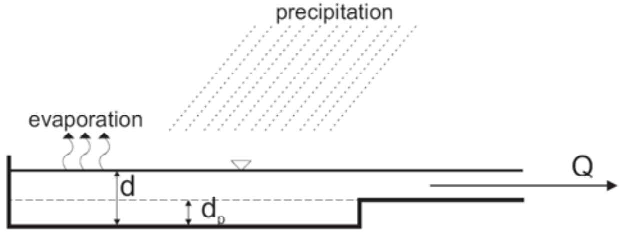


Fig. 1. The surface runoff model in SWMM program: $d$ – water layer height, $d_p$ – height of water layer retained in depressions, $Q$ – runoff from the catchment area

A runoff from a catchment area is treated as the outflow from a nonlinear reservoir filling of which equals the amount of water that has fallen onto the surface area under consideration with losses resulting from water evaporation, soaking and retention in land depressions taken into account, as shown in Fig. 1 [12].

Magnitude of precipitation water runoff from the catchment area is determined in the *SWMM* program by means of the formula (1) [13].

$$Q = \frac{W(d - d_p)^{5/3} i^{1/2}}{n} \tag{1}$$

where: $Q$ – runoff from the catchment area, m$^3$/s, $W$ – runoff strip width, m, $n$ – Manning's roughness coefficient, s/m$^{1/3}$, $d$ – water layer height, m, $d_p$ – height of water layer retained in terrain depressions, m, $i$ – land slope.

The amount of water soaking into the ground from the terrain surface at the precipitation location is taken into account in the mass balance. In the developed hydrodynamic model of the catchment, Horton's infiltration model was used according to which the soil absorptivity decreases asymptotically in time from an initial value $f_c$ representing the maximum infiltration rate to a final value $f_0$.Infiltration intensity is calculated by means of equation [14]:

$$f = f_c + \left(f_0 - f_c\right)\mathrm{e}^{-\beta t} \tag{2}$$

where: $f$ is the infiltration intensity, mm/h, $f_c$ – final infiltration rate, mm/h, $f_0$ – maximum infiltration rate, mm/h, $\beta$ – infiltration intensity decay constant, 1/h, $t$ – infiltration process duration time, h.

The program user may select also "Green – Ampt and Curve Number" options, where the runoff is calculated with different types and use of soils and the assumed average moistness conditions prevailing in the catchment area are taken into account [14].

## 3. INPUT DATA OF THE MODEL

The subject of the study was the analysis of hydraulic conditions prevailing in Zasanie district and modernization variants for the combined sewage network constituting the left-bank part of the city of Przemyśl. The town is situated in south-eastern Poland and has ca. 70 thousand inhabitants. The catchment area is served by a combined, partly separated sewage system. The receiving water for local wastewaters is the river San protected under Natura 2000 program; this imposes fundamental restrictions on modernization undertakings concerning the sewage system.

Sewage from Zasanie district is transported through a pumping system to the expansion chamber located on the other bank of the river San. Maximum capacity of the pumping station is 900 dm$^3$/s. Schematic diagram of the modeled network's main collector sewers cooperating with storm overflow and the pumping station is presented in Fig. 2. In the case of intensive rainfalls, significant part of the sewage system is subject to overloading which results in inundation of urban areas and frequencies of storm discharges to the river exceeding limits determined in applicable regulations [15]. Parameters describing the catchment were determined based on actual data made available by the network operator. Additionally, topographic maps of the terrain in question were used in order to obtain the highest possible accuracy in reproduction of altitude of individual collecting sewers and other elements of the sewage system.

