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Article

Evaluation of the Influence of Catchment Parameters on the Required Size of a Stormwater Infiltration Facility

Sabina Kordana-Obuch *, Mariusz Starzec and Daniel Słyś

Department of Infrastructure and Water Management, Rzeszow University of Technology, al. Powstańców Warszawy 6, 35-959 Rzeszow, Poland
* Correspondence: sk@prz.edu.pl

Abstract: One sustainable method of stormwater management is surface infiltration with retention. Proper design of stormwater infiltration facilities ensures a reduction in flood risk within urban catchments. However, this is not possible without considering the key design parameters of such facilities. The aim of this paper is to determine the influence of the parameters characterizing the catchment area on the size of the stormwater infiltration facilities. The research used SWMM 5.1 and Statistica software. It was carried out on the example of model catchments and a real urban catchment. The analysis showed that it is of key importance in the design of stormwater infiltration facilities to accurately determine the total catchment area, the type of soil within it, and the proportion of impervious surfaces. The relevance of the other parameters that characterize the catchment area is clearly lesser. However, they cannot be completely ignored, and their values should be determined as accurately as possible. These research results can guide stakeholders in the decision-making process during investment planning and implementation.

Keywords: storm water management model (SWMM); Bogdanowicz–Stachy rainfall model; Green–Ampt infiltration model; nature-based solutions; green infrastructure; design of experiments (DOE)

Citation: Kordana-Obuch, S.; Starzec, M.; Słyś, D. Evaluation of the Influence of Catchment Parameters on the Required Size of a Stormwater Infiltration Facility. *Water* **2023**, *15*, 191. https://doi.org/10.3390/w15010191

Academic Editor: Gordon Huang

Received: 29 November 2022
Revised: 28 December 2022
Accepted: 30 December 2022
Published: 2 January 2023

1. Introduction

The progression of urbanization, despite the undoubted advantages resulting from the socio-economic changes that take place in society, also has unfavorable consequences [1]. These consequences are particularly felt in relation to environmental issues [2]. Increased atmospheric pollution due to rising energy demand [3,4], increased levels of water and soil pollution [5,6], increased waste generation [7], and water deficit due to rising water demand [8,9] are just a few. An inherent consequence of urbanization is also an increase in the area of impervious land [10]. This leads to a reduction in biodiversity within cities and an intensification of surface runoff [11]. This problem is exacerbated by climate change, manifested in the extension of rainless periods and the increase in the intensity of extreme precipitation [12,13], which can cause additional difficulties in the operation of drainage systems [14].

Considering the range of challenges facing global communities, solving the problem of stormwater management cannot be done without getting closer to achieving the Sustainable Development Goals [15]. Particular attention should be paid to the need to ensure the health [16] and well-being [17] of people in the drained area and to guarantee universal access to potable water [18]. Equally important are the issues of creating sustainable cities and communities [19], responsible consumption and production [20], and protecting life on land, for example, by preventing flooding [21,22] and sewer overload [23]. The implementation of rainwater harvesting systems can be helpful in achieving the above goals [24,25]. The application of nature-based solutions is also important [26]. In the case of stormwater management, low-impact development (LID) facilities are particularly popular [27,28]. The concept of sponge cities is also gaining importance [29], and in many countries the focus is on blue–green infrastructure [30].

For Central Europe, one of the most important sustainable ways of managing stormwater is surface infiltration with retention [31]. In this situation, excess surface water is discharged into infiltration basins or infiltration tanks. Previous studies by the authors showed that the application of such devices is the most favorable way to manage stormwater in newly designed residential areas [32]. The use of stormwater infiltration facilities is limited, mainly due to the prevailing soil and water conditions and the availability of land for development [33,34]. The poor quality of infiltrating water can also be a problem [35]. However, the environmental benefits that arise from their application offer prospects for their development and increased use [36]. The most important of these include a reduction in adverse phenomena that occur in stormwater receivers [37], as well as the supply of groundwater resources and an increase in the biodiversity of urban areas [38,39].

