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# An innovative rainwater system as an effective alternative for cubature retention facilities

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**Abstract:** The paper focuses on the possibilities of rainwater flow control in an innovative rainwater system which is equipped with a retention canals system. Sewage retention canal is a modern solution that provides effective retention of excess rainwater by using a capacity of sewer pipes and manholes. The retention is possible by using special damming partitions which have flow openings. The hydraulic working of the traditional rainwater system and the innovative rainwater system were compared with each other. The analysis was based on the results obtained from simulations using hydrodynamic modeling. Maximum possible values of rainwater outflow intensity from outlet nodes for the traditional rainwater system and the innovative rainwater system were discussed. On the basis of the analysis it was shown that the innovative rainwater system outweighs the classic rainwater one. It discharges two functions: transports and simultaneously retains excess rainwater in canals.

**Keywords:** Innovative rainwater system; sewage retention canal; rainwater retention; flow reduction.

## 1 Introduction

Nowadays, rainwater retention is one of the most serious problems of water and sewage management. Proper management of rainwater is an extremely difficult task because of changing climatic conditions.

The purpose of rainwater management is to provide an effective way to manage excess rainwater based on principles of sustainable development and with the least possible interference with the environment [9, 15, 16].

Dynamic development of urban areas and progressive urbanization in recent years, have contributed to the reduction of green areas and have caused an increase of paved surfaces [12, 17, 40]. These phenomena disturb the balance between precipitation processes and runoff, soaking and transpiration of rainwater [3]. Due to the intensification of the degree of development in recent years, a negative impact of climate change is observed, which results in more frequent extreme rainfall [10, 16, 13, 38]. According to hydrological forecasts, the frequency of extreme precipitation will increase in the coming years [20, 31, 32]. These phenomena cause an increase of rainwater surface runoff, which negatively affects not only sewerage systems, but also water receivers [15, 33]. A lack of a sufficient hydraulic reserve in the existing sewage system makes increasingly local flooding and overflow rainwater from the sewerage system on the land surfaces [9, 4, 12, 13, 14]. All of these phenomena enforce to look for an effective water management method in order to reduce the risk of flooding in urban areas and prevent failure of the operation sewage system.

The existing sewerage systems, because of overloading, require an extension or building additional retention facilities. In the case of projected sewerage systems, the main problem is the cost of construction canals with significant geometries and cubature facilities for rainwater retention. Additionally, it is also necessary to have enough area of land for the construction of retention facilities, which in the case of urban areas is often impossible.

As it was shown in many works [8, 9, 23, 37] upper spaces in the canals are empty and are not fully used even during the maximum rains. The sewage retention canal [7] is a modern solution, which allows a practical use of this space and includes it into the usable retention capacity of the sewer system. In this solution vertical damming partitions are installed in manholes at certain distances.

Rainwater flows in sewage systems are most often rapid. A very large volume of rainwater are transported in a short time through the system of canals to the receiver.

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Such a situation causes numerous technical difficulties and a number of negative environmental consequences such as a rapid inflow of rainwater to the receiver, an increase in the speed of water flow in the river, floods, intensification of erosion phenomena, movement of river sediments, disturbances in functioning of aquatic ecosystems.

Limiting these negative phenomena is possible by regulating the runoff of rainwater from urbanized areas through the use of facilities for their temporary storage, e.g. retention reservoirs described in patents [41-47].

Traditional retention facilities usually occupy large areas, which in cities are valuable for residential, commercial and service development. In addition, they are expensive investments but necessary due to the regulation of the outflow of excess rainwater. All activities supporting this process and reducing the cost of its implementation are expected and valuable.

In the paper the role of retention in drainage systems is discussed. A hydraulic model of an innovative rainwater system equipped with a retention canals is presented, the model subcatchment is characterized, and the research methodology is described. The results are obtained based on simulations using hydrodynamic modelling. Additionally, the hydraulic functioning of traditional stormwater drainage system and innovative storm water drainage system equipped with retention canals were compared. On the basis of the analysis, a lot of advantages of the innovative sewage systems over the classic sewage system were shown.

## 2 The role of retention in drainage systems

In recent years, there has been a rapid development of the urbanization which, according to forecasts, will be growing rapidly [30, 34]. A replacement of natural permeable areas with paved surfaces brings an increase of surface runoff and more rainwater discharge through sewer system [17]. Additionally, an extreme weather phenomenon such as heavy rains have been observed more frequently recently [13, 32, 35]. These cause a number of negative effects, for example hydraulic overloading of the rainwater system and treatment plants, local flooding, overload and pollution of the rainwater receiver [15, 29]. As a result, an increasing part of the costs is spent on repairing the consequences of flood. Therefore, it is needed to improve methods to design sewage systems and search for new effective ways of retaining and controlling rainwater flow in sewage systems [28, 17, 19, 35]. At first, the rainwater flow in stormwater systems should be reduced and delayed using infiltration and retention devices at the place of rainfall generation [27, 10]. These solutions are not always able to use, so a careful analysis of their advisability should be conducted [9]. Retention tank (fig. 1) and an additional transit canal (fig. 2) have been the most well-known design solutions to reduce hydraulic overloading in the sewer system so far [28, 27]. The use of retention tanks has both economica and environmental advantages. The problem of hydraulic overload sewage system and the objects working with it is solved and the stormwater receivers are protected against an excessive volume flow and pollutants by using retention tanks. Additionally, they allow the use of smaller geometries of sewer pipes and prevent overflowing the sewer system during heavy rains [26].

If an underground infrastructure is limited, the additional transit canal can be put in with the existing sewer system. The next possibility is to put the additional transit canal outside the urbanized area if there is dense underground infrastructure and surface development. However, location on the sewer system would interfere with investment and generate high investment costs [27].

The solutions mentioned have a limited scope of applications despite lots of advantages. There is no space for construction of such objects due to a rapid development of buildings and underground infrastructure. In addition, there are high investment costs. These are the basic disadvantages of current retention facilities. The lack of ability to use them and the growing problems of rainwater management make it necessary to look for modern solutions for rainwater retention [23, 25].

One of them is the sewage retention canal (fig. 3). This solution can be applied to both designed and already existing sewer systems. The innovative retention sewage canals can replace a retention tank or reduce its required volume. That makes the investments costs lower. It is an effective solution compared to traditional ones. It does not require an additional area to build the special retention facilities [8, 9]. The main advantage of this solution is maximizing the retention capacity of the sewage systems. This in turn, allows hydraulic relief of the sewer systems, and gives an opportunity to connect new subcatchments to the existing sewage, and reduces the cost of constructing new sewage systems. The use of innovative retention canals equipped with damming partitions does not even require simple control systems as well as energy supply [28].

Such a sewerage system can be a successful alternative for Low Impact Development facilities and traditional

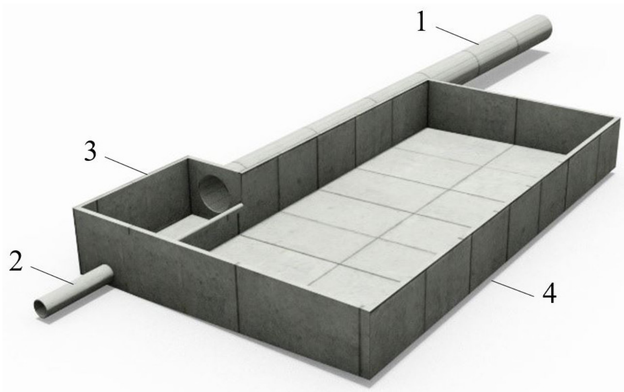


**Figure 1:** An example of a retention tank (1 - inlet canal, 2 - outlet canal, 3 - flow chamber, 4 – accumulation chamber) [28].