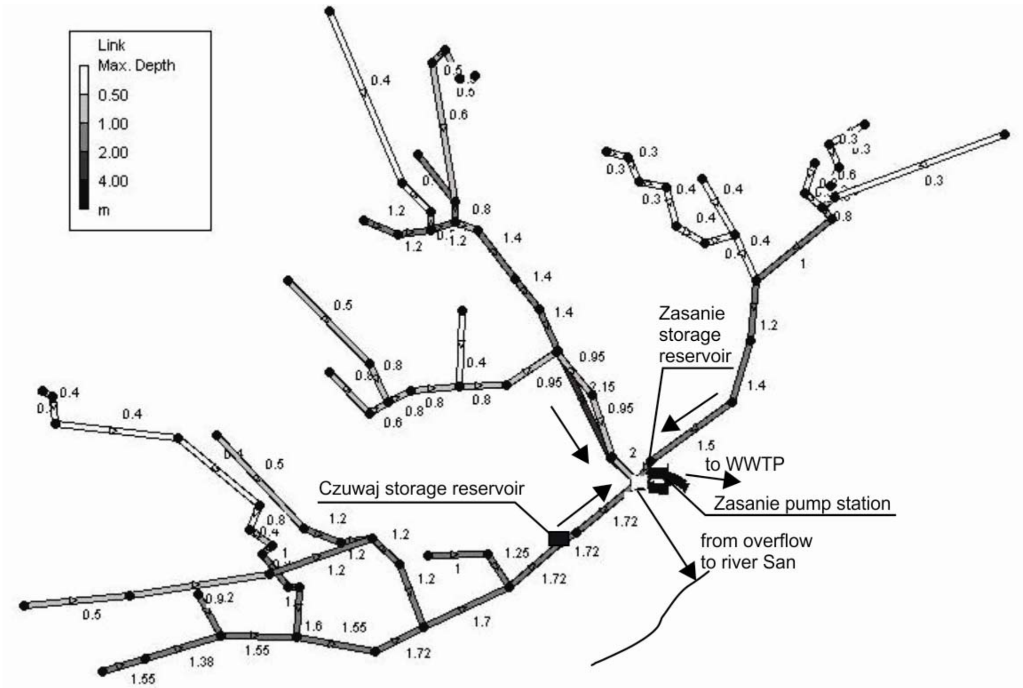


Fig. 2. Schematic diagram of main collector sewers of the modeled sewage network

In simulation of rainwater runoff from the urban catchment, precipitation data for the years 2007 and 2008 obtained from pluviometers located in three housing estates of Zasanie district were used. Their locations are shown in Fig. 3.

Surface area of the analyzed catchment is 632.88 ha. The catchment area is developed mainly with residential buildings and service centers. The total reduced area of Zasanie district is 161.52 ha, and the total runoff coefficient $\psi$ equals 0.39. The catchment area has been divided into 40 sub-areas borders of which were determined based on plans containing geodetic datums of the terrain in question, development type, routes of individual collecting sewers of the network, and main streets. Terrain slopes were entered into the SWMM program individually for each of the determined subcatchments on the grounds of actual data representing the lay of the land in question.

A very important parameter of the hydrodynamic model is the runoff strip width *W* determination of which should be considered as a priority [16]. According to Eq. (1), increase of the runoff strip hydraulic width will result in increase of runoff, while with decreased values of parameter *W*, the surface runoff from the catchment area will cease. Based on studies described in [16], parameter *W* was determined by means of equation:

$$W = \frac{A_{\text{red}}}{L_{\text{obl}}} \tag{3}$$

where: $A_{\text{red}}$ – reduced catchment area, m$^2$, $L_{\text{obl}}$ – calculation length of flow path from partial catchment area, m.

