Abstract: This article is aimed at defining the impact of the direction and velocity of waves of rainfall as they pass over interconnected stormwater detention tank systems. The simulations were conducted for a real urban catchment area as part of the Storm Water Management Model (SWMM) 5.1 programme. The results permit us to conclude that the direction and velocity of a moving wave of rainfall have a significant influence on the required volumes of interconnected stormwater detention tank systems. By comparing the modelling test results for stationary rainfall and rainfall moving over the urban catchment area, it has been demonstrated that differences in the required volume of the detention tank located at the terminal section of a stormwater drainage system are inversely proportional to the adopted value of the diameter of the outfall channel for upstream storage reservoirs. In extreme cases, the differences may be up to several dozen percentage points. Furthermore, it has been proven that the arrangement of the stormwater detention tanks in relation to one another and the adopted diameter of the outfall channel are key factors in identifying the degree to which the detention tanks are hydraulically dependent on one another.

Keywords: direction and wave of rainfall; detention tank; stormwater drainage system; urban environmental engineering

1. Introduction

In recent years, we have observed an increased frequency of extreme weather events, notably cloudbursts and long-term intensive rainfalls. Their occurrence results in the hydraulic overload of stormwater drainage system and the devices integrated within it. Local inundations, which are now happening more frequently than before, require increasing costs related to damage limitation. The issues at hand compel us to question the usefulness of the previously applied methodology for designing stormwater drainage systems and the usefulness of the assumptions made for such systems [1–3].

Sewage systems are among the most expensive and the most difficult to implement, especially when operating in a gravity system [4,5]. The most capital-intensive type of sewage system is the stormwater drainage system. In order to improve their operation, for many years, they have been equipped with various types of detention tanks [6,7]. However, it should be remembered that the choice of the appropriate project option should be supported by the analysis of many indicators [8,9], including in particular a technical and financial analysis [10–12], as well as an environmental analysis [13–15], taking into account the lifespan of the investment [16].

For the most part, according to the calculation methodology in common use, it is assumed that any rainfall is inherently static. In other words, it has neither speed nor direction. All hydrodynamic
calculations are, therefore, oversimplified, because, according to the methodology, one rainfall can be assigned to all sub-catchments distinguished within one catchment. However, this oversimplification is not reflected by the actual conditions as the intensities of rainfall vary as far as their spatial distribution is concerned [17–21]. Moreover, actual rainfalls have movement, direction, and speed [22,23]. In practice, any rainfall event will first occur in one sub-catchment section and then will successively include other sections of the catchment.

As demonstrated in earlier studies [24–26], the assumption that a rainfall event can be dynamic yields much higher peak stormwater flow rates in all drainage systems. Differences between static and dynamic rainfalls depend on a variety of factors, especially the direction of the stormwater run-off in a catchment, the shape of the catchment, and the velocity at and direction in which the rainfall moves. Catchments where flow differences are the greatest, taking the rainfall direction and speed into account, appear to be those with elongated shapes and single main stormwater run-off directions.

Stormwater detention tanks have recently become a staple of all modern stormwater drainage systems where their operation is based on the gravitational principle [27,28]. Thanks to their locations, they can serve various functions. Their application at the terminal section of a new catchment enables the basin’s connection to the earlier elements of the stormwater drainage systems without either overloading the system hydraulically or forcing the authorities to extend it [29,30].

Irrespective of the location and function served in the system, the main task of a detention tank is hydraulic relief and the accumulation of excess stormwater. With this end in mind, we can estimate its required volume based on the stormwater balance at the inlet and outlet while filling the tank [31,32]. The volume is a function of the area between specific curves plotted in hydrographs to illustrate the intensity of stormwater inflow and outflow from the detention tank in the course of a critical rainfall event. By and large, the inflow curve is plotted for a synthetic rainfall, characterised by a uniform intensity throughout [33,34]. Further, it is assumed that a rainfall event begins and ends at the same time over the entire basin. This assumption is often caused by the lack of reliable data on actual rainfall events. By including the rainfall direction and velocity, it directly alters the stormwater run-off curve for the drainage catchment. In many cases, when the direction and speed fulfil specific requirements, the curve plotted for the stormwater run-off from the catchment proves more critical than under static conditions.

More often than not, a drainage system will have several storage reservoirs. While calculating their useable volumes, it is necessary to acknowledge how the detention tanks affect one another. The required volume of each detention tank is calculated for an individual critical rainfall event duration [6,27]. This is necessitated by the distinctive character of the assigned drainage catchment, but it also stems from the adopted design parameters. The development of detention tank systems is a much more complex task; those tanks located the furthest upstream might be designed in the same way as a single tank, while those located downstream require a different approach. If the detention tank(s) is/are located along the upper reaches of the drainage catchment, then the curve indicating the stormwater run-off will be different from an arrangement without any retention structures. One important parameter that decisively influences the useable volumes of the detention tanks located downstream is the diameter of the outfall channel for the upstream reservoirs, as well as their hydraulic systems. Therefore, while designing detention tank systems, a specific modus operandi should be followed, beginning with the most upstream tanks, and finishing with the most downstream tanks. The run-off direction of the stormwater drainage system also needs to be taken into account.

