Possibility of using retention reservoirs as flow controllers

Możliwość zastosowania zbiorników retencyjnych jako regulatorów przepływu

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Rainwater runoff from urban areas is mainly controlled by the use of storm sewage systems. These systems are expected to ensure efficient drainage of rainwater from urbanized areas in terms of quantity (prevention of flooding) and quality (reduction of pollutant load discharged to natural water reservoirs). It can be expected that standards for protecting surface water from rainwater runoff discharges will be tightened in the near future, and modernization of existing storm sewage systems will be necessary. Stormwater systems should be designed in a sustainable manner. However, they cannot be implemented everywhere, mainly due to dense urban development or unfavorable soil and water conditions. Therefore, the development and modernization of underground systems, mainly by increasing their retention capacity remain a important engineering problem. The present paper discusses the concept of using a retention reservoir as a controller of rainwater runoff distribution. It offers an alternative to the flow separators used in the storm sewage systems described in the literature.
Keywords: sewage systems, semi-separate sewer system, storage tanks, SWMM 5.0, quality of rain water

Regulacja odpływu wód opadowych z obszarów miejskich jest realizowana głównie przez wykorzystanie systemów kanalizacyji deszczowej. Systemy te powinny zapewnić efektywne odprowadzenie wód opadowych z obszarów zurbanizowanych zarówno w ujęciu ilościowym (zapobieganie zjawiskom podtopień) jak i jakościowym (redukcja ładunków zanieczyszczeń odprowadzanych do odbiorników naturalnych). Można się spodziewać, że w najbliższej przyszłości standardy ochrony wód powierzchniowych przed odpływem wód opadowych ulegną zaostrzeniu i konieczna będzie modernizacja istniejących systemów kanalizacji deszczowej. Systemy odprowadzania wód opadowych należy projektować w sposób zrównoważony. Nie wszędzie można je jednak wdrożyć, głównie ze względu na gęstą zabudowę miejską lub niekorzystne warunki gruntowo-wodne. Dlatego też rozwój i modernizacja systemów podziemnych, głównie poprzez zwiększanie ich pojemności retencyjnej, pozostaje istotnym problemem inżynierskim. W artykule omówiono koncepcję wykorzystania zbiornika retencyjnego jako regulatora rozdziału odpływu wód opadowych. Stanowi alternatywę dla opisywanych w literaturze separatorów przepływu stosowanych w systemach kanalizacji deszczowej.
Słowa kluczowe: kanalizacja, kanalizacja półrozdzielcza, zbiorniki retencyjne, SWMM 5.0, jakość wód opadowych

Reducing the discharge of rainwater into a receiving water body is currently one of the most important measures to ensure adequate protection of surface water. Studies conducted in recent years have demonstrated a significant increase in the amount of pollutants found in surface runoff and a greater volume of rainwater discharged into the sewage system [8, 13, 26].

The major pollutant in rainwater runoff is suspended solids, which is also one of the most important parameters in assessing the degree of pollution of rainwater. The concentration of suspended solids in rainwater runoffs fluctuates over a wide range and usually exceeds the regulatory limit [24]. The amount of suspended solids discharged from a catchment area depends on several factors related mainly to the type and degree of sealing of the catchment area, the intensity of traffic, and parameters characterizing precipitation [1, 2, 25].

It can be expected that standards for protecting surface water from rainwater runoff discharges will be tightened in the near future, and modernization of existing sewage systems will be necessary [10]. Therefore, the development of new land and modernization and expansion of sewage systems should be planned in accordance with new guidelines and currently preferred global trends. Rainwater runoff systems should be designed in a sustainable manner [3, 5, 18, 19].

However, they cannot be implemented everywhere, mainly due to compact urban development or unfavorable soil and water conditions. Therefore, the development and modernization of underground systems, mainly by increasing their retention capacity, remains a topical engineering problem.

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Sewage systems have to meet two types of requirements [6, 11]:

- quantitative: protection against flooding of urban catchment areas at a specific level of reliability
- qualitative: protection of the aquatic environment from the effects of pollutant loads contained in discharges from sewage systems [9].

The development of the systems involves the use of retention reservoirs, with their primary purpose being different from that of reservoirs used for hydraulic relief. It should be noted that from the qualitative standpoint, the scope of application of retention facilities will be fundamentally influenced by legal changes regarding the quality of wastewater discharged to receiving bodies (list of pollutant indicators, permissible concentrations, volume, load). One of the solutions to meet the more stringent requirements is semi-separated sewage systems, which are not widely used at the moment [4, 15].

The present paper discusses the concept of using a retention reservoir as a controller of rainwater runoff distribution. It offers an alternative to the flow separators used in the sewage systems described in the literature. However, the simulations did not analyze the sedimentation process itself, taking place in reservoirs and channels of the stormwater sewage system. The research was only intended to verify the validity of the thesis regarding the possibility of using the proposed devices for the implementation of semi-separated sewage systems.

Material and methods

Design and hydraulic operation of the proposed retention reservoirs

The present study analyzed the possibility of using a retention reservoir to replace standard flow separators [7] to implement semi-separated sewage systems. Two similar designs of retention reservoirs were developed, with their design differing primarily in the location of the weir that allows the discharges of excess rainwater runoff to the receiving water. This type of difference changes the hydraulic operation of the equipment, and therefore the efficiency of the removal of pollutants using different reservoir designs.

