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Original Research

Development of Mathematical Model for Sewage Pumping-Station in the Modernized Combined Sewage System for the Town of Przemyśl

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Abstract

Our article focuses on the current issue concerning the adaptation of existing sewage systems to increasingly more restrictive regulations related to discharge of combined sewage to surface waters. The example of Przemyśl urban catchment was used to present the impact of a hydraulically overloaded sewage system on the San River and the operation of the sewage pumping station. The authors also discuss issues related to mathematical modeling and development of software used for the simulation and design of retention reservoir cooperating with the existing sewage pumping station in the part of Przemyśl located on the river's left-hand side bank.

Keywords: combined sewage system, combined sewage, storage reservoirs, simulation

Introduction

The development of urban areas and their infrastructures is usually associated with an expansion of watertight surfaces in the catchment area that significantly hinder infiltration of stormwater to the ground. Consequences of such changes include intensification of surface rainwater runoff from the catchment area. Situations involving the occurrence of short but intensive rainwater runoff from the catchment area to rivers, predominantly through closed sewage systems, result in a number of adverse effects, including a decrease in the ground water level resulting from disturbed balance between rainfall, evaporation, soaking and surface runoff; the incidence of more frequent and greater river surges; disturbances in the biological life in rivers; and erosion of river beds.

Activities aimed at counteracting such phenomena focus mainly on three tasks:

– decreasing the volume of stormwater transported to rivers by reducing the size of impervious surface areas
– developing methods of calculation and technical solutions for facilities designed to discharge stormwater to the ground [1-3]
– utilization of rainwater [4-8] and temporary storage of rainwater in order to reduce the peak flow rate values in sewage systems and receiving bodies [9-13]

An increase in the volume of stormwater brought to sewage networks frequently poses a significant technical and financial problem, and results in the necessity to increase flow capacity of sewers, or to expand the existing sewage system units and, in many cases, build new facilities.

The problem related to the efficient regulation of the flow of rainwater runoff in sewage systems has been the subject of extensive research carried out globally and focused on quality issues connected with rainwater runoff and its impact on the quality of the receivers [14, 15], improving the efficiency of technological processes used in treatment plants [16, 17], including sludge sedimentation in

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retention reservoirs [18, 19]. Additionally, current studies investigate quantitative issues such as the description of processes used for hydraulic transport of contaminants via sewage systems [20, 21], the first flush phenomenon [22-24], methodologies used in selecting design parameters for sewage networks [25], and their cooperation with other units of the system [26].

Monitoring sewage inflow to the treatment plant is especially important in the case of sewage systems based on mixed and combined transport of rainwater runoff. Substantial progress in that area should be linked with the development of theories and devices related to the control of sewage system facilities in real time, RTC [26-29].

Some studies [30, 31] point out numerous advantages of modernized combined sewage systems that commonly use storage reservoirs for excess wastewater during rainfall periods.

This study describes issues related to mathematical modelling and development of a software tool used for performance simulation of an innovative retention reservoir [32] that was part of the design concept elaborated in connection with the intended modernization of the Zasanie Combined Sewage Pumping Station located at the end of the collector of the sewage system in the part of Przemyśl located on the left-hand bank of the San River.

Location and Site Conditions

The town of Przemyśl is located in southeastern Poland near the Ukrainian border, and is one of the most important urban centers in Podkarpackie Province. It has a population of 67,000. The oldest town in the region and one of the oldest in Poland, Przemyśl is a place of historical significance. Because of its location, the town was the third largest stronghold in Europe during World War I. Przemyśl is situated in the valley of the San River, which is a tributary of the largest Polish river, the Wisła. The location of Przemyśl in Poland and Europe is presented in Fig. 1.

The spatial layout of Przemyśl is a result of the natural conditions that consititute and determine its boundaries, i.e. the San and Wiar rivers, railway lines, roads, and other local features. Three diverse areas are typically identified in the town, including:

- Stare Miasto (the Old Town), the residential area in the south, along the right bank of the San River
- Zasanie residential quarter located in the north, along the left bank of the San River
- town areas located in the east, along both banks of the Wiar River

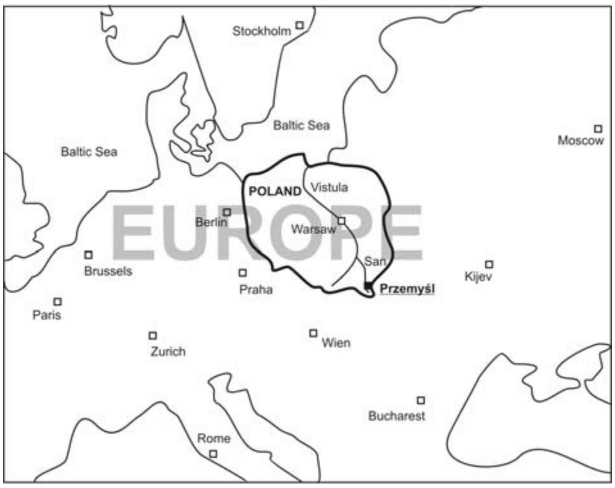

Fig. 1. The location of the town of Przemyśl.

Problem Formulation

The town of Przemyśl has a combined gravity sewer system. Sewage from the urban area is transported by means of the main collector sewers, located on both sides of the San River, to the municipal wastewater treatment plant situated in the fork created by the San and Wiar rivers.

Sewage from the catchment area in the district of Zasanie on the left bank is transported to the other side of the river via a pressure duct with the use of a pumping station. The maximum capacity of the pump system transporting sewage in rainy periods amounts to 900 dm^3/s. After being connected with the right-bank collector in an expansion chamber, the sewage flows gravitationally to the equalizing retention reservoir, with holding capacity of 9,000 m^3, located directly before the plant where excess wastewater is subject to retention. Treated effluent is discharged to the San.