The aim of the papers is to determine the degree of impact of rainfall velocity and direction on the functioning of the multi-chamber detention tanks operating in the gravitational stormwater drainage system.

2. Materials and Methods

The simulations were based on a hydrodynamic model of the real urban catchment area, which is located in Poland (Figure 1), using the Storm Water Management Model (SWMM) 5.1 programme.
The drainage catchment adopted for research is equipped with a stormwater drainage system, for which cooperation with three multi-chamber detention tanks was planned. Because of the location of detention tanks, the established catchment could be divided into three smaller drainage catchments. Catchment I, which is characterized by the largest area, is located between three adopted detention tanks. Catchment II and III are located above two designed detention tanks, DT1 and DT2. The stormwater drainage system consisted of 289 sections, from 36 to 74 m in length. The slope of the interceptors in the sewer network varied between 1.4% and 7.8‰. The total area of the drainage basin amounted to 156.95 ha. The surface run-off coefficient was in the range of 0.02 to 0.62. The total area of the reduced catchment was equal to 48.66 ha.

Figure 1. The stormwater drainage system and the location of multi-chamber detention tanks.

In order to calculate the unit rainfall intensity, the Bogdanowicz and Stachy (1) formula was applied [35]. It defines the correlations between rain intensity and duration:

\[ h_{max} = 1.42t_d^{0.33} + \alpha(R,t_d) \times (-\ln p)^{0.584} \] (1)

where \( h_{max} \) is a maximum total amount of rainfall of a predetermined duration \( t_d \) and the probability of exceeding this total \( p \), in mm; \( \alpha \) is a parameter (scale) depending on the region of Poland and duration of the rainfall \( t_d \); \( p \) is a probability of an increase in rainfall: \( p \in (0;1] \); and \( R \) is a region of Poland.

For the purpose of this simulation, the occurrence probability of precipitation was \( p = 0.5 \). The rainfall intensity estimated according to Bogdanowicz and Stachy formula referred to block rainfalls with a uniform intensity throughout. Figure 2 shows the IDF curve determined on the basis of Formula (1).

Figure 2. The IDF curve determined on the basis of the Bogdanowicz and Stachy formula.
The rainfall movement effect was simulated by assigning an individual rain file to each sub-basin in the SWMM 5.1 programme (Figure 3).

Adopting various precipitation start times in the particular sub-catchment permitted us to simulate the rainfall movement over the catchment area. The wave movement speed value defines the differences between the rainfall start times for the specific locations (sub-catchments). The simulations were carried out for a wave movement speed that would remain constant throughout. Three values were adopted for the velocity of the rainfall movement, namely, 3, 6, and 12 m·s⁻¹. To evaluate which direction would yield the most critical (maximum) values, the wave velocity range was extended by 1.5, 2, and 4 m·s⁻¹. The rainfall event that began over the entire basin was assigned an infinitely large speed, \( v = \infty \text{ m·s}^{-1} \). The rainfall velocities adopted in the studies correspond to the values that occur in reality [22].

For the purpose of this analysis, it was also assumed that the rainfall movement direction was constant throughout the simulation cycle. Moreover, it was assumed that the rainfall front might be presented as a straight line perpendicular to the rainfall movement direction. In practice, the rain started at the same moment at all the points on the lines perpendicular to the adopted movement direction. During the simulation, four main movement directions were considered, namely, east–west (E–W), west–east (W–E), north–south (N–S), and south–north (S–N).

The hydraulic systems of the examined multi-chamber detention tanks were emulated in the SWMM 5.1 programme by the use of two single-chamber tanks (storage node module). One tank served as a flow-through chamber \( KP \), whereas the second one served as an accumulation chamber \( KA \). Stormwater transport \( Q_C \) from the flow-through chamber \( KP \) to the accumulation chamber \( KA \) is defined by the function \( Outlet \), whereas the stormwater outflow \( Q_D \) from the accumulation chamber is defined by the function \( Weir \). The stormwater outflow \( Q_D \) from the accumulation chamber \( KA \) occurred when the stormwater level in this chamber was higher than in the flow-through one \( KP \). The scheme of the adopted hydraulic system of the multi-chamber detention tank is shown in Figure 4.
In the case of detention tank DT3, the simulations were conducted for three various outflow channel diameters: 0.5, 0.65, and 0.8 m, which translates into three different values for the intensity of stormwater outflow \(Q_o\) from the tanks. The larger the diameter of the outflow channel, the larger the \(Q_o\) parameter value. Similar assumptions apply to detention tanks DT1 and DT2. However, the outflow channel \(D_o\) has the diameters 0.3, 0.5, and 0.7 m, while the outflow channels of tanks DT1 and DT2 have constant diameters. With such assumptions in mind, nine options were analysed in detail.