However, in many cases, the problem is the methodology used to determine the required storage capacity of infiltration basins and tanks. For example, in Poland, an analytical method is commonly used that assumes a constant value of the filtration coefficient (k_f). It does not take into account the initial moisture content of the soil underlying the facility and its increase due to stormwater infiltration. Although a safety factor is assumed, reflecting the reduction in stormwater infiltration efficiency due to soil clogging [40], this may not be sufficient in many cases. In addition, the design process ignores most of the parameters that characterize the catchment area, and these parameters can be important for the selection of design parameters for stormwater infiltration facilities. In the commonly used calculation method [41], the application of which allows for the determination of the required capacity of the infiltration basins and tanks, only the reduced area of the catchment is considered. The reduced area can be defined as the total area of impervious land. At the same time, the permeability of native soil is mostly not considered, with the result that sands, characterized by considerable permeability, are treated on a par with clays, whose ability to seep stormwater is negligible. Other parameters that characterize the catchment are also ignored, such as the width of the overland flow path and the slope of the catchment. A similar trend is observed in the use of analytical methods to dimension sewer collectors and retention facilities [42]. However, with regard to these elements of urban infrastructure, a clear change in the described approach was observed in recent years, manifested mainly in the increase in the use of hydrodynamic modeling tools [43,44].

The application of modern methods for designing stormwater infiltration systems, including hydrodynamic modeling, is limited to devices located directly at the site of rainfall, the so-called LID facilities, whose task is to reduce stormwater runoff from the catchment area [45]. However, research indicates that the best solution is to use LID elements together with more classical methods that allow, for example, the retention of stormwater [46]. Unfortunately, in a case of facilities dedicated to stormwater infiltration with retention, where stormwater is delivered through a system of interconnected channels, the use of hydrodynamic modeling is rare. Marginalizing the importance of catchment characterization parameters can lead to the under-sizing of infiltration facilities. The consequences of this can include hydraulic overloading and flooding into the surrounding area and buildings.

Comprehensive studies of the impact of the parameters that characterize the catchment area on the size of stormwater infiltration facilities have not yet been conducted. Although the literature contains information on the influence of various parameters on the required capacity of retention reservoirs [44,47], these data cannot be applied to infiltration facilities. This is due to the fact that the intensity of stormwater infiltration into the ground is much lower than the intensity of the outflow from retention facilities. Some authors [48] have conducted sensitivity analysis for LID facilities. However, their studies focused on assessing the sensitivity of model-based water balance to LID parameters. Other researchers [49] evaluated the impact of depression storage on the runoff from impervious surfaces. Therefore, it is clear that none of the mentioned studies indicates key parameters in the process of designing stormwater infiltration facilities.

The purpose of this paper is to determine the influence of the parameters that characterize the catchment area on the required size of the stormwater infiltration facilities. SWMM 5.1 software was used for this purpose (EPA SWMM, Cincinnati, Ohio, USA). Its application, in contrast to software focused solely on the process of stormwater infiltration, makes it possible to fully map the configuration of the drainage system located above the facility. Furthermore, the SWMM 5.1 software is widely used by design offices and local government units, so the results of the analysis have broad application potential. This research focuses on infiltration basins and tanks, as these devices have the greatest potential for implementation within the stormwater drainage system [32].

2. Materials and Methods

This research was carried out according to the procedure shown in Figure 1. Determining the required area of stormwater infiltration facilities was possible through the use of SWMM 5.1 software. On the other hand, the development of a research plan and the global sensitivity analysis required the use of Statistica software (TIBCO Statistica, Palo Alto, California, USA).