The fundamental problem that currently needs to be solved pertains to the way the sewage system should operate during intense rainfall. Due to the development of the city there is an increase in the size of watertight surfaces in the area, which results in larger volumes of stormwater runoff channeled from Zasanie district through the main sewer. The most critical elements of the existing system are, starting from the final stage of sewage transport: the Zasanie sewage pumping station, the final storm overflow located slightly above the pumping station, and the sewage network located upstream from the overflow, subject to significant hydraulic overloads existing at some of its segments and resulting in its operation under pressure. Fig. 2 presents a schematic diagram of the sewage system operating in the Zasanie district, in Przemyśl, that shows the main sewers and the location of the sewage pumping station and storm overflow.

In order to protect the Zasanie sewage pumping station from excessive inflows and flooding, the sewage system operator performs limit-exceeding discharges of combined sewage through the storm overflow, via the storm sewer directly to the San River.

Legal regulations and methods of protecting water in reservoirs receiving effluent from combined sewage systems vary from country to country. Yet of critical importance are the criteria of both quantity and quality, or quantity alone, with regard to the volume and the number of stormwater discharges annually [33-37].

In Poland, the currently binding legal regulations [38] allow for a maximum number of 10 combined sewage discharges via a storm overflow per one year.

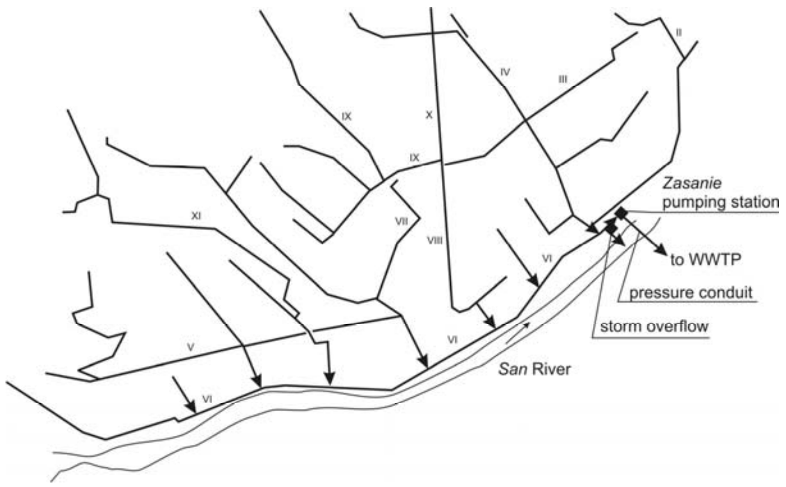

Fig. 2. Schematic diagram of the sewage system existing in the Zasanie district of the town of Przemyśl.

Observations and measurements performed on the storm overflow located above the Zasanie Sewage Pumping Station and constituting one of the most sensitive points in the whole system showed that the number of actual sewage discharges was definitely higher than the number permitted by law. Fig. 3 presents the numbers and volumes of stormwater discharges from the storm overflow in order to provide hydraulic relief to the Zasanie Sewage Pumping Station in 2006-08.

Another issue that must be investigated by the operator is the need to comply with the local regulations, providing that any excess of combined sewage must be carried outside the town limits. These provisions result from the assumption that the banks of the San River situated in the centre of Przemyśl function as a public beach and recreation grounds. Due to the fact that those grounds are located in close proximity to the outlets of storm sewers carrying the excess combined sewage, they were excluded from the system and the whole volume of runoff occurring during rainfalls is transited, together with consecutive inflows along the whole length of the left-bank collector down the San River as far as the aforementioned final storm overflow situated above the Zasanie Sewage Pumping Station. As a result, frequent flooding occurs along the collector route during intense rainfall. Such a situation results in a necessity to provide hydraulic relief to the sewage system collector and the cooperating facilities, especially the Zasanie Combined Sewage Pumping Station, with the simultaneous requirements to discharge any excess sewage outside the town limits, and comply with the regulations limiting the number of such discharges in order to protect the quality of water in the San River.

The adverse impact of the Zasanie district sewer system on the quality of water in the San River results from both the hydraulic overload of selected collector segments and the design solution adopted for the existing sewage pumping station. The pumping station capacity was determined adequately to the discharge capacity of the wastewater treatment plant. On the other hand, each increase in the volume of sewage during rainfall exceeding the specified pumping station capacity results in the phenomenon of the backwater effect, and the overflowing of the excess combined sewage to the San River via the final storm overflow located upstream of the pumping station.

According to measurements carried out in 2005-08, there were 170 discharges of stormwater runoff to the San River on the final overflow, which also protects the Zasanie Pumping Station against flooding. That gives an average of over 42 storm discharges per year. The number of discharges is over four times higher than the maximum number permitted by Polish law [38].