3. Results and Discussion

The calculations confirm that, aside from rain intensity and duration, another aspect that also has a significant impact on the maximum value of the peak stormwater flow rate \(Q_A\) in the sewers network is the velocity of the rainfall event, and especially the direction in which the wave of rain moves. The values and differences estimated for adopted stormwater drainage can be found in Table 1. By and large, the slower the rainfall moved in the main direction of the stormwater flow in the stormwater drainage, the higher the registered maximum critical flow rate \(Q_A\). It ought to be noted that this condition applies only up to a certain extent \((v = 2 \text{ m·s}^{-1})\); as the wave movement velocity continues to decrease, the peak stormwater flow rate \(Q_A\) also decreases. This correlation stems from the fact that the stormwater run-off time along the stormwater drainage is shorter than the duration of the wave of rainfall. In practical terms, stormwater drained from the initial sub-catchments will reach the terminal stormwater drainage cross-section (in the analyzed case, detention tanks) before the rainfalls over the sub-catchments are assigned to the terminal sections. Hence, the short-term peak flow rates from all the sub-catchments will not overlap, and as a result, the flow rate \(Q_A\) in the analysed cross-section is smaller.

Table 1. Maximum peak flow of stormwater \(Q_A\) for the storage reservoir at the assumed variants.

| Detention Tank DT3 | Static Conditions \(v = \infty \text{ m·s}^{-1}\) | Dynamic Conditions |
|--------------------|---------------------------------|------------------|
| \(D_o\) for DT1 and DT2 | \(Q_A\) \(t_d\) | \(Q_A\) \(t_d\) \(K\) \(v\) \(R_v\) |
| \(D_o\) | [dm\(^3\)·s\(^{-1}\)] | [min] | [dm\(^3\)·s\(^{-1}\)] | [min] | [-] | [m·s\(^{-1}\)] | [%] |
| 0.7 | 3987.87 | 20.0 | 5189.66 | 10.0 | W–E | 2.0 | 30.14 |
| 0.5 | 3305.39 | 20.0 | 4552.83 | 10.0 | W–E | 2.0 | 37.74 |
| 0.3 | 2757.19 | 20.0 | 4023.02 | 10.0 | W–E | 2.0 | 45.91 |

| Minimum peak stormwater flow rates \(Q_A\) |
|---------------------------------|
| \(D_o\) | \(Q_A\) \(t_d\) | \(Q_A\) \(t_d\) \(K\) \(v\) \(R_v\) |
| 0.7 | 3987.87 | 20.0 | 3281.85 | 30.0 | E–W | 3.0 | −17.70 |
| 0.5 | 3305.39 | 20.0 | 2646.67 | 27.0 | E–W | 3.0 | −19.93 |
| 0.3 | 2757.19 | 20.0 | 2239.36 | 25.0 | E–W | 3.0 | −18.78 |

| Detention tank DT1 |
|------------------|
| Maximum peak stormwater flow rates \(Q_A\) |
| 1983.86 | 10.0 |
| Minimum peak stormwater flow rates \(Q_A\) |
| 1983.86 | 10.0 |

| Detention tank DT2 |
|------------------|
| Maximum peak stormwater flow rates \(Q_A\) |
| 1486.25 | 14.0 |
| Minimum peak stormwater flow rates \(Q_A\) |

* \(D_o\)—diameters of the outflow channels for tanks DT1 and DT2, m; \(Q_A\)—stormwater inflow rate, dm\(^3\)·s\(^{-1}\); \(t_d\)—rainfall duration, min; \(K\)—flowing direction of the wave of rainfall; \(v\)—flowing velocity of the wave of rainfall, m·s\(^{-1}\); \(R_v\)—percentage difference between the static and dynamic conditions.
Figure 5 shows the hydrographs illustrating the stream of stormwater $Q_A$ supplied to detention tanks $DT1$, $DT2$, and $DT3$ during the adopted rainfall event for specific directions and velocities.

![Hydrographs](image)

**Figure 5.** (a) Hydrographs of the stormwater flow rate $Q_A$ for tank $DT1$ at the specific duration of rainfall $td = 10$ min, (b) hydrographs of the stormwater flow rate $Q_A$ for tank $DT2$ at the specific duration of rainfall $td = 10$ min, (c) hydrographs of the stormwater flow rate $Q_A$ for tank $DT3$ at the specific duration of rainfall $td = 10$ min and diameter of the outflow channels from tanks $DT1$ and $DT2$ equal $Do = 0.3$ m.
Minimum values of the stormwater peak flow rate $Q_A$ were registered during a rainfall event moving in the opposite direction, from east to west. As the velocity of the wave of rainfall decreased, the registered peak value of the stormwater flow rate $Q_A$ also decreased. The lowest value was registered at the lowest adopted rainfall movement speed ($v = 3 \text{ m} \cdot \text{s}^{-1}$).

The study also demonstrated that the duration of the rainfall yielding the maximum peak flow rate $Q_A$ is affected by the rainfall velocity and movement direction. As long as the wave directions are similar to the stormwater run-off in the stormwater drainage system, the maximum value of the peak stormwater stream $Q_A$ observed during rainfall events is shorter than those falling under the static conditions. For example, for a $DT2$ tank, it was observed that the duration of a rainfall event yielding a critical concentration time $Q_A$ shortened from 14.0 to 10.0 min. Given that the directions are opposite, the duration of a critical rainfall lengthens. As for the movement from east to west, the maximum peak value of the stormwater flow $Q_A$ is elicited by a block hyetograph with a duration of 22 min.