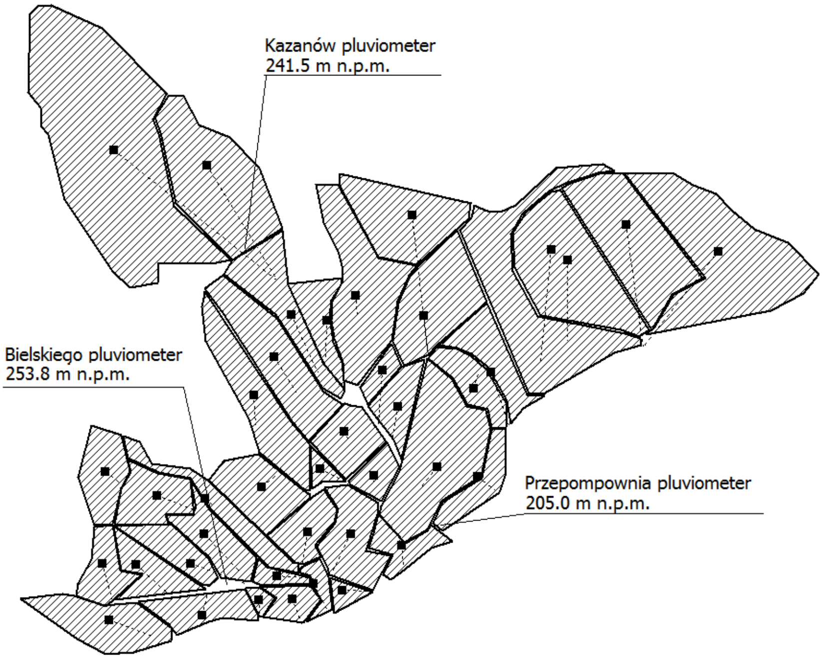


Fig. 3. Schematic diagram of Zasanie catchment area together with partial catchment areas and location of pluviometers

The remaining parameters characterizing the catchment (Table 1) were chosen based on data obtained from the network operator and recommendations published in references [14, 17, 18]. Hydrodynamic model includes channels from 0.3 m to 1.72 m in diameter and total length of 17.82 km. Secondary small bore channels (maximum 0.3 m in diameter) were omitted.

Table 1

Input data for modelling runoff
from Zasanie district catchment area in *SWMM* program

| Parameter | Value |
|---|---|
| Catchment impermeability ratio, % | 10–60 |
| Manning coefficient for impermeable surfaces | 0.015 |
| Manning coefficient for permeable surfaces | 0.30 |
| Retention height for impermeable surfaces, mm | 1.5 |
| Retention height for permeable surfaces, mm | 7.0 |
| Minimum infiltration rate, mm/h | 20 |
| Maximum infiltration rate, mm/h | 90 |
| Infiltration intensity decay constant, 1/h | 4 |
| Time for saturated soil to fully drain, D | 4 |
| Runoff strip width, m | 50–75 |
| Land slope | 0–0.05 |

## 4. CALIBRATION OF THE MODEL

After entering all the necessary pluviographic data and parameters characterizing the catchment and its sewerage network together with storm overflow and sewage pumping station to the program, the accuracy of the model was checked as for its ability to reproduce conditions prevailing in the actual system. Calibration was carried out for such parameters as water retention height of permeable and impermeable surfaces, runoff strip widths, and infiltration rates as defined in Horton's infiltration model. To this end, measurement data were used on annual number of discharges occurring through the storm overflow and volumes of individual storm discharges obtained from measurement taken in the years 2007–2008 at the storm overflow P7. Actual volumes of storm flows were compared with data obtained as a result of dynamic simulation.

The average error of modelling was about 18%. The obtained results allow one to conclude that the developed model is characterized by a satisfactory accuracy. Observed discrepancies between the model and the actual system resulted primarily from imperfect reproduction of precipitation variability over the whole of the catchment area.

## 5. MODERNIZATION VARIANTS

Hydrodynamic studies were carried out for three selected variants of modernization of the Przemyśl city's combined sewage system.

- Variant 1. Elevation of edge in the storm overflow upstream the Zasanie pumping station up to the level 0.80 m or 1.00 m or 1.20 m over the overflow chamber bottom.
- Variant 2. Construction of Zasanie retention reservoir of the capacity of 5000 $m^3$ relieving the left-bank Zasanie sewage pumping station.