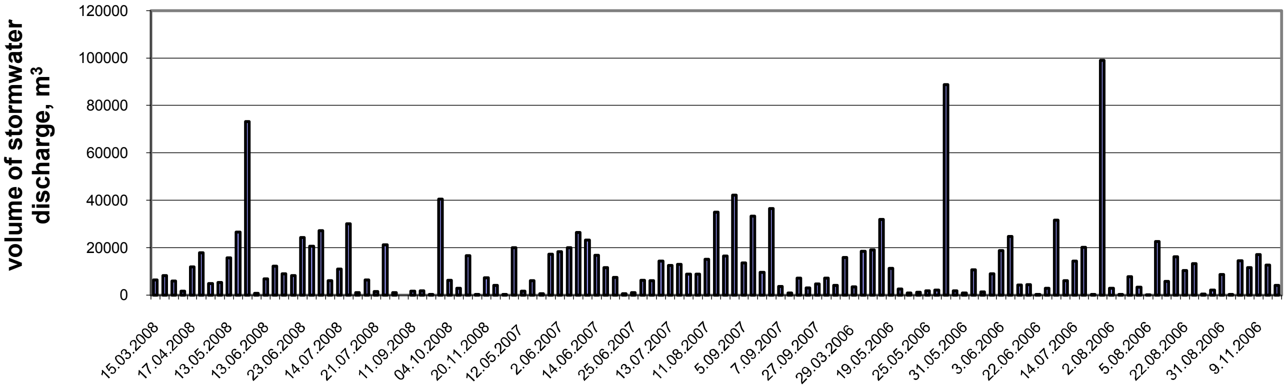

Fig. 3. Combined sewage volumes discharged from storm overflow upstream of the Zasanie Sewage Pumping Station, in 2006-08.

The total volume of sewage discharged to the San River via the final overflow located upstream of the Sewage Pumping Station in the last three years was: 2008, 441,473 m^3; 2007, 471,800 m^3; 2006, 604,000 m^3; and 2005, 912,500 m^3.

Average annual volume of stormwater discharge in 2005-08 reached the amount of 607,443 m^3, while average volume of a single discharge was 14,293 m^3 of sewage.

According to the performed research, the average BOD_5 value of raw sewage in rainfall periods from 2002 to 2007 amounted to 285.67 g O_2/m^3. Hence the average discharge of contaminants via the final storm overflow relieving the Zasanie Sewage Pumping Station in 2005-08, expressed as BOD_5, amounted to 173,528.3 kg O_2 per year.

Adopting, in accordance with the currently binding Polish regulations [39], the load of biodegradable organic substances expressed as the rate of five-day biochemical oxygen demand (equal to 60 g of oxygen per day) as a measure representing one equivalent number of inhabitants (ENI) it was determined that the average annual discharge of contaminants via the storm overflow located upstream of the Zasanie Sewage Pumping Station, contained in stormwater sewage $Pl_{y(ENI)}$ expressed in ENI and determined by means of the formula:

$$Pl_{y(ENI)} = \frac{V_{ay} \cdot BOD_5}{60} \tag{1}$$

(where: V_{ay} – annual average volume of sewage discharged to the river via the storm overflow, m^3, BOD_5 – biological oxygen demand within the period of five days, gO_2/m^3), amounted to 2,892,150.

The average load of contaminants within a single storm discharge via the overflow of the Zasanie Pumping Station $Pl_{p(ENI)}$, determined by means of the formula:

$$Pl_{p(ENI)} = \frac{V_{ap} \cdot BOD_5}{60} \tag{2}$$

(where: V_{ap} denotes average volume of a single sewage discharge to the river via the storm overflow, m^3), amounted to 68,860 ENI.

Modernization of the Sewage Pumping Station

A reduction in both frequency and volumes of combined sewage discharges via the final storm overflow upstream from the Zasanie Pumping Station is feasible only as a result of the modernization of the sewage system that should primarily involve construction of new facilities for temporary storage of excess combined storm sewage.

On the other hand, the limited hydraulic capacity of the Zasanie Sewage Pumping Station is a consequence of both the specific flow capacity of the modernized wastewater treatment plant and the necessity to ensure the correct parameters of the technological sewage treatment processes. It is also closely related to the frequency and effectiveness of operation of the storm overflow located upstream of that Pumping Station, both of those features depending on the location level of the overflow side edge. Previous operational experience shows that exceeding the assumed capacity of the Pumping Station at its inlet causes sewer backflow, which results in discharge of a limit-exceeding volume of stormwater to the San River and, as already demonstrated, the number of such discharges is currently many times more than the maximum permissible figure.

Bearing in mind the negative phenomena occurring in the Zasanie Pumping Station operation, it should be emphasized that any improvement strategy should involve the construction of facilities providing hydraulic relief for the Zasanie Pumping Station, as well as the construction of network retention reservoirs that would retain a specified excess amount of combined sewage that is to be transported to the central treatment plant. That solution would allow for compliance with regulations related to the treatment of a scpecified volume of sewage during rainfall.

Research [40] has suggested a unique modernization concept for Zasanie Pumping Station involving construction of a multi-chamber retention reservoir with a gravitational-pumping system of accumulation chambers. This investment is located in an area with difficult ground-water conditions, and with limited land area available for construction of the retention reservoir. Financial analysis carried out for several different design concepts provided grounds for the choice of the most effective solution related to the hydraulic system of the retention reservoir cooperating with the sewer system. Fig. 4 presents a schematic diagram of the Zasanie district sewage network including the Zasanie and Czuwaj retention reservoirs planned for construction in the near future.

Simulation and Dimensioning of the Retention Reservoir for Zasanie Pumping Station

Retention Reservoir Hydraulic System

The hydraulic system of the designed retention reservoir located upstream of the Zasanie Sewage Pumping Station consists of two accumulation chambers differing in the purpose and function to be performed in the sewage accumulation process. The lowest unit is the gravitational pumping chamber *KT*, which is connected to the left-bank delivery collector transporting sewage from the Zasanie catchment sewage network. Two pumping systems are located in the pump chamber *KT*. One of them transports sewage from the pump chamber to the expansion chamber located of the other bank of the San River, while the second system pumps the excess quantity of inflowing sewage to the accumulation chamber *KAW*. The accumulation chamber *KAW* is connected hydraulically with the pumping chamber *KT* by means of an outflow opening with controlled flow rate. The pumping chamber *KT* is equipped with devices allowing for measurement and control of sewage outflow rate from the accumulation chamber *KAW*