As the data in Table 1 show, the estimated differences in the flow rates $Q_A$ in the stormwater drainage system determined in the static and dynamic conditions for tank $DT3$ exceed even 40%. The lowest differences in the flow rates $Q_A$ in the stormwater drainage system were established for tank $DT1$. Catchment 1 is characterized by the most compact channel scheme. As the authors of other studies [22,26] have observed, the catchment shape is a decisive factor for differences in the flows $Q_A$ determined under static and dynamic conditions.

The reliance of the detention tanks on each other is greater if they are located along the same stormwater run-off axis. In order to properly dimension the downstream detention tanks, aside from the catchment run-off, it is important to properly estimate the stormwater outflow from the upstream detention tanks. The outflow from the detention tanks is divided into two stages: accumulation and emptying. Accumulation occurs when the stormwater stream inflow $Q_A$ into the tanks exceeds the outflow rate $Q_O$, while emptying occurs when the outflow rate $Q_O$ exceeds the inflow rate $Q_A$. The outflows of stormwater from the upstream reservoirs are added to the outflow of stormwater from the catchment located between them. Because of this, an important factor affecting the required volume of the downstream detention tanks is the hydraulic system applied in the upstream tanks.

The use of high-efficiency hydraulic systems in upstream detention tanks will cause the stormwater outflow $Q_O$ from these reservoirs to be maintained at a predetermined, constant level throughout the retention period. Even so, it should be mentioned that higher stormwater outflows from the upstream tank will result in increasing the required volume of the downstream detention tanks. Yet another vital factor is the period within which the stormwater drained from the upstream tank will be supplied to the flow-through chamber $KP$ of the downstream tank. Assuming the most extreme option, the stormwater supply from the upstream detention tank might not even cause the required volume of the downstream tank to increase. Such a situation is likely to occur when the total stormwater stream from the upstream tank plus from the catchment area between the tanks is, at a given point in time, below the value of the stormwater outflow from the downstream tanks.

With detention tank $DT3$ in use, both reservoirs $DT1$ and $DT2$ affect its required retention volume. Taking various diameters of outflow channels into consideration, the required volumes were calculated for detention tanks $DT1$ and $DT2$. The simulation results are presented in Table 2.
Table 2. Required volumes of detention tanks DT1 and DT2 determined at the specific diameters of the outflow channels Do.

| Speed of Rain Movement $v$, m·s$^{-1}$ | Diameter of the Outflow Channel $D_0$, m | Max Stormwater Outflow Rate $Q_{O}$, dm$^3$·s$^{-1}$ | Required Useable Volumes of Detention Tank DT V, m$^3$ | Direction of the Wave of Precipitation |
|---------------------------------------|----------------------------------------|----------------------------------------------|---------------------------------|-------------------------------|
|                                       |                                        |                                              | W–E   | E–W   | N–S   | S–N   |
| ∞                                     | 0.3                                    | 200.0                                        | 1694.88 | X     | X     | X     |
|                                       | 0.5                                    | 500.0                                        | 940.56  | X     | X     | X     |
|                                       | 0.7                                    | 875.0                                        | 498.48  | X     | X     | X     |
| 1.5                                   | 0.3                                    | 200.0                                        | 1689.78 | X     | X     | X     |
|                                       | 0.5                                    | 500.0                                        | 982.24  | X     | X     | X     |
|                                       | 0.7                                    | 875.0                                        | 561.87  | X     | X     | X     |
| 2.0                                   | 0.3                                    | 200.0                                        | 1727.04 | X     | X     | X     |
|                                       | 0.5                                    | 500.0                                        | 1007.04 | X     | X     | X     |
|                                       | 0.7                                    | 875.0                                        | 585.6   | X     | X     | X     |
| 3.0                                   | 0.3                                    | 200.0                                        | 1715.88 | 1683  | 1719.12 | 1685.52 |
|                                       | 0.5                                    | 500.0                                        | 988.08  | 872.28 | 961.44  | 914.64  |
|                                       | 0.7                                    | 875.0                                        | 568.44  | 402.24 | 526     | 452.52  |
| 4.0                                   | 0.3                                    | 200.0                                        | 1712.28 | X     | X     | X     |
|                                       | 0.5                                    | 500.0                                        | 976.68  | X     | X     | X     |
|                                       | 0.7                                    | 875.0                                        | 553.8   | X     | X     | X     |
| 6.0                                   | 0.3                                    | 200.0                                        | 1709.16 | 1685.04 | 1710.24 | 1687.44 |
|                                       | 0.5                                    | 500.0                                        | 966.72  | 890.64 | 949.44  | 924.72  |
|                                       | 0.7                                    | 875.0                                        | 540.24  | 427.32 | 519.36  | 469.8   |
| 12.0                                  | 0.3                                    | 200.0                                        | 1703.88 | 1690.68 | 1701.84 | 1691.04 |
|                                       | 0.5                                    | 500.0                                        | 959.4   | 915    | 947.04  | 931.56  |
|                                       | 0.7                                    | 875.0                                        | 519.48  | 454.2  | 512.88  | 483     |