- Variant 3. Construction of Zasanie retention reservoir of the capacity of 5000 m$^3$ relieving the left-bank Zasanie sewage pumping station and Czuwaj retention reservoir of the capacity of 5000 m$^3$ relieving the main collecting sewer.

## 6. RESULTS

In order to mitigate negative effects related to insufficient throughput capacity of the sewage system of the city of Przemyśl, various options for extension of the system have been developed. The study [19] presented a concept consisting in extension of the system with retention facilities, for which a dynamic simulation of the network operation after the extension was carried out together with assessment of the achieved environmental effect.

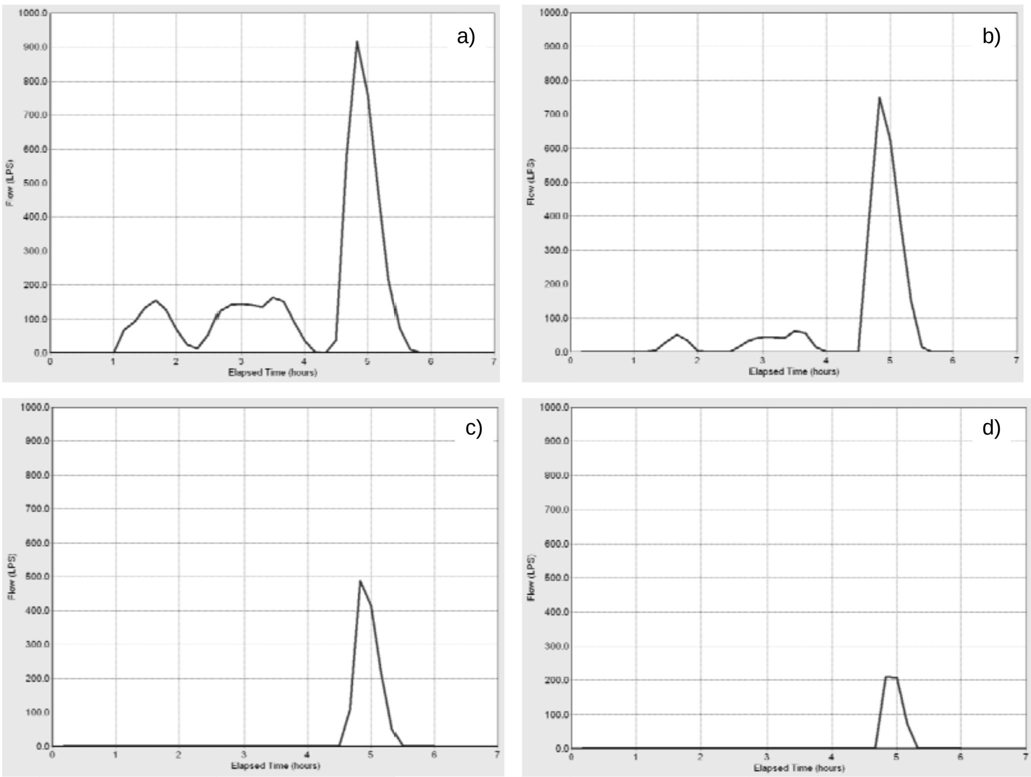


Fig. 4. Results of simulations of flows in the storm sewer channeling wastewater to the river for rainfall of 8 September 2007 at the overflow edge located at height of: a) 0.67 m (existing state), b) 0.8 m, c) 1.0 m, d) 1.2 m

Combined sewage from Zasanie catchment area is directed to the treatment plant situated on the other bank of the river San, via the sewage pumping station. In the course of intensive precipitation, the pumping station is unable to transport the whole volume of combined sewage which causes backflows towards the storm overflow and consequently results in discharging the wastewater into the receiving water body.