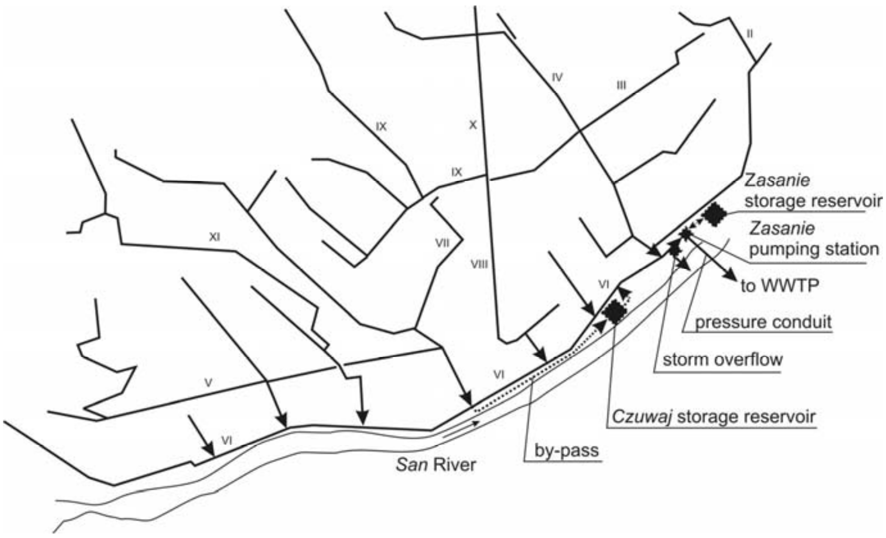

Fig. 4. Schematic diagram of sewage network of the Zasanie residential quarter in Przemyśl with Zasanie and Czuwaj retention reservoirs planned for construction.

in a way that allows for retaining adequate hydraulic load on the pumping station and the wastewater treatment plant facilities. Fig. 5 depicts a schematic diagram of the hydraulic system applied in the gravitational-pumping retention reservoir, with a description of parameters characteristic for the adopted hydraulic model.

Mathematical Model of the Retention Reservoir

The development of the simulation model for the Zasanie retention reservoir required formulation of a mathematical model describing its function in various operationally significant stages. The presented mathematical model is general in nature and has been specified in more detail at the stage of developing the simulation model for operation of the gravitational-pumping retention reservoir. In the whole operation cycle of the innovative Zasanie retention reservoir, we can distinguish the characteristic phases determined by means of boundary conditions related to the filling levels and sewage flow rates.

- Stage 0 — operation of the retention reservoir in dry weather conditions

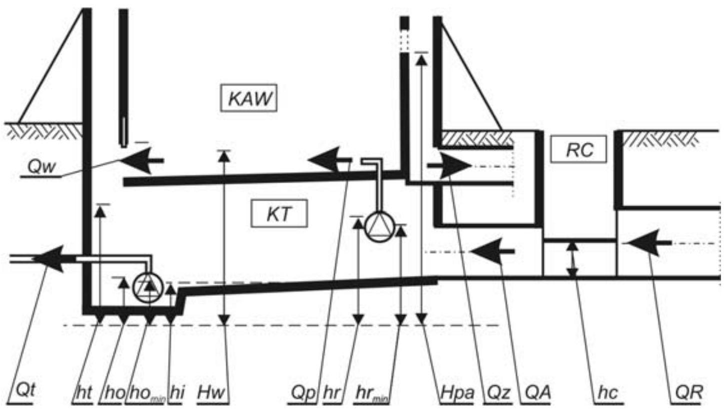

Fig. 5. A schematic diagram of the reservoir hydraulic system and the characteristic parameters of its hydraulic model (*hc* – elevation of storm overflow edge, *hi* – average elevation of the transport chamber bottom with respect to the reference level, *ho* – switch-on level for the system of sewage pressure transport from the pumping chamber *KT* to the expansion chamber with respect to the reference level, ho_{min} – switch-off level for the system of sewage pressure transport from the pumping chamber *KT* to the expansion chamber with respect to the reference level, *Hpa* – edge level of the emergency overflow with respect to the reference level, *hr* – switch-on level for the system of sewage pressure transport from the pumping chamber *KT* to the accumulation chamber *KAW* with respect to the reference level, hr_{min} – switch-off level for the system of sewage pressure transport from the pumping chamber *KT* to the accumulation chamber *KAW* with respect to the reference level, *ht* – instantaneous level of sewage filling up the pumping chamber *KT* with respect to the reference level, *Hw* – instantaneous level of sewage filling up the accumulation chamber *KAW* with respect to the reference level, *QA* – sewage inflow flux from the storm overflow to the retention reservoir, *Qp* – capacity of the pumping system transporting sewage from pumping chamber *KT* to accumulation chamber *KAW*, *QR* – rate of sewage inflow from sewage network to the storm overflow, *Qt* – rate of sewage outflow from the pumping chamber *KT* to the expansion chamber, *Qw* – instantaneous sewage outflow rate from accumulation chamber *KAW* to pumping chamber *KT*, and *Qz* – sewage outflow rate from accumulation chamber *KAW* through the emergency overflow.

- Stage I — filling pumping chamber *KT*
- Stage II — filling accumulation chamber *KAW*
- Stage III — emptying accumulation chamber *KAW*
- Stage IV — emptying pumping chamber *KT*

In Stage 0, pumping chamber *KT* of the retention reservoir functions as the pumping station for sanitary sewage transported by the sewage system during dry periods. The boundary conditions for that phase are as follows: $0 \leq ht < hr$, $ht < ho$, $Hw=0$, and $QA=Qt$.