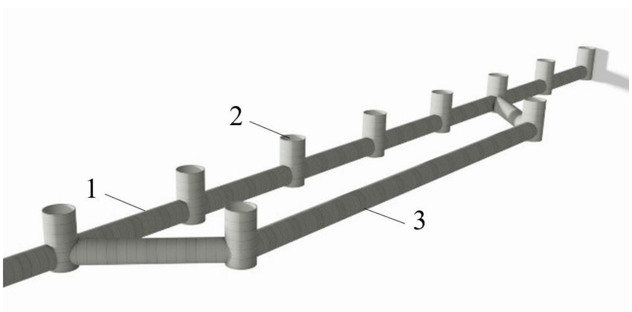


**Figure 2:** An example of an additional transit canal (1 – sewer canal, 2 - sewer manhole, 3 - additional transit canal) [28].

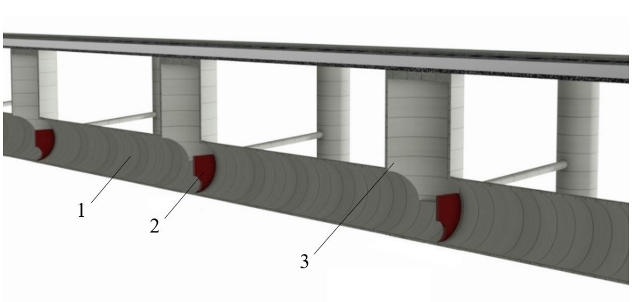


**Figure 3:** An example of a rainwater system equipped with a retention sewage canals (1 - canal, 2 - piling partitions, 3 - manhole) [28].

retention reservoirs or cooperate with them in order to maximize the efficiency of the whole sewerage system [9, 23]. This solution minimalizes the risk of urban flooding, does not interfere with the natural environment, protects rainwater receivers and complies with the principles of sustainable development. The hydraulic model of the innovative rainwater network is discussed in sec. 3.

# 3 Hydraulic model of an innovative rainwater system

Retention sewage canal is a patented solution RP no. 217405 [7]. Its primary advantage is an ability to utilize the capacity of the sewer systems, including pipes and manholes, which had not previously been utilized in full. It enables retention of excess rainwater. In many cases, this solution makes sewer system to function without any additional retention facilities, especially retention tanks [4].

This solution consists in equipping the canalization with a system of retention canals with special damming baffles. The damming elements are installed in inspection manholes, perpendicular to the flowing wastewater (fig. 4). Damming partitions enable damming of rainwater throughout the sewage systems [28]. There is an opening flow at the bottom of each baffle and an overflow edge at the top, which is the leading discharge overflow [8, 24]. The damming baffles are mounted to the inside walls of the canals.

The principle of operation of the innovative rainwater sewage system is shown in Figure 5 allow for effective use of the drainage system capacity [23]. Mounted damming partitions into canals create rainwater retention chambers. It is recommended to start filling these chambers from the highest chamber which has the smallest opening. The next lower chambers have larger flow openings [28].

The rainwater inflow to the accumulation chamber located below depends on the rainwater outflow from the chamber located above and the surface runoff entering the sewage systems. The efficiency of the innovation sewer systems is determined by the critical values of the stormwater outflow from the damming baffle $Q_{o_{Imax}}$. The slope, diameters of retention canals and the geometry of the damming partition have a significant influence on the outflow $Q_{o_{Imax}}$. A designer should not only fit slopes and diameters of canals but also design correctly the dimensions of damming baffles, including their height and size and the shape of flow holes. This is a basic task to be performed by a designer. The establishment of critical rainfall is necessary to project damming partitions. A full utilization of the space in the canal ensures the lowest rainwater outflow $Q_{o_{Imax}}$ from an outlet node. It is determined by the value of the rainwater flow reduction coefficient $\beta_{KR}$ [28].

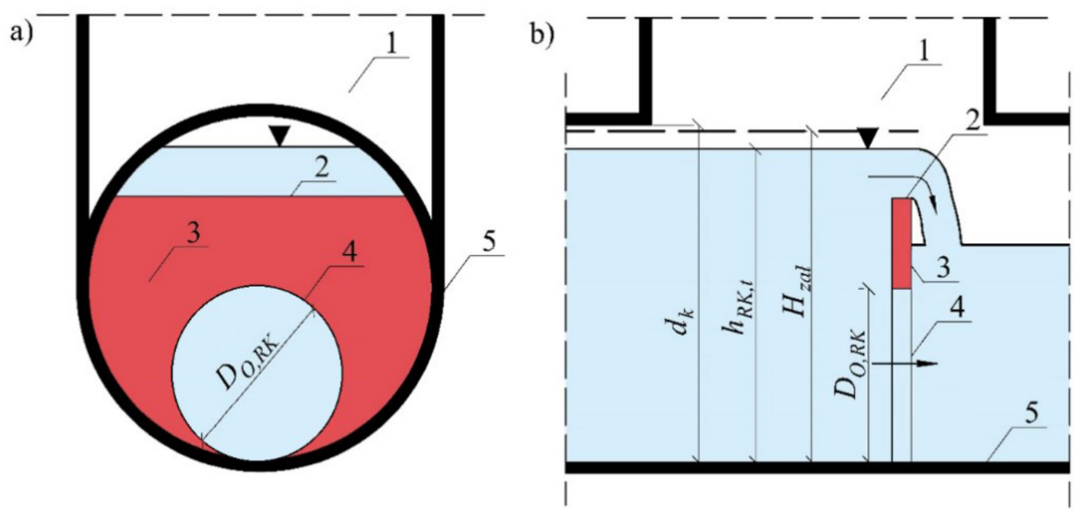


**Figure 4:** Scheme of the damming partition installed in a sewage manhole (a) cross section; (b) longitudinal section; 1 - sewer manhole, 2 - overflow edge, 3 - piling partition, 4 - flow opening, 5 – canal, $D_{O,RK}$ – diameter of the flow opening, $d_k$ - diameter of canal, $h_{RK,t}$ – rainwater height in the canal during the time *t*, $H_{zal}$ - maximum acceptable height of rainwater before the damming partition [9].

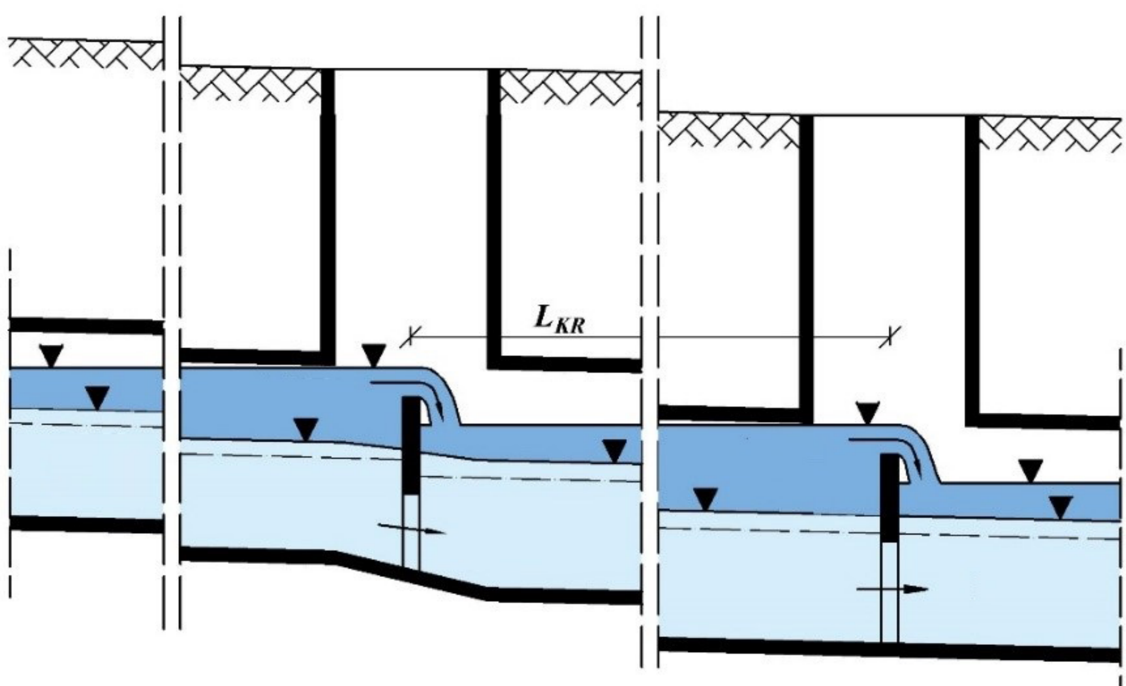


**Figure 5:** Scheme of the retention sewage canal with damming partitions that create stormwater canal retention spaces (the light blue - average distribution of the liquid stream mirror in the conduits of a traditional rainwater systems; the blue - liquid stream distribution and retention capacity of the rainwater sewage system after equipping it with damming partition), $L_{KR}$—distance between adjacent damming partitions [7].