The first of the proposed solutions is a retention reservoir WRP1 (Fig. 1), in which rainwater runoff, flowing through a stormwater collector (2), flows directly into the retention chamber (1) of the system. The weir and channel (4) that allows excess rainwater runoff to be discharged to the receiving water is located in the retention chamber (1). An outflow orifice (3) is located at the lowest point of the reservoir, through which wastewater continuously enters the domestic sewage system. In this case, a elctric gate valve was used with the degree of opening depending on the capacity of the sewage channel.

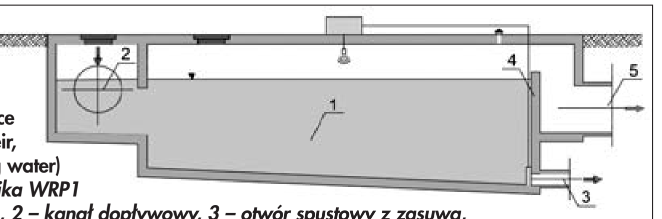


Fig. 1.
Diagram of a WRP1 reservoir (1 – retention chamber, 2 – inflow sewer, 3 – outflow orifice with gate valve, 4 – weir, 5 – outflow to receiving water)
Rys. 1. Schemat zbiornika WRP1 (1 – komora retencyjna, 2 – kanał dopływowy, 3 – otwór spustowy z zasuwą, 4 – przelew, 5 – odpływ do odbiornika)

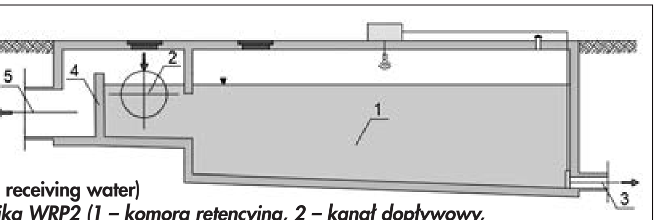


Fig. 2.
Diagram of a WRP2 reservoir (1 – retention chamber, 2 – inflow channel, 3 – outflow orifice with gate valve, 4 – weir, 5 – outflow to receiving water)
Rys. 2. Schemat zbiornika WRP2 (1 – komora retencyjna, 2 – kanał dopływowy, 3 – otwór spustowy z zasuwą, 4 – przelew, 5 – odpływ do odbiornika)

A distinctive feature of the second reservoir (WRP2, Fig. 2), is that the inflow to the retention chamber (1) is directly connected to a weir (4) that discharges excess rainwater to the receiving water body. As in the case of the WRP1 reservoir, rainwater runoff goes directly into the retention chamber (1) of the system, where the location of the outflow orifice (3) is the same as in the previous reservoir. Controlling the outflow of runoff to the sewage system occurs in the same way as in the WRP1 design. In both cases, the elctric gate valve can be replaced by a hydraulic system. It should be noted that the variants discussed allow for using sewer retention of the system above the reservoir.

The hydraulic operation of the systems discussed is similar. The only difference is the phase in which the reservoir is filled to an assumed filling height equal to the height of the weir edge, and the inflow rate is greater than the instantaneous outflow rate. In this case, in the WRP1 reservoir, the entire volume of rainwater runoff flows through the retention chamber, and its excess is discharged to the receiving water through the weir. Furthermore, in the case of the WRP2 reservoir, only the volume of wastewater that is at the same time discharged through the outflow orifice into the sanitary channel flows through the retention chamber.

The examination was conducted using a model of a real urban catchment area located in Raków district in Częstochowa, Poland, setup up as the EPA SWMM program. The modeled area covers an area of about 69 hectares. The model of the analyzed system consists of 138 conduits (Fig. 3a) with circular cross-sections and diameters ranging from 0.2 m to 0.9 m. Rainwater runoff is discharged to the outlet by a collector with a diameter of 1 m. The shape of the sub-catchment boundaries was determined based on terrain profile, sewer routes, land use, and type of urban development. The main streets in the catchment area were identified for the qualitative model used in the further stage of the research. In total, 197 sub-catchments were included in the model (Fig. 3b). A more detailed description of the catchment area, along with the parameters used in the hydraulic model calibration was presented in previous publications [14, 16].

The simulations used precipitation recorded in Czestochowa on a SEBA RG50 rain gauge located at Częstochowa, ul. Brzeźnicka. The simulation was continuous, from March

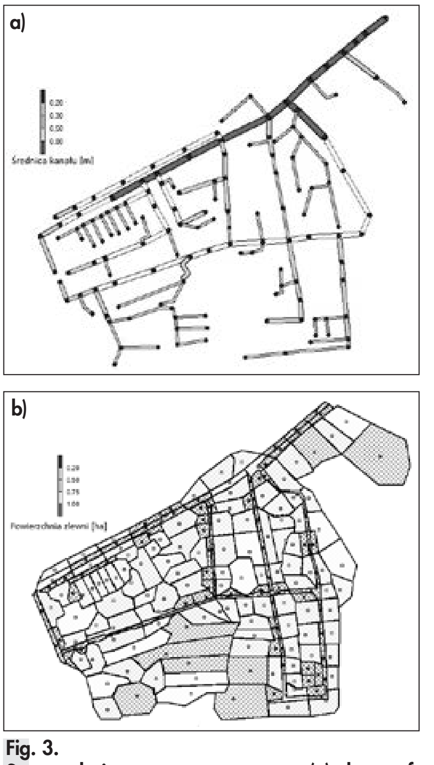


Fig. 3.
System design stormwater system: (a) shape of channels; (b) division into sub-catchments
Rys. 3. Schemat sieci: a) przebieg kanałów; b) podział na zlewnie cząstkowe

to October. Total precipitation during this time was 750.5 mm (361.8 mm in 2011, 388.7 mm in 2012).