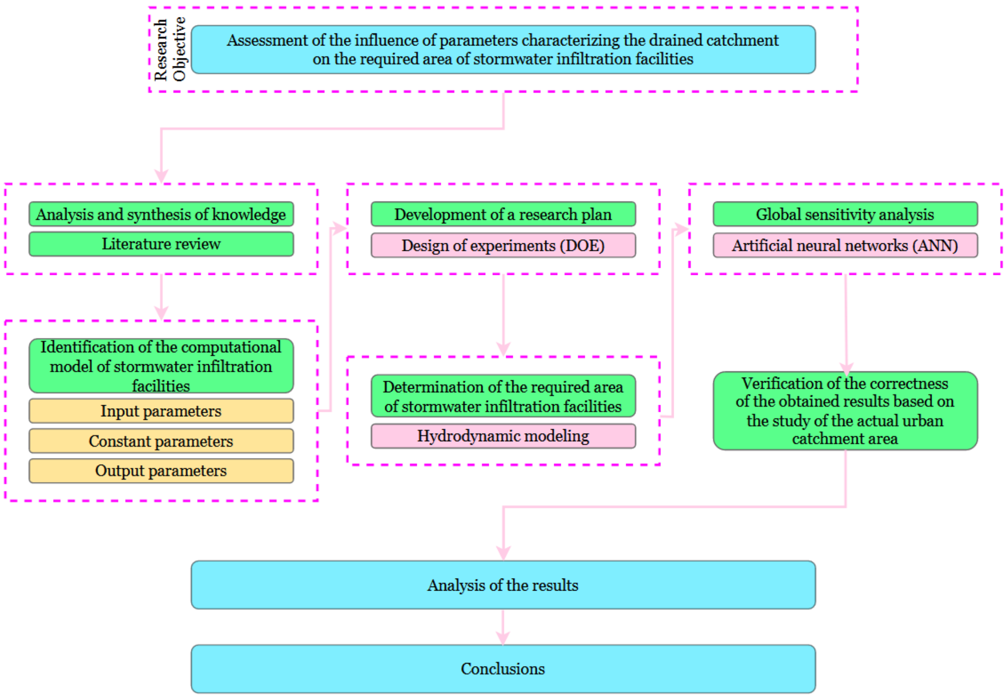


Figure 1. Research plan.

2.1. Rainfall Model

The research used the rainfall model developed by Bogdanowicz and Stachy [50]. Its use is recommended for the territory of Poland when the storm event return period is 2, 5 or 10 years. This model is widely used in stormwater management analysis [44,51,52]. It is also often recommended for use by local authorities in Poland. It excludes mountainous areas and divides the rest of Poland into central, southern and coastal, and northwestern regions, depending on the duration of rainfall.

When the described model is used, the maximum rainfall is determined based on Equation (1) [50].

$$h_{max} = 1.42 \cdot t^{\,0.33} + \alpha(R,t) \cdot (-\ln p)^{\,0.584}, \tag{1}$$

where h_{max}—maximum height of rainfall, mm; p—probability of occurrence, $p \leq 1$; $\alpha(R,t)$—parameter depending on the region of Poland and the duration of the rainfall t.

The value of the parameter $\alpha(R,t)$ for the central region of Poland, which covers the largest part of the country, can be determined from Equations (2)–(4) [50].

$$\alpha(R,t) = 4.693 \cdot \ln(t + 1) - 1.249, \text{ if } t \geq 5 \text{ min}, t < 120 \text{ min}, \quad (2)$$

$$\alpha(R,t) = 2.223 \cdot \ln(t + 1) + 10.639, \text{ if } t \geq 120 \text{ min}, t < 1080 \text{ min}, \quad (3)$$

$$\alpha(R,t) = 3.01 \cdot \ln(t + 1) + 5.173, \text{ if } t \geq 1080 \text{ min}, t < 4320 \text{ min}. \quad (4)$$

The research was carried out assuming a rainfall probability of p = 50%, which is recommended for residential areas [53]. Maximum rainfall heights (h_{max}) were determined for rainfall durations ranging from t = 10 min to t = 210 min. Based on the results, the rainfall characteristics were then developed and implemented in SWMM 5.1. Based on the stormwater hydrographs determined for successive durations of rainfall (t), the diameters of the drainage system conduits were selected. Using the same synthetic rainfall data, the required area of stormwater infiltration facilities was also estimated.

2.2. Stormwater Infiltration Model

The study was carried out on the basis of a modified Green–Ampt infiltration model [54]. This made it possible to consider the height of the water layer accumulated on the ground surface. The idea of the Green–Ampt model is based on the assumption of the presence of a sharp wetting front. It separates the soil with lower moisture content from the saturated soil layer above it.

The application of the model required the estimation of the hydraulic conductivity of the saturated soil (K), its porosity (η), and the suction head (Ψ). When using SWMM 5.1 software, in addition to the values of the parameters K and Ψ, the initial moisture deficit ($\Delta\theta$), which is the fraction of the soil volume that is initially dry, must also be defined.