In Stage I of the retention reservoir operation, the boundary conditions with regard to the flow rates and levels of filling with combined sewage in chambers are as follows: $0 \leq ht < hr$, $ht < ho$, $ht \leq ho_{max}$, $Hw=0$ and $QA>Qt$. Sewage weight balance in reservoir chambers is expressed by means of the following formula (3):

$$\begin{cases} \dfrac{dht}{dt} = QA \cdot F_{KT}^{-1} - Qt \cdot F_{KT}^{-1} \\ \dfrac{dHw}{dt} = 0 \end{cases} \tag{3}$$

...where:

$\dfrac{dht}{dt}$ – increase in the filling level in pumping chamber *KT* per unit time, m/s

$\dfrac{dHw}{dt}$ – increase in the filling level in accumulation chamber *KAW* per unit time, m/s

F_{KT} – surface of the horizontal projection of pumping chamber *KT* , m^2

QA – rate of sewage inflow from storm overflow to retention reservoir, m^3/s

Qt – rate of sewage outflow from pumping chamber *KT* to the expansion chamber, m^3/s

Stage II, in which accummulation chambers of the retention reservoir are filled, occurs with the following boundary conditions: $ho_{max} > ht \geq ho$, $hr \leq ht < hr_{max}$, $0 \leq Hw < Hpa$, and $QA>Qt$. Relationships describing the changes in the filling levels of the reservoir chambers are expressed by means of the following system of equations (4):

$$\begin{cases} \dfrac{dht}{dt} = QA \cdot F_{KT}^{-1} - Qt \cdot F_{KT}^{-1} - Qp \cdot F_{KT}^{-1} \\ \dfrac{dHw}{dt} = Qp \cdot F_{KAW}^{-1} \end{cases} \tag{4}$$

...where:

F_{KAW} – surface of the horizontal projection of the accumulation chamber *KAW*, m^2.

Qp – capacity of the pumping system transferring sewage from pumping chamber *KT* to the accumulation chamber *KAW*, m^3/s.

In the course of Stage III, which involves emptying accumulation chamber *KAW*, the following boundary conditions are satisfied: $ht < ho$, $hr \leq ht < hr_{max}$, $0 \leq Hw \leq Hpa$, and $QA<Qt$, and the formula specifying the changes in the sewage filling levels in the reservoir chambers is expressed by the set of equations:

$$\begin{cases} \dfrac{dht}{dt} = QA \cdot F_{KT}^{-1} + Qw \cdot F_{KT}^{-1} - Qt \cdot F_{KT}^{-1} \\ \dfrac{dHw}{dt} = -Qw \cdot F_{KAW}^{-1} \end{cases} \tag{5}$$

...where:

Qw denotes the instantaneous rate of sewage outflow from accumulation chamber *KAW* to transport chamber *KT* in m^3/s.

In the time of emptying pumping chamber *KT* (Stage IV), whose sewage weight balance is expressed by equasion (6), the following boundary conditions must be met: $ht < ho$, $hr \leq ht < hr_{max}$, $Hw=0$, and $QA<Qt$:

$$\begin{cases} \dfrac{dht}{dt} = QA \cdot F_{KT}^{-1} - Qt \cdot F_{KT}^{-1} \\ \dfrac{dHw}{dt} = 0 \end{cases} \tag{6}$$

Simulation Model Parameters

In accordance with the adopted research methodology [41], a quality assessment of the mathematical model representing the performance of a multi-chamber retention reservoir within a sewage network was carried out. The activities undertaken in that scope aimed mainly at determining the set of quantities that significantly impact the course of hydraulic processes occurring in the facility for which the numerical simulation was performed.

The simulation model of the reservoir took into account its characteristic parameters as well as the parameters of the storm overflow cooperating with the reservoir.

The analysis of the parameters allowed for clyssifying them into appropriate groups.

- **Test parameters** – this group of parameters includes those subject to intentional variations in the course of the research process:

c – the frequency of rainfall matching the design requirements of a sewage network and retention reservoir, years^{-1}

F – catchment surface area, ha

H – average annual precipitation level in the catchment area, mm/year

n_{rp} – ratio of initial dilution of sanitary sewage with rainwater at the storm overflow, –

n_{rz} – ratio of initial dilution of sanitary sewage with rainwater in the retention reservoir, –

Qs – outflow of sanitary sewage from the catchment area, dm^3/s

Qt – rate of reduced sewage outflow from transport chamber KT to the control chamber *KS*, m^3/s

Tp – sewage flow time from the most remote catchment point to the determined calculation cross-section, min

Tdm – duration of rainfall matching the design requirements of the retention reservoir, min

Ψ – coefficient representing stormwater runoff from the catchment, –

β – coefficient of sewage flow reduction in the retention reservoir, –

- **Output parameters** – are obtained as a result of operation of the experimental system, and are used as base for assessment of hydraulic processes in the simulation model; they are decisive for its properties and include:

Ht – instantaneous level of sewage filling pumping chamber *KT* with respect to the reference level, m

Hw– instantaneous level of sewage filling accumulation chamber *KAW* with respect to reference level, m

Qp – capacity of the pumping system transferring sewage from pumping chamber *KT* to accumulation chamber *KAW*, m^3/s

QR – rate of sewage inflow from the sewage network to the storm overflow, m^3/s

Qw– instantaneous rate of sewage outflow from accumulation chamber *KAW* to pumping chamber *KT*, m^3/s