Detention tanks DT2

|                                                | Speed of Rain Movement $v$, m·s$^{-1}$ | Diameter of the Outflow Channel $D_0$, m | Max Stormwater Outflow Rate $Q_{O}$, dm$^3$·s$^{-1}$ | Required Useable Volumes of Detention Tank DT V, m$^3$ | Direction of the Wave of Precipitation |
|------------------------------------------------|----------------------------------------|----------------------------------------|----------------------------------------------|---------------------------------|-------------------------------|
|                                                |                                       |                                        |                                              | W–E   | E–W   | N–S   | S–N   |
|                                                | ∞                                     | 0.3                                    | 175.0                                        | 1376.5 | X     | X     | X     |
|                                                |                                       | 0.5                                    | 345.0                                        | 727.8  | X     | X     | X     |
|                                                |                                       | 0.7                                    | 750.0                                        | 353.1  | X     | X     | X     |
| 1.5                                            | 0.3                                    | 175.0                                  | 1398.1                                       | X     | X     | X     |
|                                                | 0.5                                    | 345.0                                  | 829.5                                        | X     | X     | X     |
|                                                | 0.7                                    | 750.0                                  | 485.4                                        | X     | X     | X     |
| 2.0                                            | 0.3                                    | 175.0                                  | 1410.2                                       | X     | X     | X     |
|                                                | 0.5                                    | 345.0                                  | 836.2                                        | X     | X     | X     |
|                                                | 0.7                                    | 750.0                                  | 499.0                                        | X     | X     | X     |
| 3.0                                            | 0.3                                    | 175.0                                  | 1400.1                                       | 1333.5 | 1377.6 | 1374.6 |
|                                                | 0.5                                    | 345.0                                  | 810.5                                        | 626.6  | 731.2  | 724.2  |
|                                                | 0.7                                    | 750.0                                  | 470.7                                        | 218.4  | 359.9  | 347.2  |
| 4.0                                            | 0.3                                    | 175.0                                  | 1392.6                                       | X     | X     | X     |
|                                                | 0.5                                    | 345.0                                  | 783.1                                        | X     | X     | X     |
|                                                | 0.7                                    | 750.0                                  | 452.6                                        | X     | X     | X     |
| 6.0                                            | 0.3                                    | 175.0                                  | 1385.7                                       | 1345.9 | 1377.0 | 1375.2 |
|                                                | 0.5                                    | 345.0                                  | 761.6                                        | 659.9  | 729.9  | 726.0  |
|                                                | 0.7                                    | 750.0                                  | 419.7                                        | 249.6  | 357.2  | 349.6  |
| 12.0                                           | 0.3                                    | 175.0                                  | 1379.6                                       | 1361.6 | 1376.9 | 1385.7 |
|                                                | 0.5                                    | 345.0                                  | 746.9                                        | 691.2  | 728.6  | 761.6  |
|                                                | 0.7                                    | 750.0                                  | 388.6                                        | 299.7  | 354.9  | 419.7  |

After determining the required volumes of detention tanks DT1 and DT2, it was possible to determine the required volume of the downstream detention tank DT3. The required volume of detention tank DT3 was determined on the basis of a series of simulations, with the consideration of different rainfall durations. The curves defining the required volume of the tank at the specific velocities and directions of the rainfall movement can be found in Figure 6.
After determining the required volumes of detention tanks DT1 and DT2, it was possible to determine the required volume of the downstream detention tank DT3. The required volume of detention tank DT3 was determined on the basis of a series of simulations, with the consideration of different rainfall durations. The curves defining the required volume of the tank at the specific velocities and directions of the rainfall movement can be found in Figure 6.

Figure 6. Curves defining the required volume of detention tank DT3 at the specific diameter of the outflow channels from tanks DT1 and DT2 with Do = 0.3 m and outflow channel from reservoir DT3: (a) Do = 0.8 m, (b) Do = 0.65 m, and (c) Do = 0.5 m.
The movement of the wave of rainfall over the catchment changes the shape of the hydrograph illustrating the stormwater flow rate $Q_A$ in the stormwater drainage system over time (Figure 5). Because the required volume of the detention tanks is determined on the basis of the balance stormwater flow rate at the inlet $Q_A$ and outlet $Q_O$ while filling the tank, this correlation directly affects the estimated required tank volume.

The directions and speed of rain movement over the catchment are included to elicit different volumes of tanks for all adopted rainfall durations. The results demonstrate that the inclusion of rainfall event movement directly affects the determination of the required volumes of interconnected detention tank systems.