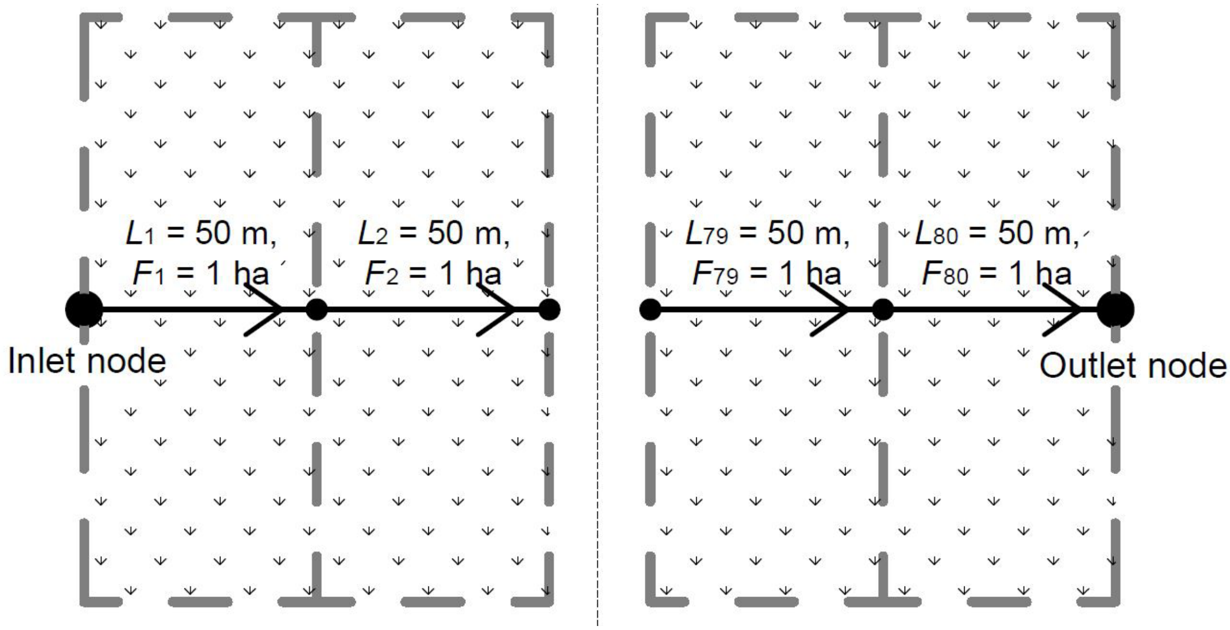


**Figure 6:** The scheme of the model catchment, total drainage area $F$ = 80 ha (developed based on [1]).

## 4 Model catchment with innovative rainwater system

A model catchment consists of 80 sub-catchments, where a total drained catchment area equals $F$ = 80 ha. The same hydrological parameters were assumed for each sub-catchment. Three concepts of rainwater sewer system were considered, varying in canal slopes.

Concept I - the canals bottom slope amounts $i_k$ = 1 ‰.
Concept II - the canals bottom slope amounts $i_k$ = 2 ‰.
Concept III - the canals bottom slope amounts $i_k$ = 3 ‰.

It was assumed that the sewage system examined ha a linear sewer system in each design concept. It consisted of 80 pipes of equal length (Fig. 6).

Hydrodynamic modelling with the SWMM 5.1 program was used for the analysis. The surface runoff coefficient $\Psi$ = 0.5, the slope of the drainage area $i_ż$ = 10 ‰, the catchment roughness coefficient $n_z$ = 0.015 s/m$^{1/3}$ and the canals roughness coefficient $n_k$ = 0.010 s/m$^{1/3}$ were assumed.

At the first stage, three concepts of traditional rainwater sewer system were considered. For each of them the maximum value of rainwater outflow from the sewer at outlet node $Qo_{Tmax}$ and the calculative time for rainwater sewage system dimensioning $t_m$ were determined. At the next stage, each of sewers was equipped with damming partitions. Three different spacings between the damming baffles $L_{KR}$ were assumed, such that nine variants of innovative sewer system equipped with the retention canals system were obtained. For that model of the sewer system, the maximum value of the rainwater outflow from outlet node in the innovative systems $Qo_{Imax}$ and the calculative reliable rainfall time to dimension the innovative rainwater canals $t_M$ were determined.

## 5 Precipitation model and research methodology

Precipitation models are used in the design of rainwater and combined sewer systems and facilities working with them. They allow determining the relationship between the intensity of the critical rainfall and the rainfall time and the probability of its occurring. The knowledge on critical rainfall is needed during hydrodynamic modelling [11, 19].

The data on the functioning of the innovative rainwater system come from hydrodynamic modelling using the Bogdanowicz and Stachy rainfall model. It was developed on the basis of rainfall measurements from 20 meteorological stations of Institute of Meteorology and Water Management in the years 1960 - 1990 in Poland [8, 22]. It is a probalistic model of maximum rainfall heights. It considers the time of rainfall and probability of occurring [9]. It is described in the publication [21] by the following formula (1):

**Table 1:** A set of basic hydraulic parameters of the traditional rainwater system.

| The traditional rainwater sewage system | | | | |
|---|---|---|---|---|
| **No.** | **Conception** | **Slope of canals bottom** | **Maximum value of rainwater outflow from the traditional rainwater sewer at outlet node** | **Calculative time for rainwater sewage system dimensioning** |
| - | - | $i_k$, ‰ | $Qo_{Tmax}$, dm³/s | $t_m$, min |
| 1. | Conception I | 1 | 2887.7 | 32 |
| 2. | Conception II | 2 | 3692.8 | 26 |
| 3. | Conception III | 3 | 4175.8 | 25 |

**Table 2:** A Set of the values of the basic hydraulic parameters of the innovative rainwater sewage with retention canals system.

| The innovative rainwater sewage system (traditional sewage system after installation of damming baffles) | | | | | | | |
|---|---|---|---|---|---|---|---|
| **No.** | **Conception** | **Considered variant** | **Slope of canals bottom** | **Maximum value of rainwater outflow from the innovative rainwater sewer at outlet node** | **Calculative time for innovative rainwater sewage system dimensioning** | **Damming baffles spacing** | **Rainwater flow reduction coefficient** |
| - | - | - | $i_k$, ‰ | $Qo_{Imax}$ ,dm³/s | $t_M$, min | $L_{KR}$, m | $\beta_{KR}$, - |
| 1. | Conception I | Variant 1 with $L_{KR1}$ | 1 | 981.6 | 88 | 200 | 0.34 |
| 2. | | Variant 2 with $L_{KR2}$ | 1 | 1063.4 | 84 | 300 | 0.37 |
| 3. | | Variant 3 with $L_{KR3}$ | 1 | 1159.6 | 78 | 400 | 0.40 |
| 4. | Conception II | Variant 1 with $L_{KR1}$ | 2 | 1775.1 | 56 | 200 | 0.48 |
| 5. | | Variant 2 with $L_{KR2}$ | 2 | 2120.8 | 46 | 300 | 0.57 |
| 6. | | Variant 3 with $L_{KR3}$ | 2 | 2362.8 | 42 | 400 | 0.64 |
| 7. | Conception III | Variant 1 with $L_{KR1}$ | 3 | 2445.3 | 40 | 200 | 0.59 |
| 8. | | Variant 2 with $L_{KR2}$ | 3 | 2899.5 | 34 | 300 | 0.69 |
| 9. | | Variant 3 with $L_{KR3}$ | 3 | 3118.8 | 30 | 400 | 0.75 |

$$h = 1{,}42\, t^{0{,}33} + \alpha(R,t) \bullet (-\ln p)^{0{,}584} \tag{1}$$

where: $h$ - maximum rainfall height, mm; $t$ - rainfall duration, min; $p$ - probability of rainfall occurrence, $p \in (0;1]$; $\alpha$ - parameter depending on the region of Poland $R$ and time $t$, -.