V_{KAW} – volume of sewage accumulated in accumulation chamber *KAW*, m^3

V_{KT} – volume of sewage accumulated in pumping chamber *KT*, m^3

- **Fixed parameters** – this group consists of the parameters that remain constant in the course of the simulation experiment or such variable parameters whose impact on the simulation model of the retention reservoir does not belong to the scope of the current research, and includes:

hc – elevation of overflow edge in storm overflow, m

hi – average elevation of bottom of transport chamber *KT* with respect to the reference level, m

ho – switch-on level for the system of sewage pressure transport from pumping chamber *KT* to control chamber *KS* and wastewater treatment plant with respect to the reference level, m

ho_{min} – switch-off level for the system of sewage pressure transport from pumping chamber *KT* to control chamber *KS* and wastewater treatment plant with respect to the reference level, m

Hpa – edge level of the emergency overflow with respect to the reference level, m

hr – switch-on level for the system of sewage pressure transport from pumping chamber *KT* to accumulation chamber *KAW* with respect to the reference level, m

hr_{min} – switch-off level for the system of sewage pressure transport from the pumping chamber *KT* to accumulation chamber *KAW* with respect to the reference level, m

F_{KT}– surface of the horizontal projection of pumping chamber *KT*, m^2

F_{KAW} – surface of the horizontal projection of accumulation chamber *KAW*, m^2

Algorithm of PSZ Simulation Program

The developed software tool allows for the simulation of hydraulic parameters that impact the function of the retention reservoir and the cooperating storm overflow in a dynamic system. The simulation process is carried out in real time, so it is possible to perform ongoing analysis of the processes occurring in the retention reservoir. The developed calculation procedure allows for examining the hydraulic system of the reservoir while adopting arbitrary functions that describe the course of variations of sewage inflow to the storm overflow.

The course of calculations performed by the PSZ simulation program is described in general terms by the algorithm presented in Fig. 6.

After entering the input simulation parameters and launching the appropriate subroutine, the calculation program performs an analysis of instantaneous values of sewage inflow rates *QR* to the storm overflow, and then determines the values of sewage flow rates *QA* toward the retention reservoir and calculates the expected sewage discharge rate *QB* through the storm overflow. The next step determines the filling increase rate for transport chamber *KT* and performs analysis of boundary conditions determining switch-on and switch-off times for the system of pumps transferring sewage to the expansion chamber on the other side of the river, as well as to accumulation chamber *KAW*.

In the case of connecting the system of sewage pressure transport from pumping chamber *KT* to accumulation chamber *KAW*, the program determines instantaneous level of sewage filling up accumulation chamber *KAW*.

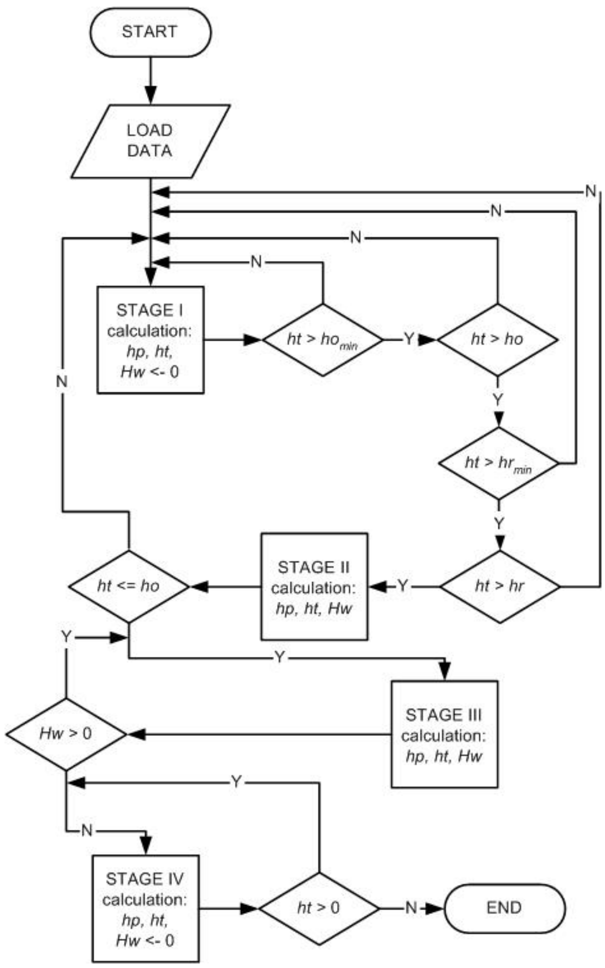

Fig. 6. Algorithm of PSZ simulation program.

From the moment of disconnecting the pumping system that fills the accumulation chamber *KAW*, the program checks hydraulic conditions in pumping chamber *KT* in order to determine the flow rates of sewage transferred by the relief system from accumulation chamber *KAW* to pumping chamber *KT*.

The calculations are conducted many times, depending on the adopted simulation period that results from the duration of rainwater flow and assumed calculation stage.

Sewage Inflow Function

The phenomenon of sewage gravitational flow through sewage systems is a complicated issue and its detailed description requires the application of a complex mathematical model.

A mathematical approximation of actual hydraulic conditions which describe the conditions of the investigated process of sewage flow in the system was reflected in a simplified way by means of, among other things, a model of transient flows in the form of dynamic and kinematic waves [42, 43].

A practical application of hydrodynamic models is frequently limited due to insufficient measurement data and their considerable complexity. At the same time, the stationary flow model is still commonly used in engineering calculations.

Reference [44] contains a detailed analysis and mathematical representation of the function characterizing sewage flow in a system for select functions describing variability of rainfall intensity in time [45].