One of the parameters decisive for assessment of correct operation of a storm overflow is the number of its activations occurring in a year. In the case of the allowable number of discharges being exceeded, it seems to be reasonable to increase height of the overflow edge. The edge is currently located 0.67 m above the overflow chamber bottom. Simulation of flows in the sewage network was carried out for the edge altitudes of 0.80 m, 1.00 m and 1.20 m. Figure 4 shows plots of intensity of sewage inflow to the receiving body for various storm overflow edge heights. Further, Table 2 presents the number of storm discharges occurring through the storm overflow to the river San for selected most intensive rainfalls.

Table 2

Number of storm wastewater discharges to the river San
for the storm overflow in the existing state (0.67 m)
and after increasing the overflow edge height

| Date month/day/year | Overflow edge height [m] | | | |
|---|---|---|---|---|
| | 0.67 | 0.80 | 1.00 | 1.20 |
| | – | – | – | – |
| 08/11/2007 | 1 | 0 | 0 | 0 |
| 08/18/2007 | 2 | 1 | 1 | 1 |
| 09/05/2007 | 4 | 4 | 3 | 2 |
| 09/06/2007 | 4 | 3 | 3 | 3 |
| 09/08/2007 | 2 | 2 | 2 | 1 |
| … | … | … | … | … |
| 06/15/2008 | 1 | 1 | 1 | 0 |
| 06/23/2008 | 1 | 1 | 1 | 1 |
| 07/25/2008 | 3 | 3 | 3 | 3 |
| 08/09/2008 | 1 | 1 | 1 | 1 |
| 09/18/2008 | 2 | 2 | 1 | 0 |

Results of the performed simulation studies show, as expected, that elevation of the storm overflow edge has an important effect on both volumes and number of storm wastewater discharges that is a parameter regulated in applicable Polish legislature [15]. After elevating the storm overflow edge up to the level of 1.2 m, it could be seen that in periods of intensive precipitation, Zasanie sewage pumping station would be unable to cope with the resulting relating amounts of sewage thus posing a threat of flooding the pumping station and the sewage network. Results of the simulation are presented in Fig. 5.

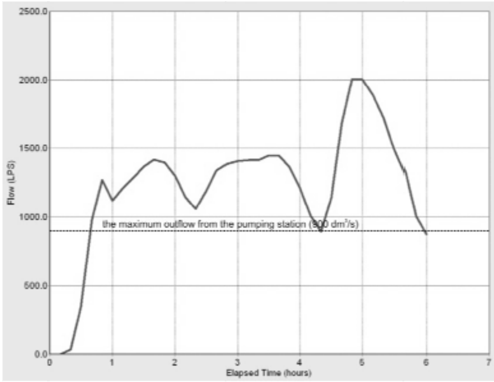


Fig. 5. Results of simulation of flows in collecting sewer supplying sewage to Zasanie sewage pumping station for the precipitation of 8 September 2007 for the overflow edge located at height of 1.2 m

According to the adopted conception of modernization of the pumping station [19], construction of Zasanie retention reservoir providing temporary relief to the pumping system was planned (Fig. 6). After cessation of runoffs caused by intensive rainfalls, sewage from the tank would be channeled to the pumping station, then pressed into the collecting sewer on the other bank of the river San and further to the wastewater treatment plant.

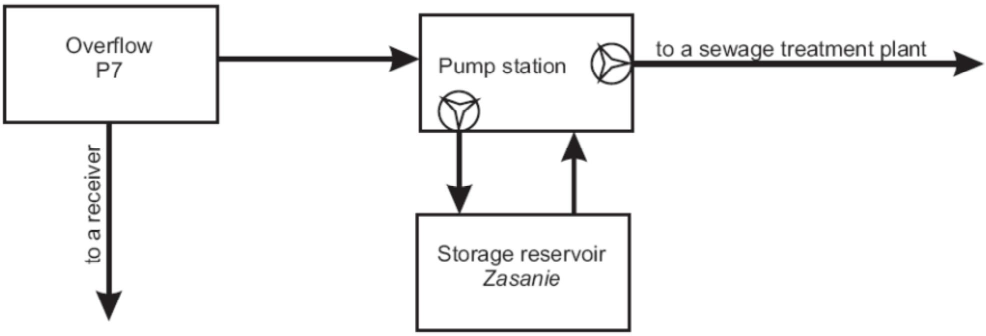


Fig. 6. Schematic diagram of the modernized sewage system in the area of Zasanie sewage pumping station