The values of the required volume of tank $DT3$ for all the design options can be found in Tables 3–5. The analysis of the data gives the conclusion that the wave velocity and direction are significant factors in the process of estimating the maximum volume of detention tank $DT3$. The maximum required volumes of the tank were determined every time when the rainfall event was moving from west to east (W–E), which corresponded to the stormwater run-off direction for the majority of the drainage channels analysed during the research. The second highest results were obtained for the direction from north to south (N–S), as a number of the channels in the stormwater drainage system have run-off directions that coincide with the analysed wave movement direction. Other values of the required volume of tank $DT3$ were obtained for the movement direction from south to north (S–N). The lowest volumes for tank $DT3$ were registered for the rainfall event moving over the basin from east to west (E–W).

By comparing the results obtained for the rainfall moving over the catchment with the results obtained for the stationary rainfall, a certain correlation was observed. In the case of two rainfall movement directions, namely W–E and N–S, the required detention tank volumes were higher in relation to the static conditions. As for the remaining two directions, the required tank volumes were lower.

**Table 3.** Required volumes of detention tanks $DT3$ determined at the specific diameter of the outflow channels from reservoirs $DT1$ and $DT2$, $D_O = 0.3$ m.

| Speed of Rain Movement $v$, m·s$^{-1}$ | Diameter of the Outflow Channel $D_o$, m | Max Stormwater Outflow Rate $Q_O$, dm$^3$·s$^{-1}$ | Required Useable Volumes of Detention Tank $DT3 V$, m$^3$ | Direction of the Wave of Precipitation |
|---------------------------------------|----------------------------------------|-----------------------------------------------|-------------------------------------------------|-------------------------------------|
|                                       |                                        |                                               | $W$–$E$ | $E$–$W$ | $N$–$S$ | $S$–$N$ |
| $\infty$                              | 0.5                                    | 750.0                                         | 2453.39 | X       | X       | X       |
|                                       | 0.65                                   | 1210.0                                        | 1241.19 | X       | X       | X       |
|                                       | 0.8                                    | 1825.0                                        | 435.24  | X       | X       | X       |
| 1.5                                   | 0.5                                    | 750.0                                         | 2679.25 | X       | X       | X       |
|                                       | 0.65                                   | 1210.0                                        | 1575.24 | X       | X       | X       |
|                                       | 0.8                                    | 1825.0                                        | 824.69  | X       | X       | X       |
| 2.0                                   | 0.5                                    | 750.0                                         | 2749.01 | X       | X       | X       |
|                                       | 0.65                                   | 1210.0                                        | 1657.12 | X       | X       | X       |
|                                       | 0.8                                    | 1825.0                                        | 907.05  | X       | X       | X       |
| 3.0                                   | 0.5                                    | 750.0                                         | 2687.12 | 2253.12 | 2478.82 | 2422.37 |
|                                       | 0.65                                   | 1210.0                                        | 1589.23 | 951.13  | 1282.05 | 1197.50 |
|                                       | 0.8                                    | 1825.0                                        | 834.26  | 147.23  | 483.29  | 381.19  |
| 4.0                                   | 0.5                                    | 750.0                                         | 2606.86 | X       | X       | X       |
|                                       | 0.65                                   | 1210.0                                        | 1454.50 | X       | X       | X       |
|                                       | 0.8                                    | 1825.0                                        | 693.13  | X       | X       | X       |
| 6.0                                   | 0.5                                    | 750.0                                         | 2555.63 | 2341.27 | 2469.26 | 2430.58 |
|                                       | 0.65                                   | 1210.0                                        | 1384.71 | 1050.23 | 1268.26 | 1218.52 |
|                                       | 0.8                                    | 1825.0                                        | 610.85  | 298.75  | 462.38  | 402.23  |
| 12.0                                  | 0.5                                    | 750.0                                         | 2505.89 | 2378.25 | 2462.31 | 2441.23 |
|                                       | 0.65                                   | 1210.0                                        | 1325.68 | 1154.28 | 1252.89 | 1232.57 |
|                                       | 0.8                                    | 1825.0                                        | 536.81  | 345.69  | 449.26  | 421.59  |
Table 4. Required volumes of detention tanks DT3 determined at the specific diameter of the outflow channels from reservoirs DT1 and DT2, \( D_O = 0.5 \) m.

| Speed of Rain Movement \( v \), m \( \cdot \) s \(^{-1} \) | Diameter of the Outflow Channel \( D_O \), m | Max Stormwater Outflow Rate \( Q_O \), dm \(^3\) \( \cdot \) s \(^{-1} \) | Required Useable Volumes of Detention Tank DT3 \( V \), m\(^3\) | Direction of the Wave of Precipitation |
|---------------------------------|-----------------|-----------------|--------------------------|----------------------|
| \( \infty \) | 0.5 | 750.0 | 5286.74 | W–E |
| | 0.65 | 1210.0 | 2686.67 | E–W |
| | 0.8 | 1825.0 | 1035.57 | N–S |
| | 1.5 | 0.5 | 750.0 | 5611.57 | S–N |
| | 0.65 | 1210.0 | 2987.26 | X |
| | 0.8 | 1825.0 | 1478.56 | X |
| | 2.0 | 0.5 | 750.0 | 5645.07 | X |
| | 0.65 | 1210.0 | 3055.12 | X |
| | 0.8 | 1825.0 | 1575.45 | X |
| | 3.0 | 0.5 | 750.0 | 5621.42 | X |
| | 0.65 | 1210.0 | 2886.71 | X |
| | 0.8 | 1825.0 | 1311.79 | X |
| | 4.0 | 0.5 | 750.0 | 5478.31 | X |
| | 0.65 | 1210.0 | 2866.71 | X |
| | 0.8 | 1825.0 | 1311.79 | X |
| | 6.0 | 0.5 | 750.0 | 5415.65 | X |
| | 0.65 | 1210.0 | 2886.71 | X |
| | 0.8 | 1825.0 | 1311.79 | X |
| | 12.0 | 0.5 | 750.0 | 5345.12 | X |
| | 0.65 | 1210.0 | 2784.23 | X |
| | 0.8 | 1825.0 | 1156.28 | X |