The parameter α depends on the region of Poland and the rainfall duration [22, 21]. The precipitation model can be used for the whole Poland except for mountainous regions. The rainfall model of Bogdanowicz and Stachy is recommended for rainfall frequency $C$ = 2, 5, 10 years [10].

The simulation of the phenomena in the sewer system was performed by using hydrodynamic modelling with the help of Storm Water Management Model program (SWMM 5.1). The probability of rainfall occurrence was assumed $p$ = 50 %. The phenomena were simulated using the dynamic wave model. It can truly reflect the functioning of the sewer during changing water flows in time, the occurrence of backwater and the retention of rainwater in the sewer [39]. The flow along the sewer system is gravitational. The hydrodynamic models obtained reflect different conditions of sewer system operation considering three different canals bottom slopes and three different spacing between damming baffles.

# 6 Results and discussion

The analysis of the innovative rainwater system functioning in relation to the classical rainwater system was based on the results from Tables 1 and 2. Table 1 presents the data from simulation for traditional stormwater system with three variants of canals bottom slopes like $i_k$ = 1 ‰, $i_k$ = 2 ‰ and $i_k$ = 3 ‰. Drained catchment is $F$ = 80 ha. For those three concepts, the values of the maximum rainfall outflow at the outlet node from catchment $Qo_{Tmax}$ and the calculative times for sewage system dimensioning $t_m$ were determined. Table 2 shows the values of parameters after

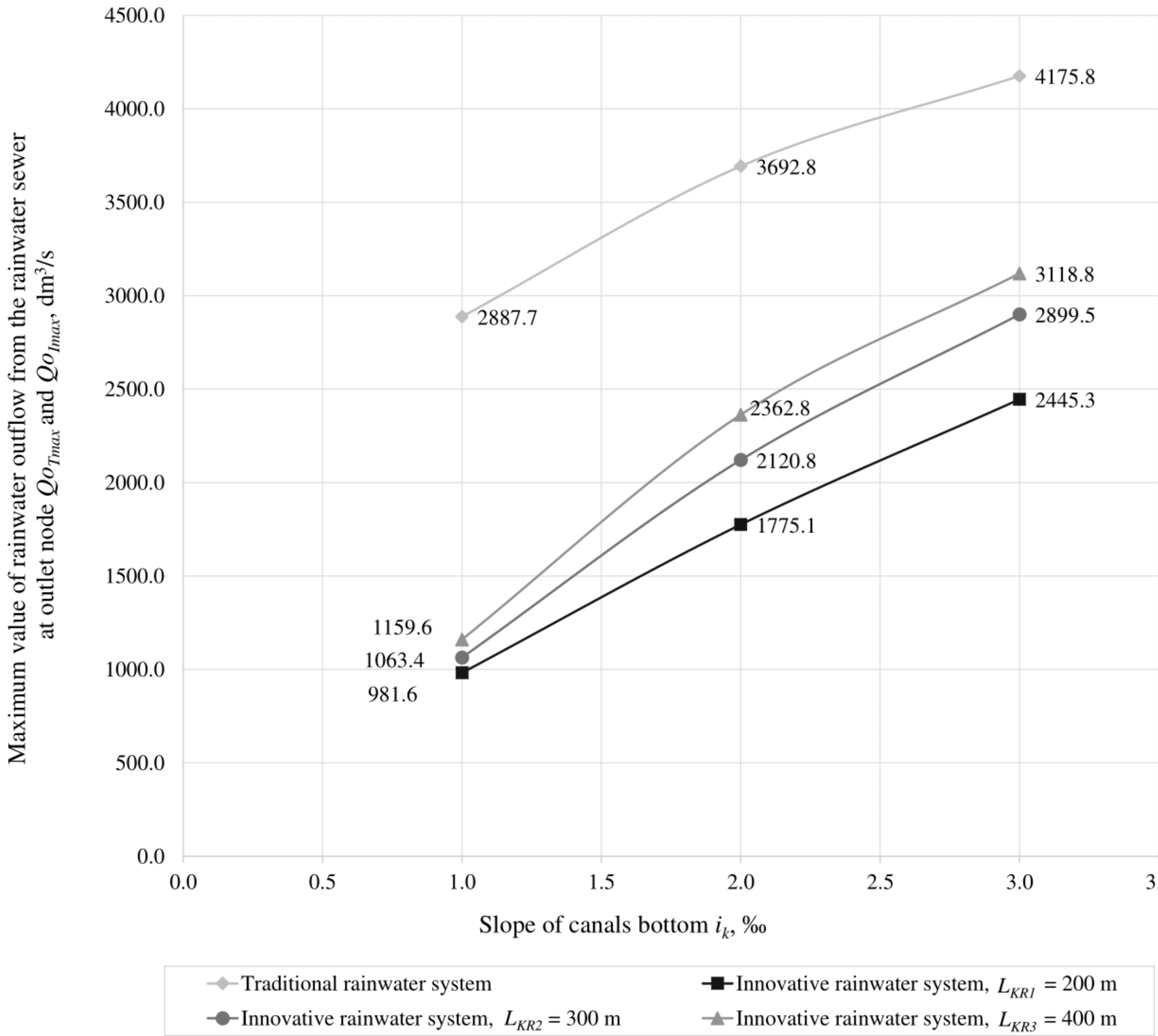


**Figure 7:** Maximum rainwater outflow at the outlet from the drainage catchment for traditional storm water system $Qo_{Tmax}$ and innovative storm water system $Qo_{Imax}$, catchment area $F$ = 80 ha (developed on the basis of [1]).

equipping the classic stormwater system with damming baffles. Each conception of innovative rainwater sewage system takes into account three various distances between damming partitions like $L_{KR1}$ = 200 m, $L_{KR2}$ = 300 m, $L_{KR3}$ = 400 m.

In that way 9 different variants of innovative rainwater systems with retention canals were analyzed. TThe rainwater flow reduction coefficient $\beta_{KR}$ of the outflow from the innovative rainwater system was determined along with the parameters $Q_{o_{Imax}}$ and $t_M$. The cross-sections of conduits and slopes of canals bottoms were identical in each concept.

The data presented in Tables 1 and 2 are the results of simulation from hydrodynamic modelling [1]. They present that the value of the maximum rainwater outflow from the outlet node in innovative system $Qo_{Imax}$ is lower than $Qo_{Tmax}$ in the classic stormwater sewer system in each case.

The results of the research presented in Tables 1 and 2 confirm that with an increase of the slope of the canal bottom $i_k$, the critical time for dimensioning the traditional sewerage system $t_m$ decreases. It simultaneously causes that the rainwater outflow at the outlet node $Qo_{Tmax}$ increases. The canal slope $i_k$ affects directly the retention capacity of the innovative system. The rainwater retention effects of the system increase as the slope decreases. This is why the higher canals slope $i_k$, the higher flow velocity of rainwater in the sewage $v_{TK.,}$ so that the rainwater is transported faster towards the outlet node and the flow time $t_p$ in the sewer decreases.