It follows from the performed studies that introduction of a retention reservoir relieving the sewage pumping station, even with the present position of the storm overflow edge, has a positive effect on operation of the whole hydraulic system. One can observe significant reduction of sewage volumes discharged to the receiving body ranging at 30–40% of the original discharges for the largest rainfalls to 100% for minor rains. Results of simulations aimed at determination of wastewater discharges occurring to the receiving water for selected rainfalls are summarized in Table 3.

Table 3

Volumes of discharges from the storm overflow [m$^3$]

| Date month/day/year | The system in the existing state | The system with Zasanie reservoir | The system with Zasanie and Czuwaj reservoirs |
|---|---|---|---|
| 08/11/2007 | 51.08 | 0.00 | 0.00 |
| 08/18/2007 | 12 777.89 | 9024.90 | 7669.52 |
| 09/05/2007 | 23 739.25 | 14 688.48 | 12 098.11 |
| 09/06/2007 | 14 261.95 | 8312.37 | 6218.72 |
| 09/08/2007 | 2969.52 | 623.01 | 376.21 |
| … | … | … | … |
| 06/15/2008 | 59.56 | 0.00 | 0.00 |
| 06/23/2008 | 1369.65 | 374.75 | 296.27 |
| 07/25/2008 | 6666.26 | 1273.97 | 596.07 |
| 08/09/2008 | 4053.32 | 1331.52 | 506.72 |
| 09/18/2008 | 3094.68 | 82.20 | 0.00 |

As a result of introduction of a retention reservoir cooperating with the sewage pumping station, it was possible to reduce the frequency of occurrence of overflow phenomena. In an analysis carried out with the use of data reproducing several most intensive rainfalls of the year, no storm discharges to the receiving water were observed. For example, for the rainfall of 8 August 2007 it was possible to reduce the number of storm discharges from two to one, with volume of the discharge being significantly reduced at the same time (Fig. 7).

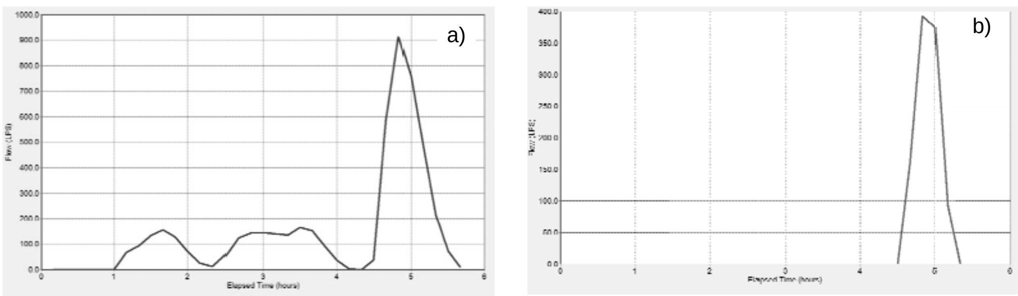


Fig. 7. Results of the storm sewer flow simulation for the rainfall occurring on 8 September 2007: a) flow in the storm sewer for the existing state (overflow edge at the height of 0.67 m), b) flow in the storm sewer after modernization

In the past, the number of storm discharges to the receiving water occurring in the analyzed sewage system during intensive rainfalls exceed significantly the allowable annual number (according to Polish regulations [15], the number must not exceed 10 occurrences per year). Introduction of the retention reservoir allowed one to reduce the number of discharges considerably (Table 4), but statutory requirements still could not be met. This induces the necessity to construct a retention reservoir and adjust the overflow edge's position.