Table 5. Required volumes of detention tanks DT3 determined at the specific diameter of the outflow channels from reservoirs DT1 and DT2, \( D_O = 0.7 \) m.

| Speed of Rain Movement \( v \), m \( \cdot \) s \(^{-1} \) | Diameter of the Outflow Channel \( D_O \), m | Max Stormwater Outflow Rate \( Q_O \), dm \(^3\) \( \cdot \) s \(^{-1} \) | Required Useable Volumes of Detention Tank DT3 \( V \), m\(^3\) | Direction of the Wave of Precipitation |
|---------------------------------|-----------------|-----------------|--------------------------|----------------------|
| \( \infty \) | 0.5 | 750.0 | 5780.03 | N–S |
| | 0.65 | 1210.0 | 4072.23 | E–W |
| | 0.8 | 1825.0 | 2341.23 | W–E |
| | 1.5 | 0.5 | 750.0 | 6098.56 | X |
| | 0.65 | 1210.0 | 4577.26 | X |
| | 0.8 | 1825.0 | 2796.23 | X |
| | 2.0 | 0.5 | 750.0 | 6196.18 | X |
| | 0.65 | 1210.0 | 4658.50 | X |
| | 0.8 | 1825.0 | 2917.30 | X |
| | 3.0 | 0.5 | 750.0 | 6102.35 | X |
| | 0.65 | 1210.0 | 5468.45 | X |
| | 0.8 | 1825.0 | 3792.23 | X |
| | 4.0 | 0.5 | 750.0 | 6004.72 | X |
| | 0.65 | 1210.0 | 4403.05 | X |
| | 0.8 | 1825.0 | 2677.35 | X |
| | 6.0 | 0.5 | 750.0 | 5930.06 | X |
| | 0.65 | 1210.0 | 4298.16 | X |
| | 0.8 | 1825.0 | 2572.21 | X |
| | 12.0 | 0.5 | 750.0 | 5845.23 | X |
| | 0.65 | 1210.0 | 4187.47 | X |
| | 0.8 | 1825.0 | 2489.56 | X |
By analysing the adopted design options, it is clear that the differences in the useable cubic volume of tank DT3 also depend, to a great degree, on the adopted movement velocity of a wave of rainfall. Speaking of the movement directions E–W and S–W, there was a trend towards decreasing the required retention volume of the tank proportionally to decreasing the wave movement velocity. In the instance of the directions W–E and N–S, a slightly different correlation could be observed. The decrease of the velocity when the wave of rain moves in these directions caused the useable cubic volume of the detention tank to increase. However, the trend was not constant and, at some point in time ($v = 2.0 \text{ m} \cdot \text{s}^{-1}$), this correlation reversed (inverse proportionality). This finding is all the more important because in designing any system, one can estimate the critical movement speed of the rain at which the detention tank volume will be the highest. So as to fully examine this correlation, for the movement direction from west to east, additional simulations were carried out for the following speeds: 1.5, 2, and 4 m s$^{-1}$. It should be noted that an identical trend was also observed while determining peak stormwater flow rates in the stormwater drainage system.

One should choose the maximum value for each of the adopted design options from the obtained set of results as these values will correspond to the required critical volume of the detention tank. Table 6 contains the percentage difference revealed by use of the two methods, namely in the static conditions and the conditions that take the rainfall movement over the catchment into account. As the data contained in Table 6 indicate, the highest percentage differences were observed for the greatest diameter of the outflow channel $D_{O} = 0.8$ m. In addition, it was demonstrated that the degree of the percentage difference depended on the diameters of the outflow channels of the upstream storage reservoirs. The greater the channel diameter, the more marginal the impact of the rainfall movement became. The percentage difference was the greatest when the outflow channel from detention tank DT3 was $D_{O} = 0.8$ m, and the outflow channels from reservoirs DT1 and DT2 had the lowest of the adopted values, $D_{O} = 0.3$ m, while the rainfall was moving from west to east at a speed of $2.0 \text{ m} \cdot \text{s}^{-1}$. Under these conditions, the percentage difference was as high as 108.41%.