**Table 3:** A comparison of rainwater outflow from traditional and innovative sewer system taking into account different variants of their working.

| **Ratio of maximum rainwater outflow traditional to innovative system, at various slope of canals bottom $i_k$ and damming baffles spacing $_{i_k}R$** | | | |
|---|---|---|---|
| $i_k = 1$ ‰ | $i_k = 2$ ‰ | $i_k = 3$ ‰ | $L_{KR}$, m |
| 2.9 | 2.1 | 1.7 | $L_{KR1} = 200$ m |
| 2.7 | 1.7 | 1.4 | $L_{KR2} = 300$ m |
| 2.5 | 1.6 | 1.3 | $L_{KR3} = 400$ m |

Changes of the canal slopes $i_k$ affect the value of maximum rainwater outflow both in the classic sewage $Qo_{Tmax}$ and in the innovative sewage $Qo_{Imax}$. This relation is shown in Fig. 7, and takes into account different spacing damming baffles $L_{KR}$.

In the case of traditional sewerage system for slope of canals $i_k = 1$‰, the maximum rainwater outflow from the sewage is $Qo_{Tmax} = 2887.7$ dm³/s. However, for slope $i_k = 2$‰ the outflow is $Qo_{Tmax} = 3692.8$ dm³/s, for slope $i_k = 3$‰ outflow intensity increases almost 1.5 times to the value $Qo_{Tmax} = 4175.9$ dm³/s.

For example, considering an innovative system for the slope of bottom $i_k = 1$ ‰ and damming barriers spacing $L_{KR1} = 200$ m, it is possible to obtain an almost threefold reduction of flow from the value $Qo_{Tmax} = 2887.7$ dm³/s to $Qo_{Imax} = 981.6$ dm³/s. For $L_{KR2} = 300$ m, the flow is reduced by 2.7 times (the outflow rate is 1063.4 dm³/s). For $L_{KR3} = 400$ m, the outflow is almost reduced by 2.5 times ($Qo_{Imax} = 1159.6$ dm³/s) compared to the traditional storm sewer.

The results of the simulation showed that the spacing of damming baffles measurably affected the rainwater flow reduction from the drainage catchment's outflow. The flow reduction effects increase according to the decreasing slopes of the canals $i_k$ and to the decreasing damming baffle spacing $L_{KR}$.

Table 3 presents the multiplicity of rainwater outflow reduction in the innovative rainwater system depending on the spacing of damming partitions for distance $L_{KR1} = 200$ m, $L_{KR2} = 300$ m i $L_{KR3} = 400$ m and bottom slopes $i_k = 1$ ‰, $i_k = 2$ ‰ i $i_k = 3$ ‰.

The above results show that after applying damming partitions in a traditional sewerage system for the slope $i_k = 1$ ‰, the flow from the outlet decreases by more than two times in almost all cases and by almost three times in some cases. In sewerage system for the slope $i_k = 2$ ‰, there is a smaller reduction of the flow, around from 2.2 to1.6 times less. In sewerage system for a slope $i_k = 3$ ‰, the flow reduction was less than 2 times in every case.

Hydrograms are often used in order to reflect the reversibility of rainwater flow in the canal [2]. A comparison of rainwater outflow variability from a traditional and innovative system with retention canal system at time $t$ was based on the hydrogram shown in Figure 8.

In the case of classical stormwater systems, the hydrogram has an unfavorable pointed shape. The use of damming partitions causes that the peak rainwater outflow intensity at the outlet node is significantly reduced and the shape of the hydrogram flattens. For a smaller distance between damming baffles, the hydrogram flattens more. The studies [1] have confirmed that spacing of damming partitions $L_{KR}$ impact on the value of the parameter $Qo_{Imax}$ independent of the considered time $t$. The smaller damming spacing, the greater the reduction of outflow $Qo_{Imax}$ from the innovative system.

Figure 9 shows the relationship between the critical time for rainwater sewage system dimensioning $t_m$ and the critical time for innovative rainwater sewage system dimensioning $t_M$. Different damming baffles spacing $L_{KR}$ was also considered for the innovative sewer system. Establishing the correct value of rain duration gives the basis for its dimensioning. However, in practice it turns out to be a very difficult task to solve because of complexity of studied phenomena [33].

As shown by the curves in Figure 9, the change of canals slope $i_k$ directly affects the determined value of critical time for dimensioning both the traditional and the innovative system. In both systems, an increase of canal slope $i_k$ results in a decrease of critical time for dimensioning sewage systems. As the spacing of the damming baffles $L_{KR}$ shortens, the value of the critical time $t_M$ increases. Many factors, especially parameters characterizing the drainage catchment impact on the value of critical ran duration. The biggest differences between the critical time for rainwater sewage system dimensioning $t_m$ and the critical time for innovative rainwater sewage system dimensioning $t_M$ occur at slopes $i_k = 1$‰.

Table 4 summarizes the values of the critical rain duration times $t_m$ and $t_M$ considering different slopes of the sewer canals $i_k$ and the spacing baffles $L_{KR}$. For instance, in a traditional sewerage system with a slope $i_k = 1$ ‰, the critical rainfall duration hits the $t_m = 32$ min. After equipping this sewage with damming partitions with $L_{KR1} = 200$ m, the critical $t_{M.}$ hit 88 min. It shows a difference of $\Delta T = 56$ min and is the highest recorded $\Delta T$ difference among all the considered design variants. For $L_{KR2} = 300$ m spacing, the value of $\Delta T = 52$ min and for $L_{KR3} = 400$ m spacing, the value of $\Delta T = 46$ min. This results in an important conclusion related to the damming partitions spacing $L_{KR}$. An increase of the spacing between baffles

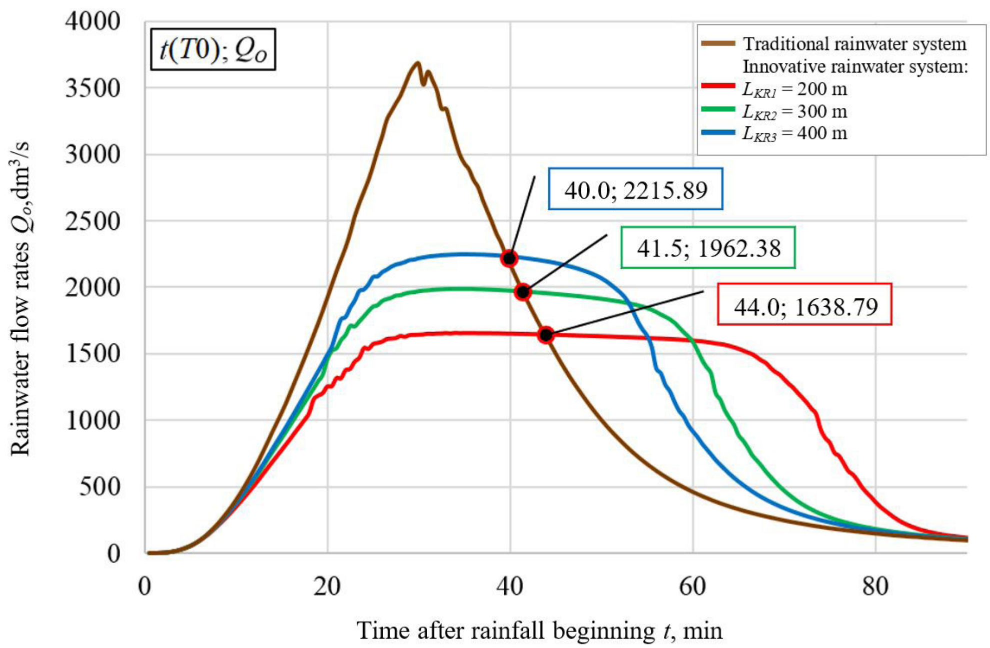


**Figure 8:** Hydrograms of rainwater outflow from the traditional and innovative sewer system at rainfall duration $t_d$ = 25 minutes, drainage catchment area $F$ = 80 ha, canal bottom slope $i_k$ = 2 ‰ and surface runoff coefficient Ψ = 0,5 [1].