Results

Examinations of hydraulic operation of retention reservoirs based on a hydrodynamic model

The first stage of the analysis involved the modernization of the existing stormwater system to a semi-separated system using the reservoirs described in the paper. The use of several volumes of retention chambers was considered: V = 112.5m^3; 225m^3, 337.5 m^3, 450 m^3, 562.5 m^3, and 675 m^3 which, computed per hectare of sealed area, translates into 5, 10, 15, 20, 25, and 30 m^3, respectively. The maximum filling of the reservoirs in each case in question was assumed to be constant (1.5m). The reservoirs were located in the final sections of the sewage system (Figure 4) to provide a connection between the stormwater system and the domestic sewage system located in the area. Based on the calculations, the diameter of the sanitary sewer (0.3m) was selected, and the sewage flows were determined for each hour of the day (described in more detail in [16, 17]. This was used to prepare a hydrograph of sewage inflow to the sewer during the day, which was used in the model. This made it possible to achieve a close-to-reality flow of domestic wastewater.

A design of the WRP1 reservoir with the components selected and arranged accordingly is shown in Fig. 4. Sewage is discharged directly to the reservoir through a rainwater sewer. When the filling level exceeded the preset value (1.5m), the wastewater, through the weir, was discharged to the receiving water.

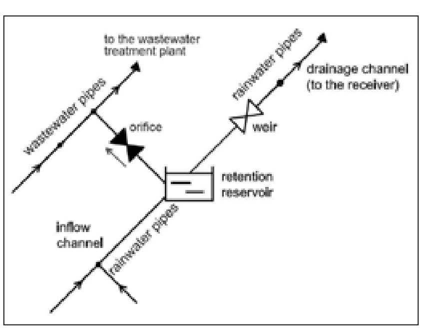


Fig. 4.
Diagram of the WRP1 reservoir in the SWMM program
Rys. 4. Schemat zbiornika WRP1 w programie SWMM

A certain volume of rainwater collected in the retention reservoir was continuously discharged into the sewage system through an orifice with a maximum diameter of 0.25 m.

A proportional-integral-differential PID controller was used to control the outflow orifice. It was assumed that the filling in the sanitary sewer during the discharge of rainwater from the reservoir should oscillate around 0.295 m to maximize the capacity of the channel without overloading.

In the case of the system using the WRP2 reservoirs, a weir is located in the well located directly before the reservoir, which, if high instantaneous flow rates occur, diverts excess sewage through the rainwater sewer to the rainwater collector, by which it is discharged directly to the receiving water (Fig. 5). By adjusting the overflow height, it is possible to achieve a set reservoir depth of 1.5 m. Controlling the outflow of wastewater into the sewage system is achieved in the same way as in the WRP1 reservoir.

The first stage of the analysis involved the examination of the hydraulic operation of the

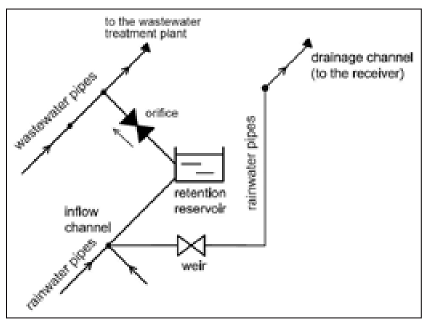


Fig. 5.
Diagram of the WRP2 reservoir in the SWMM program
Rys. 5. Schemat zbiornika WRP2 w programie SWMM

presented designs for a single rainfall. Rains characterized by relatively high intensity and short duration were chosen for the simulations. The results below were collected for rainfall on 6 August 2011 (hyetograph shown in Fig. 6) and for a reservoir with a retention volume of 337.5 m^3 (15 m^3/ha$_{imp}$).

The first parameter was the change in the filling of the retention reservoir over time. The results obtained are summarized in a graph (Fig. 7). In both cases, the wastewater is accumulated slightly over the assumed filling level (1.5 m). The maximum filling of the retention chamber is 1.65m (WPR1) or 1.58m (WPR2). During a heavy rainfall, the maximum inflow rate to the reservoir is high (more than 1,600 dm^3/s in each case), causing the reservoir with the retention capacity to fill up in a few minutes, and the level of wastewater to exceed the edge of the weir. By locating the weir in front of the reservoir (WRP2), the effect of wastewater accumulation above a certain filling level can be reduced. The reservoirs empties through an outflow orifice equipped with a controller that controls the outflow so that the full capacity of the sewage sewer can be used. For other retention capacities of the reservoir, the hydraulic operation of the system is analogous.