Table 4

Number of wastewater storm discharges occurring from the storm overflow for different sewage network modernization variants

| Date month/day/year | Sewage network in the existing state | Sewage network with Zasanie reservoir | Sewage network with Zasanie and Czuwaj reservoirs |
|---|---|---|---|
| 08/11/2007 | 1 | 0 | 0 |
| 08/18/2007 | 2 | 2 | 2 |
| 09/05/2007 | 4 | 3 | 3 |
| 09/06/2007 | 4 | 3 | 3 |
| 09/08/2007 | 2 | 1 | 1 |
| … | … | … | … |
| 06/15/2008 | 1 | 0 | 0 |
| 06/23/2008 | 1 | 1 | 1 |
| 07/25/2008 | 3 | 3 | 3 |
| 08/09/2008 | 1 | 1 | 1 |
| 09/18/2008 | 2 | 1 | 0 |

In view of occurrence of pressure flows in the middle course of the main sewer supplying sewage to Zasanie pumping station, an option consisting in construction of additional Czuwaj retention reservoir located upstream the storm overflow is also taken into consideration. The main task of the retention reservoir is to reduce maximum flows in the main collecting sewer. This is also expected to influence hydraulic conditions at the storm overflow, Zasanie sewage pumping station, and Zasanie retention reservoir.

The Czuwaj retention reservoir, in view of favorable topographic situation, will be supplied via a gravitation channel. On the other hand, evacuation of the reservoir will occur as a result of operation of the pumping system coordinated with functioning of the pumping station and operation of pumps of the Zasanie retention reservoir.

There are many possible scenarios for cooperation within the system comprising retention reservoirs, sewage pumping station, and storm overflow. The issue of selection of the optimum operational scenario is rather complex and should become the subject of a separate study with numerous criteria taken into account such as the system's energy effectiveness, achieving predetermined hydrodynamic parameters, and minimizing the environmental footprint.

The study was carried out with one of possible scenarios assuming that filling the Czuwaj retention reservoir is triggered by Zasanie sewage pumping station working at its maximum capacity and Zasanie reservoir being filled up to its maximum capacity.

In turn, the process of emptying Czuwaj retention reservoir is initiated at the moment when the amount of sewage pressed by Zasanie pumping station towards the treatment plant is lower that its maximum capacity. Sewage flows in the system configured this way for the adopted algorithm of its operation are shown in Fig. 8.

Introduction of Czuwaj retention reservoir created the possibility to relieve the main collecting sever but did not result either in any significant decrease of the number of activations of the storm overflow (Table 4) or considerable reduction of volume of combined sewage discharged from the storm overflow to the receiving water (Table 3) with respect to the variant in which Zasanie retention reservoir was planned to be used.

## 7. CONCLUSIONS

In the paper, results of hydrodynamic analysis carried out for different variants of modernization of the combined sewage system serving the city of Przemyśl were presented. The study demonstrated that the variants show different usefulness for solving the problem of hydraulic overloading of the existing sewage system and excessive number of wastewater storm discharges occurring to the river San.

For each of the analyzed variants some improvement was observed, more or less significant, of hydraulic conditions in the sewage system together with a reduction of the number of wastewater discharges.

The performed simulation tests allow to formulate the following conclusions.

Variant 1 of the modernization project providing only for elevation of edge of the storm overflow located upstream the sewage pumping station is a solution with the lowest investment outlays, but it does not ensure stability of operation of the sewage system. Reduction of wastewater discharges occurring in the course of rainfalls can result in problems with operation of Zasanie sewage pumping station and local inundations of urban infrastructure and buildings. In view of the above, this variant must be considered only a short-term solution.