**Table 4:** Comparison of calculative time $t_m$ and $t_M$ for different variants of sewer system working.

| The slope of canals bottom | Calculative time for rainwater sewage system dimensioning | Calculative time for innovative rainwater sewage system dimensioning | The difference between the calculative duration of rainfall for the dimensioning of the traditional rainwater system $t_m$ and the sewage equipped with a retention canals system $t_M$ $\Delta T = t_M - t_m$ | Damming baffles spacing |
|---|---|---|---|---|
| $i_k$, ‰ | $t_m$, min | $t_M$, min | $\Delta T$, min | $L_{KR}$, m |
| 1 | 32 | 88 | 56 | $L_{KR1}$ = 200 m |
| 1 | 32 | 84 | 52 | $L_{KR2}$ = 300 m |
| 1 | 32 | 78 | 46 | $L_{KR3}$ = 400 m |
| 2 | 26 | 56 | 30 | $L_{KR1}$ = 200 m |
| 2 | 26 | 46 | 20 | $L_{KR2}$ = 300 m |
| 2 | 26 | 42 | 16 | $L_{KR3}$ = 400 m |
| 3 | 25 | 40 | 15 | $L_{KR1}$ = 200 m |
| 3 | 25 | 34 | 9 | $L_{KR2}$ = 300 m |
| 3 | 25 | 30 | 5 | $L_{KR3}$ = 400 m |

in the retention canal system brings the $t_M$ values closer to the critical time for dimensioning the canals of the traditional system $t_m$.

The smallest differences between the times $t_M$ and $t_m$ occur for the sewage with $i_k$ = 3‰ and spacing of damming baffles $L_{KR3}$ = 400 m.

The dependence between the values of the determinate time for the dimensioning of the traditional rainwater system $t_M$ and the determinate time for the dimensioning of the retention canals system $t_M$ is described by the coefficient of the determinate times $\gamma_{TM}$ [1] by the following formula (2):

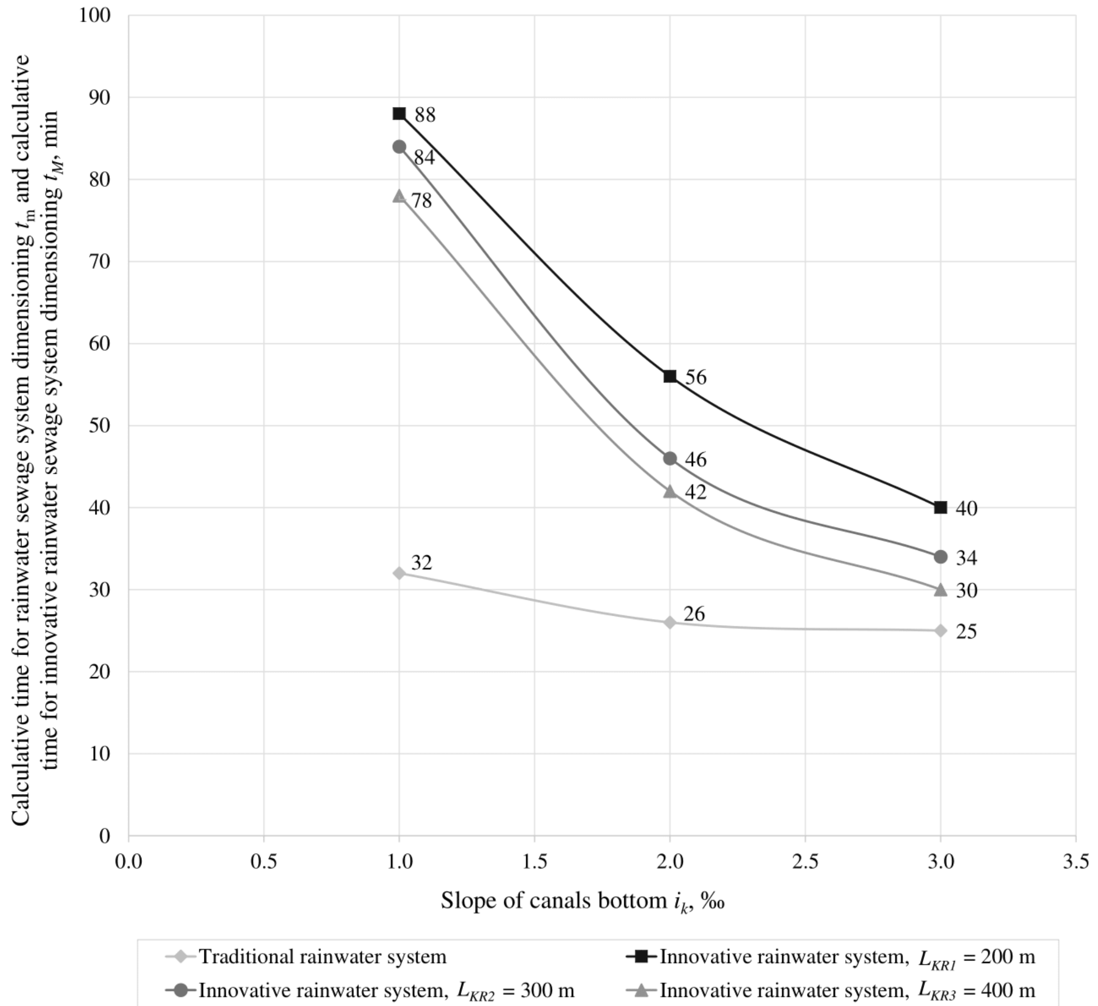


**Figure 9:** Calculative time for rainwater sewage system dimensioning $t_m$ and calculative time for innovative rainwater sewage system dimensioning $t_M$ (based on [1]).

$$\gamma_{TM} = \frac{t_M}{t_m} \tag{2}$$

where: $t_M$ - duration of the maximal (critical) rainfall determined for innovative rainwater sewage system dimensioning, min; $t_m$ - duration of the maximal (critical) rainfall determined for traditional rainwater sewage system dimensioning, min.

The relationship between the coefficient $\gamma_{TM}$ and the sewer slope $i_k$ and the spacing of damming baffles $L_{KR}$ is shown in Figure 10. The results confirm the rule that the value of the coefficient $\gamma_{TM}$ is always larger than 1. This proves that the critical time for the dimensioning of retention sewer systems $t_M$ is always larger than the critical time for the dimensioning of traditional rainwater sewage system $t_m$.

The value of coefficient $\gamma_{TM}$ decreases with increasing canal slopes $i_k$ and increasing distance between damming partitions $L_{KR}$. The biggest values of the coefficient $\gamma_{TM}$ were determined for the canals slopes $i_k$ = 1 ‰ and they are $\gamma_{TM} > 2$.

The sewage flow reduction coefficient is another important parameter which characterizes the work of innovative rainwater system. This coefficient plays a key role to determine the usable capacity of the retention tank [2, 5, 6]. Its value depends on an inflow and outflow rate. The larger the volume of rainwater necessary for retention, the smaller the value of the $\beta$ coefficient. The value of coefficient $\beta$ is greater than zero and less than unity for the classical sewage working with a retention reservoir [2, 5, 18]. In order to determine the reduction of the rainwater flow in the innovative rainwater sewage equipped with