In the case of both reservoirs, the location and dimensions of the weir and the collector discharging wastewater to the receiving water force the flow of the entire volume of wastewater in the network sewers through the reservoirs retention chambers, making the

Fig. 6.
Hyetograph of rainfall on 6 August 2011
Rys. 6. Hietogram opadu z dnia 06.08.2011

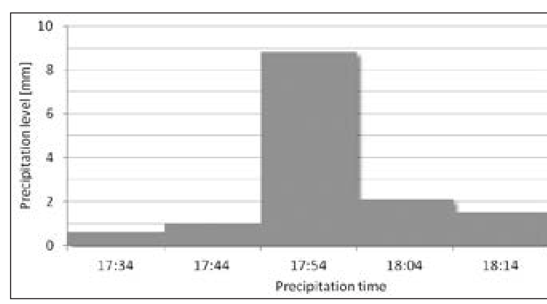


Fig. 7.
Filling a retention reservoir with a retention volume of 15m^3/ha$_{imp}$
Rys. 7. Przebieg napełnienia zbiornika retencyjnego o objętości retencyjnej równej 15m^3/ha$_{zr}$

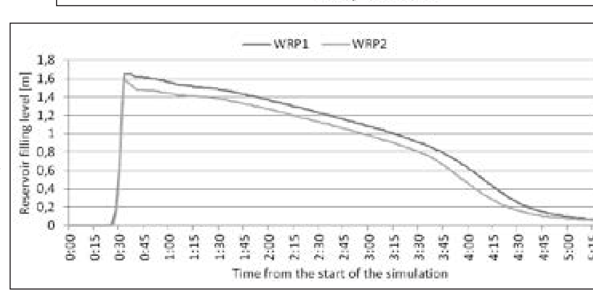
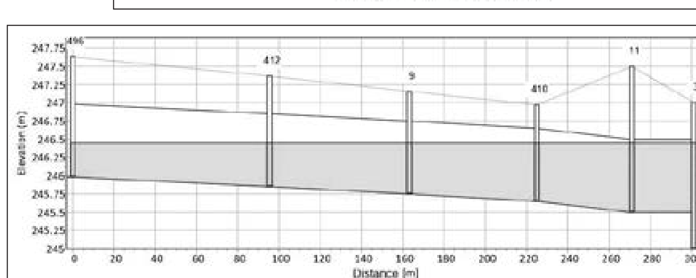


Fig. 8.
Longitudinal cross-section of the system for WRP2 reservoir
Rys. 8. Profil podłużny sieci dla zbiornika WRP2



emptying time relatively long. All available sewer retention is used in this case. Fig. 8 shows a longitudinal cross-section of the system with sewers immediately before the reservoir and the reservoir itself (Node 3).

A full description of the hydraulic operation of the reservoirs and the demonstration of the differences resulting from the location of the weirs requires an analysis of the wastewater flows in the sewers before and after the reservoir. In the WRP1 reservoir (Fig. 9a), there is the inflow sewer to the retention chamber and the weir located on the opposite side of the chamber; in the WPR2 reservoir (Fig. 9b), there is the sewer that supplies wastewater to the reservoir and the weir directly connected to the inflow sewer.

The graphs show that the inflow to the WRP1 reservoir is much higher at all times and is the sum of the outflow to the receiving water and to the sewage system. Furthermore, in the WRP2 reservoir, the inflow to the reservoir after its filling is reduced to a value equal to the instantaneous outflow through the outflow orifice into the sewage system.

The temporary lack of inflow to the retention chamber of the WRP2 reservoir, observed from the 34th to the 40th minute of the simulation is due to the accumulation of wastewater in the retention chamber above the weir edge. Once the level of the wastewater surface level

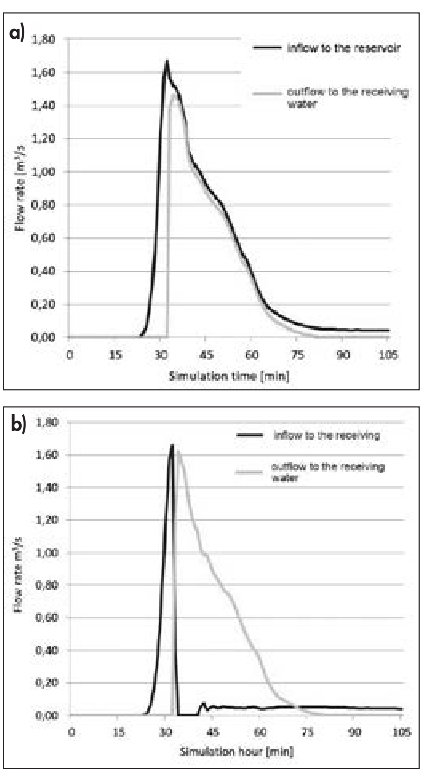
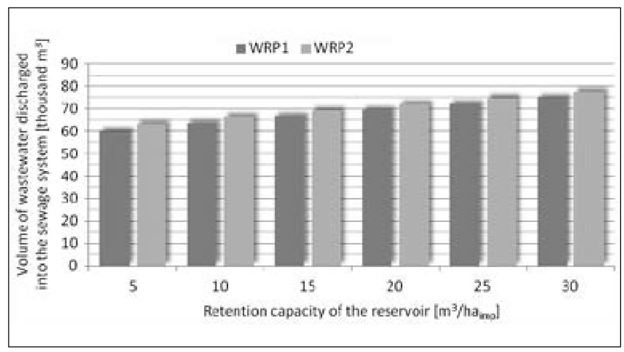


Fig. 9.
Wastewater flow at the inflow to the reservoir and outflow to the receiving water [m³/s] for reservoirs: a) WRP1; b) WRP2
Rys. 9. Przepływ ścieków na dopływie do zbiornika i odpływie do odbiornika [m³/s] dla zbiorników: a) WRP1; b) WRP2

is lowered below the set level (H<1.5m), the inflow to the reservoir is possible. Its value is equal to the rate of outflow into the sewage system. In both cases, wastewater begins to flow to the receiving water when the retention chambers are completely filled and the weirs are triggered, with the moment of triggering observed earlier in the WRP2 reservoir.