For Variant 2 of the modernization project, significant reduction of numbers and volumes of storm discharges from the storm overflow was achieved, even with the present position of the storm overflow edge. This proves that, to a considerable degree, storm overflow discharges to the river San can be attributed to the sewage pumping station. The facility has insufficient capacity which results in sewage cloggings occurring in the main inlet channel and backflows towards the storm overflow. At the same time, capacity of Zasanie pumping station is limited by the processing capacity of the wastewater treatment plant that can not be increased in present situation. For this modernization variant, stabilization of operation of the sewage pumping station and a decrease of number of floodings of the facility was also observed.

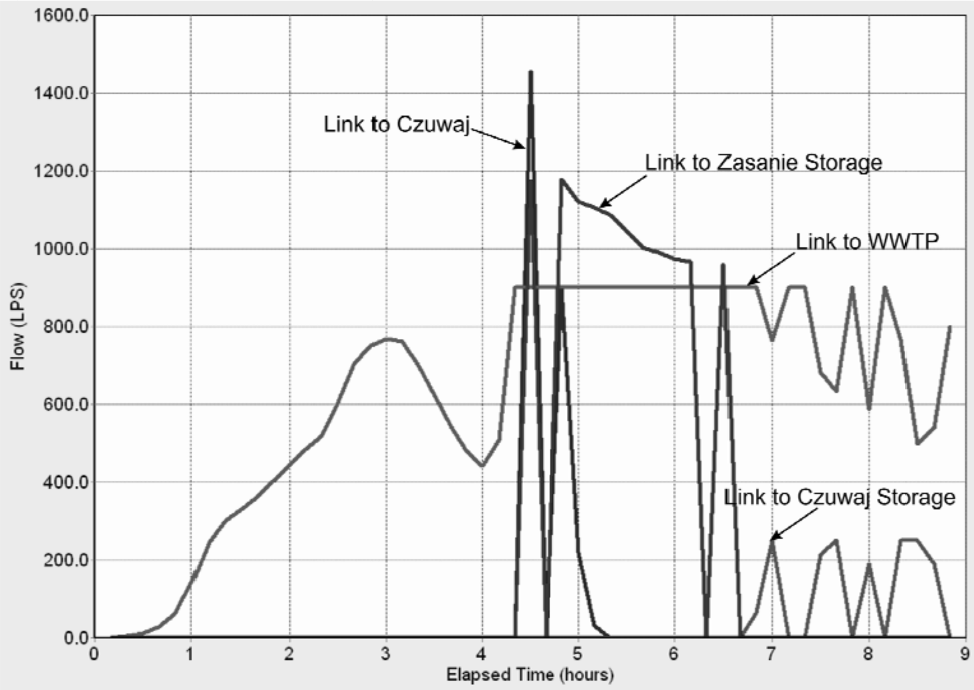


Fig. 8. Cooperation within the system controlling inflow of sewage
to the treatment station for actual precipitation of 8 September 2007

Results of the above-described analyses show that Variant 3 is the most favorable from the point of view of both operation of the system and the effect on water quality in the river San. Extension of the system by adding Zasanie and Czuwaj retention reservoirs stabilizes, to a considerable degree, sewage flows in the sewage network as well as the pumping station load. However, despite the use of a wastewater storage facility complementary to this of variant 2, simulations did not show any reduction of number of storm discharges, and reduction of wastewater volumes discharged to the river turned out to be insignificant. On the other hand, implementation of Variant 3 requires very high additional investment outlays related to construction of Czuwaj retention reservoir.

In recapitulation of results of the performed analyses, variant 2 consisting in construction of Zasanie retention reservoir should be recommended for implementation. At the same time, measures such as calibration of height of the storm overflow edge and/or construction of a flood relief channel for the sewage network section subject to overloads in the course of precipitation should be taken into account.

Detailed design options should be examined and verified by means of hydrodynamic models of the sewage system with the use of actual pluviograph records or model rains [2–22].

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