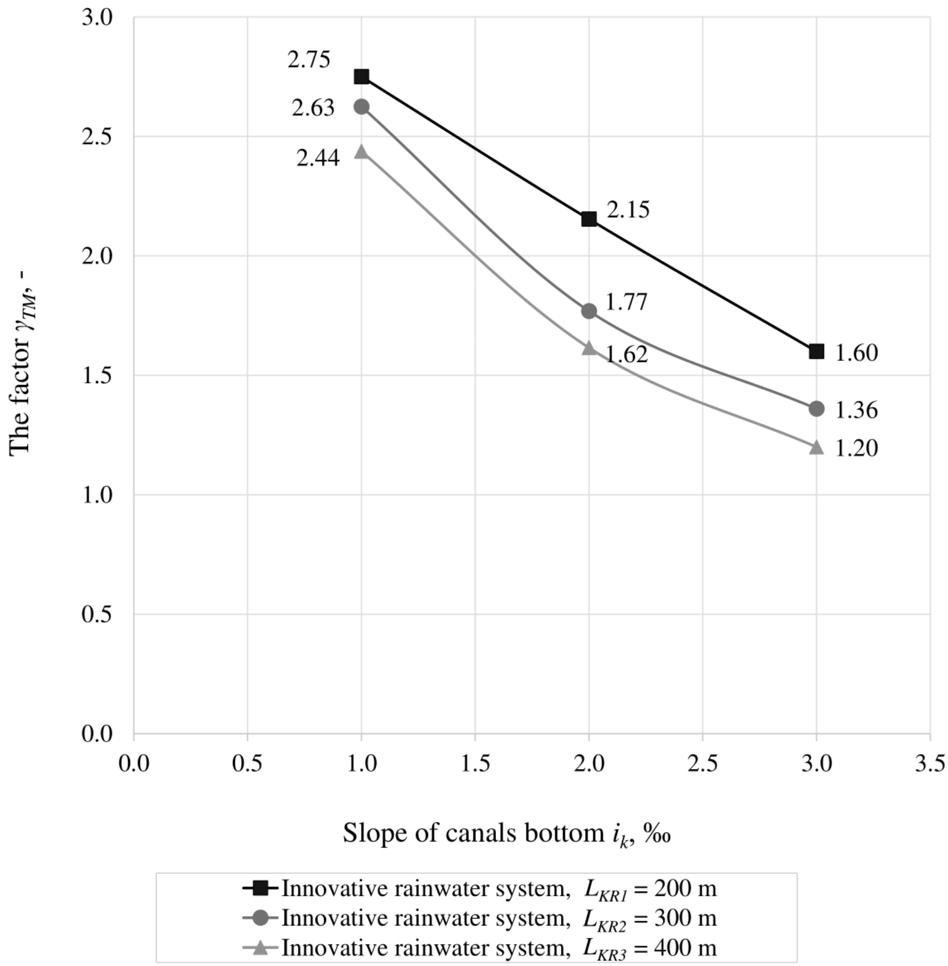


**Figure 10:** Values of the coefficient of $\gamma_{TM}$ depending on the sewer slope $i_k$ and spacing of damming partitions $L_{KR}$ (based on [1]).

the retention canal system, the rainwater flow reduction coefficient $\beta_{KR}$ was found. The value of coefficient $\beta_{KR}$ is ratio of the critical rainwater outflow intensity $Qo_{Imax}$ to $Qo_{Tmax}$. It is determined by the following relation (3):

$$\beta_{KR} = \frac{Qo_{Imax}}{Qo_{Tmax}} \quad (3)$$

where: $Qo_{Tmax}$ - maximum value of rainwater outflow from the traditional rainwater sewer at outlet node, dm$^3$/s; $Qo_{Imax}$ - maximum value of rainwater outflow from the innovative rainwater sewer at outlet node, dm$^3$/s.

It can be confirmed that the use of retention canals provides the expected flow reduction by determining the value of the rainwater flow reduction coefficient in the innovative sewer system $\beta_{KR}$. The smaller the value of coefficient $\beta_{KR}$, the greater the effects of rainwater retention in the sewage with retention canals system. When classic storm water sewage system is designed, the value of coefficient $\beta$ is determined at the initiation stage. This value affects the required volume of retention tanks [2, 5]. However, in the case of the innovative rainwater system, the value of the rainwater flow reduction coefficient $\beta_{KR}$ is not determined at the design stage, but it is the resulting value. It is calculated on the grounds of formulated procedure at the final stage of simulation calculations conducted as part of hydrodynamic modelling.

The effect of slope of canals bottom $i_k$ and damming partitions spacing $L_{KR}$ on the value of reduction coefficient $\beta_{KR}$ is shown in Fig. 11. The value of this coefficient increases with a growth of the sewer slope $i_k$. This is because the velocity of rainwater flow through the sewage increases and rainwater is retained in the sewage system for shorter time. The retention capacity of the sewage system decreases. Another parameter that affects the value of the reduction coefficient $\beta_{KR}$ is the damming partitions spacing $L_{KR}$. The larger the damming baffles spacing $L_{KR}$,

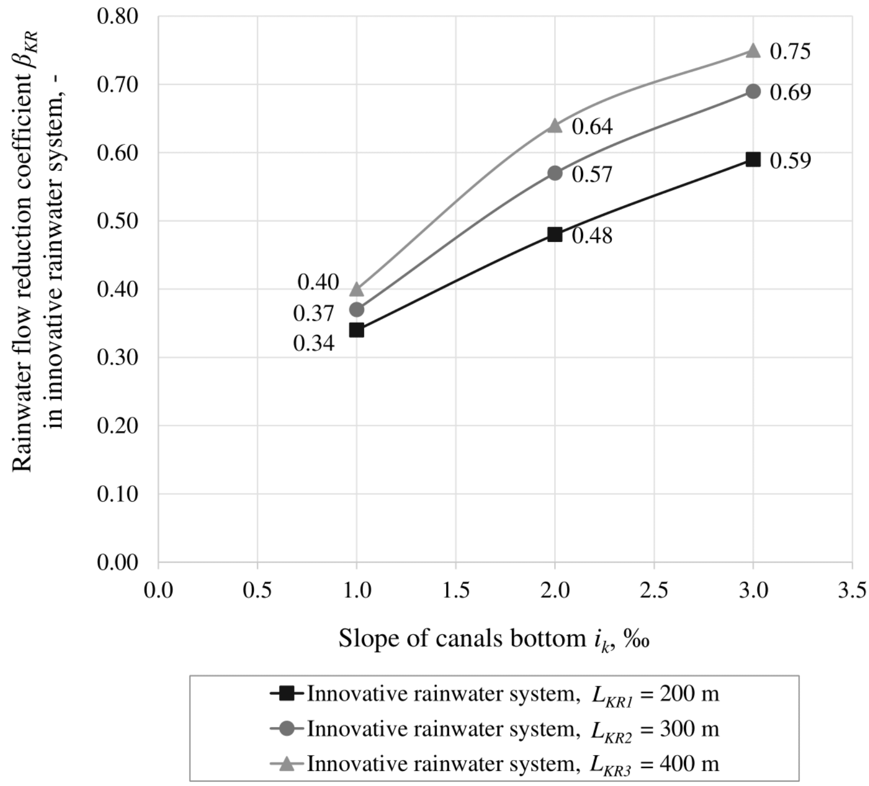


**Figure 11:** Rainwater flow reduction coefficient $\beta_{KR}$ in innovative rainwater system for different slopes of canals $i_k$ and damming baffle spacing $L_{KR}$ (based on [1]).

the smaller the retention capacity of the sewage system and the value of the $\beta_{KR}$ coefficient is larger. On the ground of Figure 11 it can be ascertained that the largest differences between the values of $\beta_{KR}$ coefficient are obtained when the slope of the canals bottom $i_k$ is changed. Considering the constant damming baffle spacing $L_{KR}$ and taking into account the change of canals slope $i_k$, the largest differences $\beta_{KR}$ coefficient were recorded at spacing $L_{KR}$ = 400 m. For instance, by reducing the canal slope from ik = 3‰ (for which the reduction coefficient $\beta_{KR}$ = 0.75) to $i_k$= 1‰ ($\beta_{KR}$ = 0.40), it was possible to obtain the value of the coefficient $\beta_{KR}$ as low as 0.35. For changing the canal slope from the value $i_k$ = 3 ‰ to $i_k$ = 2 ‰ ($\beta_{KR}$ = 0.64), the difference between the reduction coefficients was 0.11. On the other hand, decreasing the canals slope from $i_k$ = 2 ‰ to $i_k$ = 1 ‰, the reduction coefficient was lower by as much as 0.24 was achieved. These results indicate that even with significant spacing of damming baffles $L_{KR}$, the use of retention rainwater canals for sewage with low slope of canals bottom $i_k$ is fully justified.