Due to the external difficulties in acquiring sufficiently precise data on precipitation and the lack of a reliable hydrodynamic model of the analyzed catchment area, our study adopted a theoretical function representing sewage flows in order to simulate the operation of the retention reservoir within a system in the form of a hydrograph with three characteristic intervals of storm sewage flows versus time t, described by means of Eq. (7) at $0<t\leq Tp$, Eq. (8) at $T\leq t\leq Tdm$ and Eq. (9) at $Tdm<t\leq Tp+Tdm$, respectively:

$$QR = \left(qdm_{(Tdm)} \cdot F \cdot \Psi\right) \cdot t^2 \cdot Tp^{-2} + Qs \tag{7}$$

...where:

F – catchment surface area, ha

$qdm_{(Tdm)}$ – rain intensity calculated for the duration of rainfalls matching the design requirements of the retention reservoir *Tdm*, $dm^3/(s\cdot ha)$

Qs – rate of the sanitary sewage outflow from the catchment surface, dm^3/s

t – time, s

Tp – sewage flow time from the most remote catchment point to the determined calculation cross-section, min

Ψ – coefficient representing stormwater runoff from the catchment, –

$$QR = Qs + \left(qdm_{(Tdm)} \cdot F \cdot \Psi\right) \tag{8}$$

$$QR = \left(qdm_{(Tdm)} \cdot F \cdot \Psi\right) - \left(\left(qdm_{(Tdm)} \cdot F \cdot \Psi\right) \cdot (t - Tdm)^2 \cdot Tp^{-2}\right) + Qs \tag{9}$$

...where *Tdm* denotes the duration of rainfall matching the design requirements of retention reservoir, in minutes.

In the case of a reservoir cooperating with storm overflow, the inflow of sewage is reduced at storm overflow to the value of *QA*. Sewage flow separation starts at time t_1, whose value may be calculated from the formula:

$$t_1 = QS^2 \cdot {n_{rp}}^2 \cdot Tp \cdot \left(qdm_{(Tdm)} \cdot F \cdot \Psi\right)^{-0.5} \tag{10}$$

and ends at time t_2 determined as:

$$t_2 = \left(Tp^2 - \left(qdm_{(Tdm)} \cdot F \cdot \Psi\right)^{-1} \cdot Tp^2 \cdot n_{rp} \cdot Qs\right)^{0.5} + Tdm \tag{11}$$

...where n_{rp} denotes the ratio of initial dilution of sanitary sewage with stormwater at the storm overflow.

The design storm intensity value, critical for dimensioning of a retention reservoir $qdm_{(Tdm)}$, was determined by applying the Błaszczyk formula [46] commonly used in Poland. The formula is based on the so-called "block rainfall" of constant intensity in time, specified probability of its occurrence, and duration. The method was subject to criticism, e.g. in papers published by Kotowski [47], Krzanowski, and Wałęga [48], as well as Dziopak and Hypiak [49], where an understatement of necessary retention reservoir capacities was demonstrated, particularly for lower rainfall occurrence frequencies c with respect to other methods, e.g. that proposed by Bogdanowicz and Stachý [50].

The calculation formula proposed by Bogdanowicz and Stachý allows for calculating the maximum intensity of rainfalls in the territory of Poland except for the Carpathian Mountains and the Sudetes, therefore excluding also the location of Przemyśl. With the above in mind, the calculations of rainfall intensity $qdm_{(Tdm)}$ applied the commonly adopted Błaszczyk formula [46]:

$$qdm = 6.631 \cdot H^{\frac{2}{3}} \cdot c^{\frac{1}{3}} \cdot Tdm^{-\frac{2}{3}} \tag{12}$$

Input Data for PSZ Simulation Model

The ratio value of sanitary sewage dilution with stormwater at storm overflow n_{rp} was determined from the regression formula (13) [51] at the specified sewer network capacity *V*=10,000 m^3 and permissible frequency of combined sewage discharges C_{rz}=10 years^{-1}:

$$C_{op} = 7.26 \cdot C_{rz}^{0.75368} \tag{13}$$

...where: C_{rz} – frequency of combined sewage discharges to the river occurring via the storm overflow, years^{-1}; C_{op} –

Table 1. Input data for the simulation model of the retention reservoir at the Zasanie Pumping Station in Przemyśl.

c	Fzr	H	n_{rp}	n_{rz}	Qs	Qt	Tp	Tdm	F_{KT}	F_{KAW}	β	hc	hi	ho	ho_{min}	hr	hr_{min}
years^{-1}	ha	mm	-	-	dm^3/s	m^3/s	min	min	m^2	m^2	-	m	m	m	m	m	m
5	153.8	709	9.22	8	100	0.9	96.9	1,842	20	2,000	0.64	0.8	0	0.5	0.3	1.5	1.2

ratio of rainfalls resulting in discharge of combined sewage via the storm overflow to the total number of rainfalls per year, –.

In the case of the pumping chamber, the ratio value of sanitary sewage dilution with stormwater n_{rz} in pumping chamber KT is expressed with the following formula:

$$n_{rz} = Qt \cdot Qs^{-1} \quad (14)$$

...where n_{rz} denotes the coefficient of initial dilution of sanitary sewage with stormwater in a retention reservoir.

The value reflecting the duration period of design storm Tdm, assumed to be critical for performing calculations concerning the required capacity of a multi-chamber retention reservoir with an assumed sewage flow reduction ratio value β>0.5 [44], was determined by means of the following formula:

$$Tdm = \left(6,631 \cdot H^{\frac{2}{3}} \cdot c^{\frac{1}{3}} \cdot F \cdot \Psi\right)^{\frac{3}{2}} \cdot \left(n_{rp} \cdot Qs\right)^{-\frac{3}{2}} \quad (15)$$

The ratio value of the sanitary sewage dilution with stormwater at the storm overflow n_{rp} was established, taking into account the reduced catchment surface area Fzr, the values of sanitary sewage outflow rates Qs, and assuming that the critical specific rate of stormwater runoff from catchment area q_{kr} should not exceed 6 dm^3/(s·ha) [51].