In the present study, continuous simulations were performed for the years 2011 and 2012, which made it possible to check the division of rainwater volumes between those discharged to the receiving water body and those diverted to the domestic sewage system. During the period studied, about 110,200 m^3 of rainwater flowed into the stormwater runoff system. The graph shows the relationship between the volume of rainwater discharged to the sewage system (Fig. 10) depending on the volume of the retention chamber and the selected retention reservoir design.

Fig. 10.
Volume of wastewater discharged to the sanitary sewage system depending on the volume of the retention reservoir per hectare of sealed area [m³/ha$_{imp}$]
Rys. 10. Objętość ścieków odprowadzonych do kanalizacji sanitarnej w zależności od objętości zbiornika retencyjnego w przeliczeniu na 1 ha powierzchni uszczelnionej [ha$_{zr}$]



Analysis of the above data reveals a relatively small difference in the percentage distribution of rainwater runoff between that discharged to the sanitary sewage system and that discharged to the receiving water. The difference ranges depending on the size of the reservoir from ca. 6% to 7%, for the volume of wastewater discharged to the receiving water and from ca. 3.5% to 5% for wastewater discharged to the sewage system. This results from the above-mentioned relationship related to the accumulation of wastewater in the reservoir over the set filling level. Installation of the overflow in the sewer that supplies wastewater allows for the reduction of the depth of the sewage accumulation in the reservoir, and thus reduction of the volume of wastewater that reaches the receiving water through the weir located in the reservoir. As the capacity of the retention chamber of the reservoir increases, the volume of wastewater that is discharged into the sewage system increases. The controller used at the reservoir outflow, which allows maximum use of the sewage sewer capacity, protects the sanitary system from excessive hydraulic overload. However, the inflow of a large volume of rainwater into the domestic sewage system and then to the wastewater treatment plant can have a negative impact on the wastewater treatment plant operation and, in some cases, cause it to be overloaded hydraulically.

Discussion

Examinations of efficiency of retention reservoirs based on a hydrodynamic model

The SWMM program is a tool that, in addition to estimating the volume of wastewater discharged into the sewage system, also allows simulations that take into account the quality parameters of rainwater runoff. The user can define the type of pollutant modeled and different rates of pollutant accumulation and flushing depending on the type of surface, use, and land use of the sub-catchments [2, 20].

In the study, the modeled pollutant indicator was total suspended solids, which is one of the most important criteria standardized in legal regulations concerning rainwater runoffs. Each of the sub-catchments was divided by development into two land uses:

- main traffic routes, streets, and parking lots as more heavily polluted areas,
- other residential areas, primarily the roofs of buildings, where the accumulation of pollutants is lower.

An exponential function was chosen to describe pollutant accumulation:

$$B = C_1(1 - e^{C_2 t})$$

where:

B – current accumulation of pollutants [kg/ha],
C_1 – the limiting mass of accumulated pollutants [kg/ha],
C_2 – the rate of depletion of pollutants (due to wind and carried away by vehicles [d_{-1}]).

Parameters for the rate of accumulation of pollutants were selected based on the literature data to achieve a result close to the mean mass of suspended solids discharged from a hectare of impervious surface per year through the sewage system, i.e. ca. 430 kg/ha per year. The values used in the simulations are shown in Table 1.

Table 1. Parameters of the EPA SWMM model of pollutant accumulation and flushing

Type of sealed surface	Parameter			
	C_1	C_2	K_1	K_2
Streets (more heavily polluted areas)	70	0.1	0.2	2
Roofs (less polluted areas)	20	0.1	0.2	2

On the other hand, an exponential function was employed to describe the pollutant flushing process in the model:

$$W = K_1 q^{K_2} B$$

where:

W – flushed pollutant load [kg/ha],
K_1 – pollutant flushing rate [-],
K_2 – power factor [-],
q – intensity of surface runoff [mm/h],
B – current accumulation of pollutants [kg/ha].

The quality parameters were not calibrated, and their values characterizing pollutant flushing were selected based on those recommended in the literature [19, 21, 22, 23], as shown in Table 1.

The SWMM program also makes it possible to use the sewage treatment function in facilities where treatment processes occur (e.g. retention reservoirs). However, adopting parameters for the suspension removal function in the reservoir would require specifying a number of preliminary assumptions related to the sedimentation characteristics, as the SWMM program does not allow simulating the transport and removal of suspension into individual fractions. Since the aim of the research was not to thoroughly analyze the possibility of removing pollutants (total suspension) through retention reservoirs, but only to check the possibility of using the devices presented in this study to implement semi-separated sewage systems, no research was carried out related to the sedimentation phenomenon occurring in the presented devices and also in stormwater channels. Therefore, the results presented below should be treated as preliminary research for further analyses, especially when considering the practical use of any of the proposed variants.