In the case of decreasing the distance between the damming partitions $L_{KR}$ and keeping the constant slope of canals $i_k$, the desired decrease of the value of flow reduction coefficient $\beta_{KR}$ can be obtained. By reducing the distance between the damming baffles from $L_{KR3}$ = 400 m to $L_{KR1}$ = 200 m for the sewage system with a slope ik = 1‰, $\beta_{KR}$ that was lesser by 0.06 was obtained. For the sewage system with slope $i_k$ = 2 ‰, this difference is 0.16 and in the case of the sewage system with slope $i_k$ = 3‰, the value of the reduction factor $\beta_{KR}$ less by 0.16 was obtained. The key issue is the choice of an optimal solution [6]. Therefore, it is necessary to consider that the use of a smaller damming partitions spacing is justified and it provides the expected effect of reducing the rainwater flow. The studies have confirmed that each solution should be individually analyzed, both economically and ecologically. For example, for the variant with the slope of sewage canals $i_k$ = 1 ‰ and the damming partitions were localized at $L_{KR3}$ = 400 m, the flow reduction coefficient was $\beta_{KR}$ = 0.40. When reducing the spacing by 100 m, the flow reduction was determined to the value $\beta_{KR}$ = 0.37.

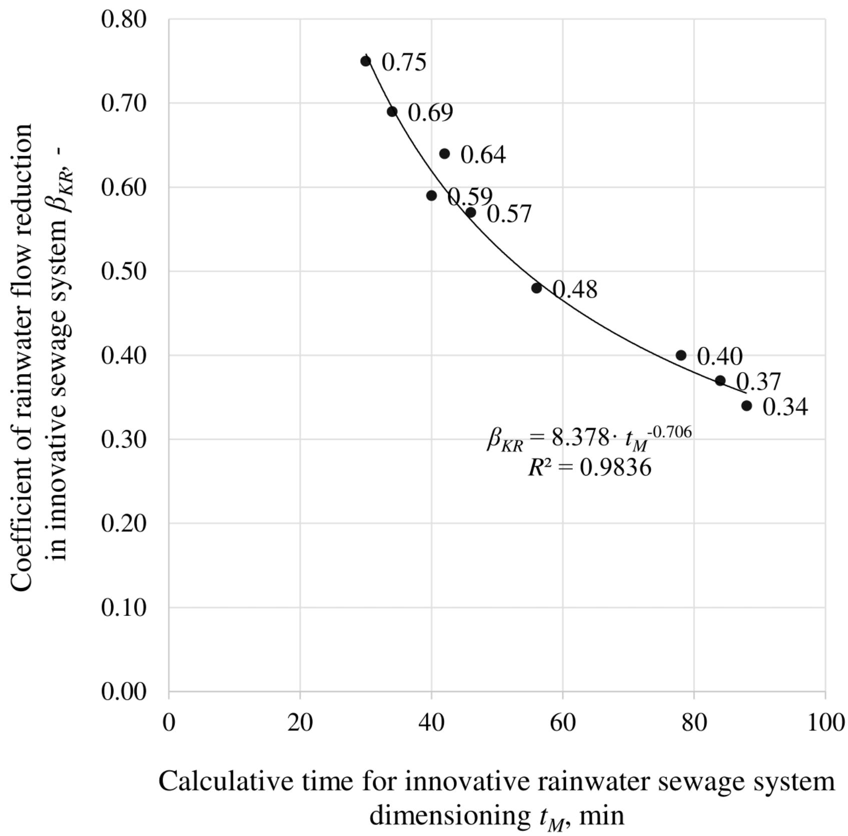


**Figure 12:** The relationship between the rainwater flow reduction coefficient $\beta_{KR}$ and the critical time $t_M$ (based on [1]).

However, on reducing the spacing by 200 m, the value of $\beta_{KR}$ coefficient was 0.34. In this case, increase in the density of the damming partition spacing causes a slight flow reduction. Considering the variant for the slope $i_k$ = 2 ‰ and $L_{KR3}$ = 400 m whose $\beta_{KR}$ = 0.64, decreasing the spacing by 100 m causes a decline of the value of this coefficient by 0.07. In the case of decreasing the spacing by 200 m, the coefficient $\beta_{KR}$ is already smaller by 0.16. In this situation, changing the spacing of the baffles affects the value of the outflow reduction coefficient more than in the previous variants. As the results for some variants show, the effect of rainwater flow reduction using close partitions spacing is the same as for larger spacing or slightly more beneficial. Therefore, it is recommended to consider the economic costs which come from the implementation and subsequent exploitation of the innovative system.

The study [2] demonstrates that there is a close relationship between the rainwater flow reduction coefficient $\beta$ and the critical time for multi-chamber tanks dimensioning $T_{MW}$ in the traditional rainwater sewage system. The work [1] showed that there was a close relationship between the rainwater flow reduction coefficient $\beta_{KR}$ in the innovative rainwater system and the critical time for innovative rainwater sewage system dimensioning $t_M$. This phenome is shown by the curve in Figure 12.

This relationship was formulated based on the pairs of results for all variants presented earlier in Table 2, including the calculative time for the innovative rainwater sewage system dimensioning $t_M$ and the corresponding rainfall flow reduction coefficient $\beta_{KR}$. Based on this, trend lines were created and the equation describing this relationship was determined. To conclude one can say that there is a close relationship between the time $t_M$ and the reduction coefficient $\beta_{KR}$. The results are well fitted to the curve as evidenced by the high value of the coefficient of determination $R^2 = 0.9836$. The studies [1] have shown that for specific design conditions, it is possible to establish an unambiguous curve of the relationship between the critical time $t_M$ and the reduction factor $\beta_{KR}$.

## 7 Summary and final conclusions

The paper presents possibilities of rainwater outflow control in an innovative rainwater system using the canal retention. The hydraulic functioning of the traditional rainwater sewage and the innovative rainwater sewage after equipping it with a retention canal system were compared. A total of 9 different functioning variants of the innovative rainwater system were analyzed. Each variant of the innovative system with damming baffles showed more favorable hydraulic conditions than in the case of an identical traditional system.

On the basis of simulation studies and an analysis carried out on the model urban catchment, a number of important conclusions of cognitive and application significance can be formulated.

1. The value of the maximum rainwater outflow at the outlet node from the innovative rainwater system $Qo_{Imax}$ is always lower than the value of the maximum rainwater outflow from the identical traditional sewer system $Qo_{Tmax}$.
2. Equipping the innovative system with damming partitions enables effective use of the sewage system capacity. This, in turn, reduces the rainwater outflow $Qo_{Imax}$ at the outlet node.
3. The slope of the canal bottom $i_k$ and damming partitions spacing $L_{KR}$ influence the value of the maximum rainwater outflow $Qo_{Imax}$ at the outlet node of the innovative rainwater system.
4. An increase of the rainwater outflow flow from the sewage outlet $Qo_{Imax}$ with a growth of the canal slope $i_k$ occurs regardless of the established damming partitions spacing $L_{KR}$. A decrease of the rainwater outflow flow from the sewage outlet $Qo_{Imax}$ of the canal slope $i_k$ occurs regardless of the established damming partitions spacing $L_{KR}$ by analogy.
5. Equipping the sewerage system with a system of retention canals allows beneficial flattening of rainwater outflow hydrogram. It has affect on the reduction of the required capacity of retention reservoirs cooperating with the sewerage system.
6. The critical rainfall time for the retention canals dimensioning operating in the innovative system $t_M$ is always greater than the critical rainfall time for the traditional sewer system dimensioning $t_m$.
7. The value of the coefficient of the critical times $\gamma_{TM}$ is always greater than the 1.0. It confirms the occurrence of the rainwater retention phenomenon in the retention canals of the innovative rainwater system.

On the basis of the analysis carried out, it was concluded that the key parameter in the innovative rainwater system is the slope of the canal bottom $i_k$ and the spacing between the damming partitions $L_{KR.}$ A properly designed sewage with damming partitions allows full utilization of the sewage capacity and flow reduction, replacing cubature objects. This solution can be successfully applied in new and existing sewerage systems instead of assigning new land for construction of, for example, retention reservoirs. An innovative rainwater system provides an efficient rainwater management and prevention of urban flooding. It can become a breakthrough, as well as a simple and effective solution to solve the problems associated with rainwater management.

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