### Table 6. Percentage differences of volume detention tank DT3 between static and dynamic condition.

| Detention Tanks DT3 | Diameter of the Outflow Channel Do from Detention Tank, m | Required Useable Volumes of Detention Tank DT3 | Percentage Differences $R_v$ |
|---------------------|----------------------------------------------------------|-----------------------------------------------|-------------------------------|
|                      | Statics Conditions | Dynamic Conditions |                                  |                              |
|                      | $V_r$, m$^3$ | $t_d$, min | $V_r$, m$^3$ | $t_d$, min | [%]                        |
| DT1, DT2 | DT3 | 0.5  | 2453.39  | 90  | 2749.01  | 80  | 12.05                        |
| 0.65 | 1241.19  | 30  | 1657.12  | 25  | 33.51                        |
| 0.8 | 435.24  | 25  | 907.05  | 20  | 108.41                        |
| DT1, DT2 | DT3 | 0.5  | 5286.74  | 130  | 5645.07  | 120  | 6.78                        |
| 0.65 | 2686.67  | 110  | 3055.12  | 100  | 13.71                        |
| 0.8 | 1035.57  | 30  | 1575.45  | 25  | 52.13                        |
| DT1, DT2 | DT3 | 0.5  | 5780.03  | 90  | 6196.18  | 80  | 7.20                        |
| 0.65 | 4072.23  | 70  | 4658.50  | 60  | 14.40                        |
| 0.8 | 2341.23  | 70  | 2917.30  | 60  | 24.61                        |

In practically identical conditions, by only changing the diameter of the outflow channels from tanks DT1 and DT2 from 0.3 m to 0.5 m, the percentage difference was lower, at 52.13%. A slightly lower value, 24.61%, was elicited when the diameter of the outflow channels from tanks DT1 and DT2 had the highest of the adopted values, that is, $D_{O} = 0.7$ m. The rainfall movement velocity appeared to be critical in this case, at $v = 2.0 \text{ m} \cdot \text{s}^{-1}$, which was the same value as at the diameters $D_{O} = 0.3$ and 0.5 m.

As for the remaining two adopted diameters of the outflow channel from detention tank DT3, significantly lower percentage differences were observed in the estimated volumes of reservoir DT3.
Notwithstanding, at all times, the highest value was registered for those conditions taking the wave movement over the basin into account. Smaller differences stemmed from assuming the effective rainfall duration for the purpose of determining the critical volume $V$ of the tank. These times have significant values and they can be found in Table 6. As confirmed by the results, the movement of the wave of rain for longer durations did not increase the peak values of the stormwater flow rate $Q_A$ through the network [23]. The movement of the wave only caused waste water to run off from the basin more quickly, which resulted in a more compact flow hydrograph.

4. Conclusions

The research results permit us to conclude that the omission of both the direction and speed of rain movement led to undersizing interconnected detention tank systems. This statement especially applies to the downstream reservoirs.

The research has confirmed that the decisive factors that affect the differences between the tank volumes determined under static and dynamic conditions are the direction and speed of rain movement.

As revealed by the study of the system of detention tanks, an important factor affecting the level of impact of the rainfall movement is the adopted diameter of the outfall channel for the upstream detention tanks. It was found that the smaller the diameter of the outfall channel adopted for the upstream tanks, the greater the impact of the rainfall movement on the downstream tanks. This correlation was observed for all the design options of stormwater outflow rate from the downstream tank $DT3$.

According to the research, the detention tank will be undersized the most when (1) a static rainfall is considered at the design stage, (2) the downstream tank has a high diameter of the outfall channel, and (3) the upstream tanks have a small diameter of the outfall channel. The maximum difference established during the research on the required volume of reservoir $DT3$ was as much as 108%.

Aside from the direction and velocity of a wave of rainfall, the basin shape and waste water run-off directions of the waste water network channels also affect the differences between static and dynamic conditions. In the case of the examined basin, the waste water run-off has two directions, which decreases the impact of the rainfall movement on the required volumes of the detention tanks.

The research has confirmed the thesis that the movement of the wave of rainfall should be taken into account, as its omission causes undersizing of both the stormwater drainage system and detention tanks integrated within it. It should also be noted that the detention tanks are more susceptible to being undersized than the stormwater drainage system itself. The wave movement should especially be considered in catchments with single stormwater run-off directions. Regarding detention tanks, the decisive parameters are the adopted diameter of the outfall channel $D_0$, which affects the value of the outflow of stormwater $Q_O$ from detention tank and the locations of the detention tanks in relation to one another.

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Abbreviations

Do diameters of the outflow channels for tank, m;
QO stormwater outflow from the tanks, dm³·s⁻¹;
QA stormwater inflow to the tanks, dm³·s⁻¹;
QC stormwater transport from the flow-through chamber KP to the accumulation chamber KA, dm³·s⁻¹;
QD stormwater outflow from the accumulation chamber KA to the flow-through chamber KP, dm³·s⁻¹;
KA accumulation chamber;
KP flow-through chamber;
td rainfall duration, min;
t time that has elapsed since the beginning of the rainfall, min;
V required volume of tank, m³;
Rv percentage difference in required volume of tank between the static and dynamic conditions;
K flowing direction of the wave of rainfall, -;
v flowing velocity of the wave of rainfall, m·s⁻¹;

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