2.3. Computational Model

The research was carried out on the basis of a computational model of infiltration facilities cooperating with the drainage system. The facilities are characterized by an established maximum fill level (h_{imax}), which was assumed to be 0.30 m and 1.0 m for infiltration basins and tanks, respectively [55], and strictly defined soil parameters. It was assumed that it would be sand, the attributes of which were determined according to the guidelines of the US Environmental Protection Agency [56].

The parameters describing each subcatchment and the infiltration facilities were assigned to groups of input, output, and fixed parameters (Figure 2). Furthermore, the input variables were assigned ranges of values for which their impact on the required area of the stormwater infiltration facilities (Si) was analyzed. Due to the large number of parameters, the width of the overland flow path (W) was defined as the doubled length of the conduit [56], which is directly derived from the catchment load (L_c). A range of values for the roughness coefficient of the catchment (n_c) and the parameters of individual soils were also determined based on guidelines [56]. The maximum size of the catchment area was adopted in accordance with the DCR recommendations [40] regarding the use of facilities dedicated to the surface infiltration of stormwater with retention.

The various input parameters, with the exception of the duration of the rainfall (t), were examined in terms of their impact on the required area of stormwater infiltration facilities (S_i). The need to consider them during the design of infiltration basins and tanks was also evaluated. On the other hand, the duration of the rainfall (t) was treated as a decisive parameter for reaching the maximum fill level in the facilities (h_{imax}). Therefore, it was always analyzed over the full range of assumed values to determine the critical value.

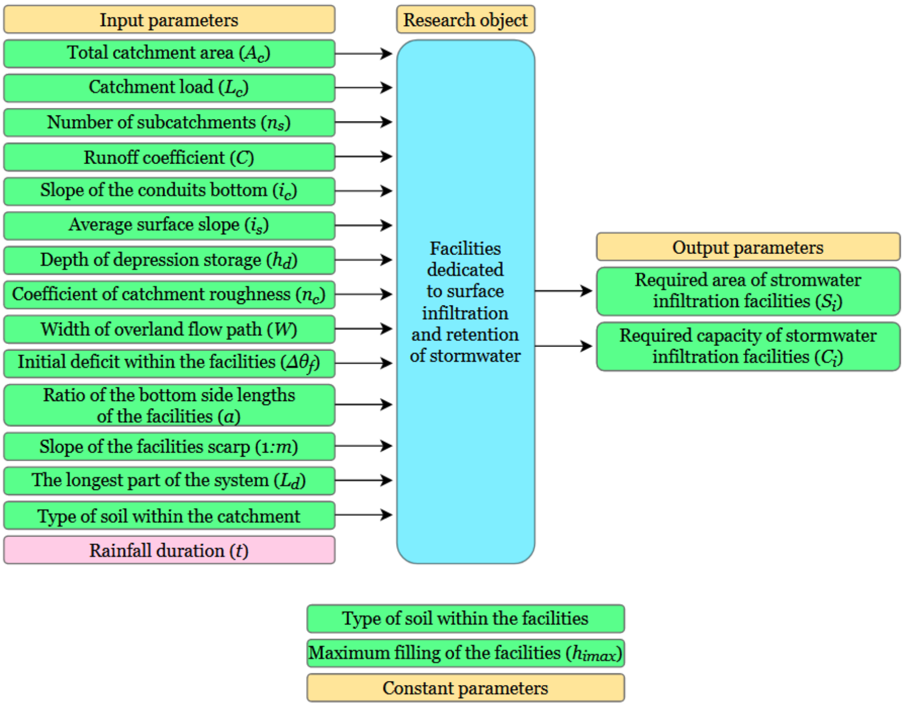


Figure 2. Computational model.

2.4. *Evaluation of the Influence of Catchment Parameters on the Required Area of Stromwater Infiltration Facilities*

Considering the large number of variables and the relatively wide range of their values, this research used the design of experiment theory (DOE) [57]. Statistica software was employed to determine the optimal combinations of input parameters [58]. Due to the limitations of the software regarding the number of parameters that can be considered, only the following ones were included in the research plan: total catchment area (A_c), average runoff coefficient (C), catchment load (L_c), number of subcatchments (n_s), average slope of the bottom of the conduits (i_c), average slope of the catchment surface (i_s), depth of depression storage (h_d) and catchment roughness coefficient (n_c). The generated research plan is shown in Appendix A.