As before, the results were collected using continuous simulation for two years (2011 and 2012). In total, 17,900 kilograms flowed out of the sewage system during the period of the study, which amounts to 795 kilograms per hectare of sealed area. The graph in Fig. 11 shows the comparison of a load of suspended solids discharged to the receiving water depending on the selected variant and capacity of the reservoir.

As can be seen, much better results were obtained using the WRP2 reservoir, that is, a reservoir with a weir located on the inflow. Analysis of the results of the simulation concerning the operation of the proposed retention reservoir solutions reveals that the distribution of the suspended solids loads into that discharged to the sewage system and that discharged to the receiving water for the same variants depends primarily on the size of the system used (the capacity of the retention chamber). The graph in Fig. 12 shows data describing the percentage change in the mass of suspended solids discharged to the receiving water for the different variants as the volume of the reservoir increases for a reservoir with a volume of 5 m^3/ha_{imp}.

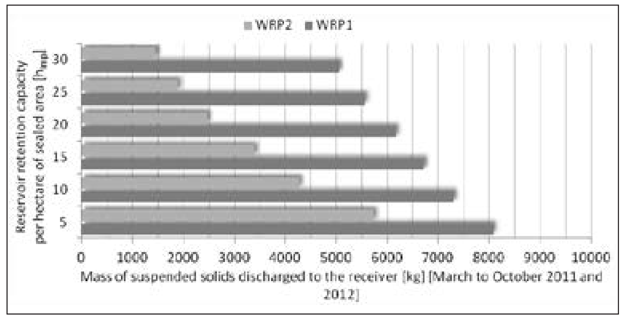


Fig. 11.
The mass of suspended solids discharged to the receiving water depending on the selected variant and the retention capacity of the reservoir [March to October 2011 and 2012]
Rys.11. Masa zawiesiny odprowadzona do odbiornika w zależności od wybranego wariantu i pojemności retencyjnej zbiornika

5 m^3/ha_{zr}), for the reduction of the mass of suspended solids at the outflow by as much as 37% (WRP1) to 74% (WRP2).

One of the most important parameters compared in the present study was the suspended solids reduction rate. The following data (Fig. 13) confirm that significantly better results in treating rainwater runoff were obtained using the WRP2 reservoir. Depending on the volume of the reservoir, the suspended solids reduction rate ranged from 67% to 92%. For the WRP1 reservoir, it ranged from 55% to 72%.

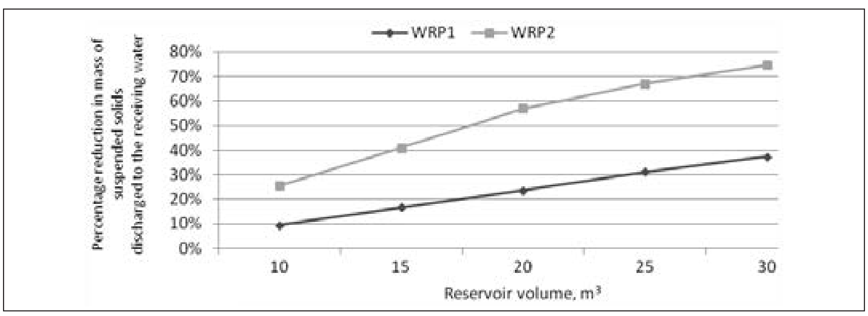


Fig. 12.
Percentage reduction in the mass of suspended solids discharged to the receiving water as the volume of reservoir increases for a reservoir with a volume of 5 m^3/ha_{imp}
Rys. 12. Procentowa zmiana masy zawiesiny odprowadzanej do odbiornika wraz ze zwiększaniem objętości zbiorników w odniesieniu do zbiornika o objętości równej 5 m^3/ha_{zr}

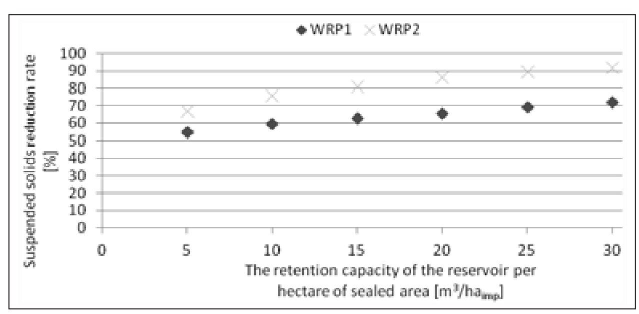


Fig. 13.
Suspended solids reduction rate depending on reservoir variant and volume per hectare of sealed area [m^3/ha_{imp}]
Rys. 13. Stopień redukcji zawiesiny w zależności od wariantu zbiornika i jego objętości w przeliczeniu na hektar powierzchni uszczelnionej [m^3/ha_{zr}]

As can be seen from the graph, increasing the volume of the reservoir results in a significant reduction in the mass of suspended solids discharged with wastewater into the receiving water. By doubling the capacity of the retention chamber from 5 to 10 m^3/ha_{zr}, it is possible to reduce the load of suspended solids discharged to the receiving water, depending on the variant used, from ca. 9% (WRP1) to ca. 26% (WRP2). On the other hand, the largest reservoir used in the analysis (volume of 30 m^3/ha_{zr}) allows, compared to the smallest reservoir (volume of