The value of sewage flow reduction coefficient β in the retention reservoir is expressed by the following formula:

$$\beta = n_{rz} \cdot n_{rp}^{-1} \quad (16)$$

Table 1 contains a summary of all input parameters of the simulation model representing the innovative gravitational-pumping reservoir at the Zasanie Pumping Station obtained by means of calculations, measurements, and analysis of available technical documentation.

Results

The numerical simulation performed for the functioning of the innovative retention reservoir included in the design documentation for the intended extension of the Zasanie Sewage Pumping Station in Przemyśl, in the predetermined inflow conditions and the assumed hypothetical hydrograph representing inflow of storm sewage to the reservoir, allowed for establishing the values of model input parameters that are essential from the point of view of the design and implementation premises assumed for that facility.

The required retention reservoir capacity established by means of the simulation study amounts to 12,984 m^3 (Fig. 7), with the balance inflow from the catchment area to the storm overflow amounting to 113,530 m^3. With the assumed horizontal surface area of the reservoir, the established maximum sewage level in the accumulation chamber KAW amounts to 6.48 m. The time to the maximum filling of the retention reservoir, counted from the start of a rainfall, amounts to 1,877 minutes.

The minimum capacity in the system of sewage pressure transport from pumping chamber KT to accumulation chamber KAW should amount to 102 dm^3/s. The lifting

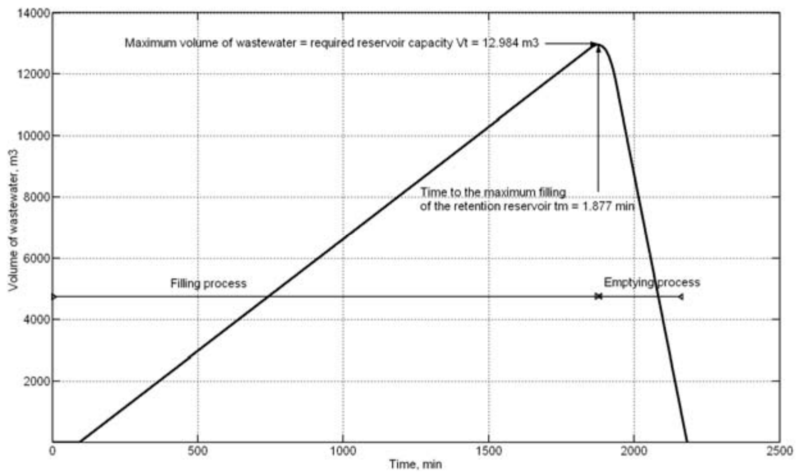

Fig. 7. Determination of the maximum storage reservoir capacity.

head Hp of the pumping system should be at least 5.28 m and should be enlarged by the figure representing hydraulic losses in the pump pressure and suction pipelines and the elevation difference between the bottom of accumulation chamber *KAW* and the switch-off level for the sewage pressure transport system hr_{min}.

Conclusions

In order to comply with legal requirements related to the protection of the quality of water in bodies used as receivers for the existing sewage systems, it is necessary in many cases to undertake extensive and capital-intensive activities that involve construction and modernization of sewers, facilities cooperating with them, and wastewater treatment plants.

The weakest link in the urban sewage system of Przemyśl is the subsystem used for pressure transfer of sewage from the left-bank catchment to the catchment located on the right bank of the San, where the WWTP is located. This situation was caused by changes in the function of the sewage network that involved closing down the storm overflows along the San in order to improve water quality.

The imbalance in the amount of sewage transported through the sewers and channeled to the receiver in Zasanie resulted in adverse phenomena such as pressure flows in the main riverbank sewer of that neighbourhood and sewage discharges via the final storm overflow exceeding the applicable standards.

The first solution undertaken in order to amend these adverse outcomes involves the construction of the retention reservoir located at the Zasanie Pumping Station. It will allow for the consistent operation of the station without the risk of its frequent flooding, as well as for discharging combined sewage via the final storm overflow to the San River in accordance with regulations.

The article describes the foundations of mathematical modeling and the PSZ simulation model used for an innovative design of the retention reservoir, which is included in the design concept for this strategic investment.

The elaborated simulation model will allow for performing analysis of the variability of parameters that are essential for the retention reservoir design, and it can be adopted to any selected function of sewage flow resulting from either isolated rainfall or a series of consecutive rainfalls.

In the case of Zasanie storage reservoir, all input parameters of simulation model presented in Table 1 were clearly set out in the developed project documentation, which is supported by analysis of hydraulic conditions of sewage network as well as by technical parameters and geometry of the currently working object. A detailed analysis of the impact of model input parameters in the whole range of their values on design parameters of storage reservoirs has been featured in publication [44].

Due to the limited information available on rainfall parameters in the investment location and the lack of a quantitative sewage monitoring system that would allow for development and adequate calibration of the catchment and sewage network hydrodynamic model, the authors applied their own calculation procedures and software to perform the analysis, taking into consideration the static functions representing sewage flow in sewage networks.

The construction of the Zasanie retention reservoir will represent an interesting subject for further theoretical and practical research studies aimed at the adaptation of the developed solutions to other similar facilities in existing sewage systems.

The performed analysis of pollutant loading transported via the existing sewers to WWTP, both currently and after the intended modernization of the sewage system (including the construction of the Zasanie storage reservoir with the calculated usable capacity of 12,984 m^3, as well as the reconstruction and calibration of the final storm overflow upstream the Zasanie Sewage Pumping Station) will allow for channelling a significantly larger volume of sewage to the WWTP. The implementation of this investment will allow for a significant reduction, according to predictions – (exceeding 75%) of annual pollutant loads discharged to the San River from the left bank of Przemyśl and for the related profound environmental effect.

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