The next graph (Fig. 14) shows the mean concentrations of suspended solids in wastewater discharged to the receiving water body calculated from the simulation results. As can be seen in the figure below, significantly higher values of suspended solids concentration (mean over the entire simulation period) were recorded for the WRP1 reservoir and ranged from 160 to 143 mg/l depending on the size of the reservoir. This is due to the position of the weir in the retention chamber. This design causes the entire volume of wastewater to flow through the reservoir. Wastewater

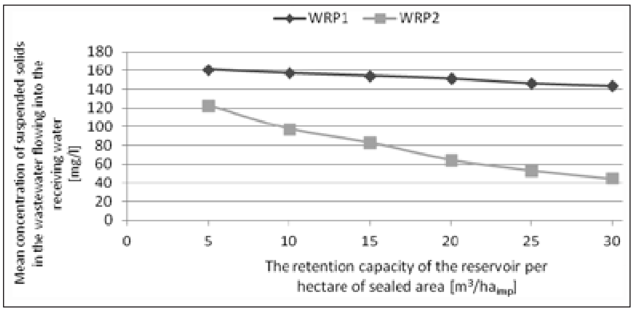


Fig. 14.
Mean concentrations of suspended solids in wastewater discharged to a receiving water body [mg/l]
Rys. 14. Średnie stężenia zawiesiny w ściekach zrzucanych do odbiornika [mg/dm³]

with a smaller load of suspended solids (after the first wave) flows through the retention chamber causing the more heavily polluted wastewater to be carried away into the receiving water.

In the WRP2 reservoir, a weir located in the inlet channel allows excess wastewater to be discharged into the receiving water before the reservoir, preventing pollutants from being carried out of the retention chamber. This is confirmed by the next diagram (Fig. 15), which shows the mean concentrations of suspended solids at the outflow to the sewage system. In the WRP1 reservoir, the value of mean concentrations is almost constant for all wastewater volumes and ranges from about 165 to 175 mg/l[3]. In WRP2, slightly higher concentrations

Table 2. Results of simulation of the performance of the different variants of reservoirs for the rainfall of 6 August 2011

	WRP1	WRP2
Mass of suspended solids discharged to the receiver [kg] – **A**	256	129
Mass of suspended solids discharged to sewage system [kg] – **B**	35	160
Volume of wastewater discharged to receiving water [m³]	1568	1550
Volume of wastewater discharged to the sewage system [m³]	816	834
Suspended solids reduction rate $\frac{A}{A+B}\cdot 100\%$	12	55
Mean concentration of suspended solids in wastewater flowing into receiving water [mg/l]	163	83
Mean concentrations of suspended solids in wastewater discharged to the sewage system [mg/l]	43	192

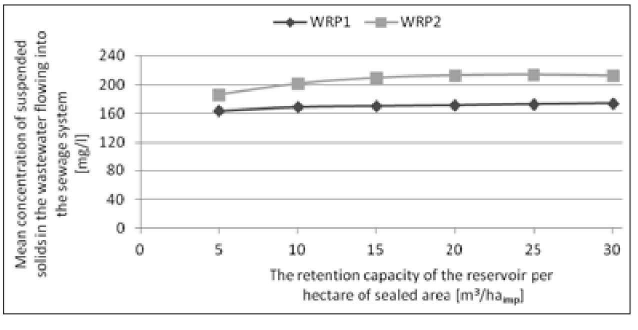


Fig. 15.
Mean concentrations at the outflow to sewage system [mg/l]
Rys. 15. Średnie stężenia na odpływie do kanalizacji ściekowej [mg/dm³]

were observed, which varied with increasing reservoir volume from 185 to 215 mg/l.

To further investigate the mechanism of separation of suspended solids in the systems studied, simulations were carried out for individual receiving waters. The simulations were based on the rainfall of 6 August 2011, previously used to study the hydraulic operation of the reservoirs. Simulations were conducted for a reservoir with a capacity of 15 m³/ha_{imp}. The results obtained for each variant are summarized in Table 2.

The above summary confirms the results of analyses conducted for continuous simulations. The WRP1 reservoir is a solution in which the efficiency of suspended solids removal is significantly lower. For a single rainfall and a given reservoir volume, the suspended solids reduction rate was only 12% (only 35 kg of suspended solids were removed), and was much lower than the mean of this parameter for this reservoir volume over the entire period studied (63%). In this case, the value of mean concentrations in wastewater discharged to the sewage system is 43 mg/l, which is lower than in wastewater discharged to the receiving water (163 mg/l). This distribution of mean concentrations confirms that with this design, there is dilution of wastewater and the carrying of pollutants from the system through the weir to the receiving water. Such a large difference in the suspended solids reduction rate and in mean concentrations may be due to the characteristics of the precipitation chosen for the simulation and the washing out of a large amount of pollutants by rain in a short period of time. Not all rainfalls cause wastewater runoff with a large mass of suspended solids in the initial phase of the rain. Furthermore, not every volume of precipitation cause the reservoir to overflow, especially since channel retention is available for this option, which allows it to accommodate an additional volume of precipitation with a certain mass of suspended solids. Therefore, the continuous simulations yielded a higher reduction rate and different values of average concentrations at the outflow to the sewage system.

In order to further analyze the operation of the equipment and explain the reasons for the differences in suspended solids removal efficiency, simulations were carried out to determine the changes in the suspended solids load in the wastewater flowing into the reservoir and flowing out to the receiving water (Fig. 16).

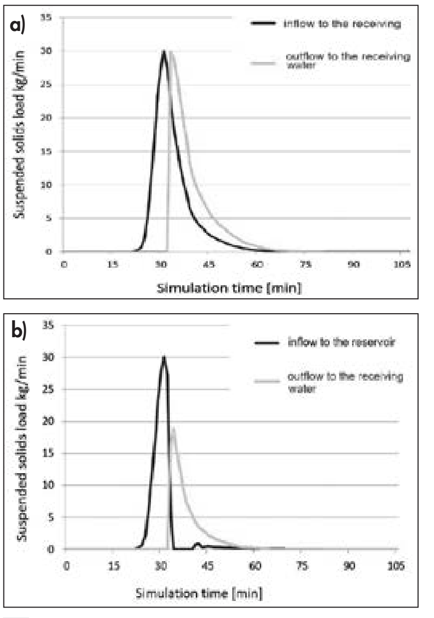


Fig. 16.
Suspended solids load in wastewater at the inflow to the reservoir and outflow to the receiving water [m³/s] for: a) WRP1; b) WRP2
Rys. 16. Ładunek zawiesiny w ściekach na dopływie do zbiornika i odpływie do odbiornika [m³/s] dla: a) WRP1; b) WRP2

As can be seen in the graph, the load at the inflow increases until the reservoir is filled, and is about 30 kg/min in both cases. When the maximum level of wastewater in the retention chambers is reached, the weirs begin to operate and the discharge of wastewater with a load of suspended solids into the receiving water begins. In the case of WRP1 (Fig. 16a), when the reservoir is filled, the instantaneous value of the suspended solids load discharged to the receiving water is greater than the suspended solids load flowing into the retention chamber, so a small suspended solids reduction rate (12%) is achieved for the WPR1 reservoir.

Wastewater flows into the reservoir all the time, carrying suspended solids and diluting the remaining volume of wastewater in the retention chamber so that the reservoir in such a system allows for the removal of a small mass of suspended solids. On the other hand, the WRP2 reservoir (Fig. 16b) discharges a volume of wastewater (with the load) that currently flows to the location of the weir. A volume of wastewater and the mass of suspended solids remain in the channels and is discharged through the reservoir into the sanitary sewage system.

Conclusion

The study showed that it is possible to use retention reservoirs as flow controllers. The solutions presented differ from each other both in terms of hydraulic operation and efficiency of removing suspended solids contained in rainwater runoff. Based on the results it can be concluded that WRP1 is the least favorable design. It allows for achieving a suspended solids reduction rate of 55% to 72% but the volume of wastewater discharged into the sewage system is only slightly less than in WRP2. In terms of the suspended solids reduction rate, WRP2 performs much better (the reduction rate ranges from 67% to 92%). It should be borne in mind that depending on the size of the reservoir, 57% to 60% of the total volume of wastewater flowing from the catchment area into the sewage system is discharged through the reservoirs into the sewage system in this solution, which results in significant amounts of wastewater received in the treatment plant. Admittedly, the controller located on the outflow prevents hydraulic overload to the channel but the inflow of such a large additional volume of wastewater will certainly adversely affect the treatment plant. The study also showed that the location of the weir is of great importance when it comes to the efficiency of suspended solids removal. Although the reservoirs operate hydraulically similarly, the obtained results of the suspended solids reduction rate differ significantly. The use of a weir at the inflow channel allows for a significant improvement in the efficiency of the removal of pollutants and this solution should be used.

It is also worth noting that the WRP1 and WRP2 reservoirs are heavily influenced by channel retention, which in a different catchment area may have a different volume and thus affect the effectiveness of the reservoirs. However, the results obtained confirm that it is possible to use retention reservoirs as flow controllers, and their operation makes it possible to significantly reduce the amount of suspended solids that are discharged into the receiving water.

The results obtained in the tests conducted in the study, regarding the amount of suspended solid, should be treated as preliminary since in reality, the degree of the suspended solids reduction may be greater than in the above simulations.

Actually, the suspended solids reduction rate may be greater than in the above simulations. This is due to the previously mentioned to the way the SWMM program performs calculations. Models of accumulation, flushing, and transport of pollutants are based solely on empirical formulas. The calculations are simplified and do not take into account the division of particles into fractions. The application treats sections of the sewage system as full mixing reactors, where the same mass of pollutants flows throughout the volume. In fact, there is a higher concentration of suspended solids at the bottom of the channel. Therefore, the reservoirs can hold a greater mass of pollutants. However, this does not change the fact that the retention reservoirs proposed in this study seem to be a solution that allows for easy modernization of the existing distribution sewage system to a semi-separated one, thus significantly limiting the discharge of pollutants contained in rainwater sewage to the receiver. Based on the conducted analyses, it can be concluded that the retention reservoir WRP2 is a better solution and in this case, it is worth considering more detailed analyses taking into account the course of the sedimentation process occurring in the device.

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