Using Statistica software, 85 combinations of parameters were identified, five of which represent a repeating central point. All of these combinations (with the exception of a system consisting of a single conduit) were investigated using SWMM 5.1 software on the example of three catchments (Figure 3). Given that the results of central point hydrodynamic simulations would be the same in each case, this combination of parameters was also analyzed for different conduit layouts.

The research was carried out by assuming a square bottom shape and a constant slope of the infiltration facility scarp, which was equal to 1:2. Both the case when the sand within it is fully drained and when it is completely water saturated were analyzed. To preliminarily determine the effect of the soil permeability within the catchment on the required area of the infiltration facility, the entire study was repeated for three types of soil with different characteristics, that is, clay, silt loam, and loamy sand. Therefore, the implementation of the research required analyzing 3036 catchments.

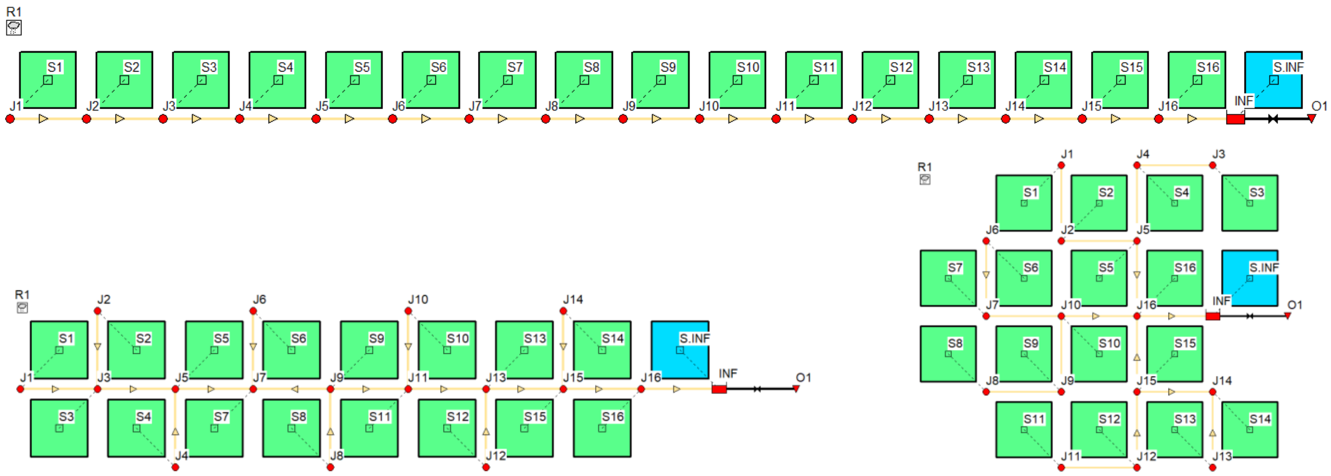


Figure 3. The analyzed catchments, consisting of sixteen subcatchments (J1–J16—junctions; S1–S16—subcatchments; S.INF—subcatchment simulating rainfall over an infiltration facility; INF—infiltration facility; R1—rain gage; O1—outlet from the overflow).

In each case, an area of the bottom of the infiltration facility (S_i) was sought such that, with the rainfall generating the accumulation of the highest amount of stormwater, the fill level in the facility would be equal to the maximum value (h_{imax}). For this purpose, different areas of the bottom of the facility (S_{ij}) were assumed. On the basis of the assumed value of S_{ij}, the area of the object at the level of maximum fill level (S_{ijmax}) was calculated, which was also assigned to the subcatchment connected to the infiltration basin/tank. The drainage system was loaded with successive rainfalls and the maximum fill level (h_{ijmax}) of the facility was determined. The simulations were run until the target value was reached (h_{ijmax} = h_{imax}). The procedure described is presented in figures generated using Scilab 6.0.1 (Figures 4 and 5). Both figures are based on the same input data, and the searched point is marked with a dot.

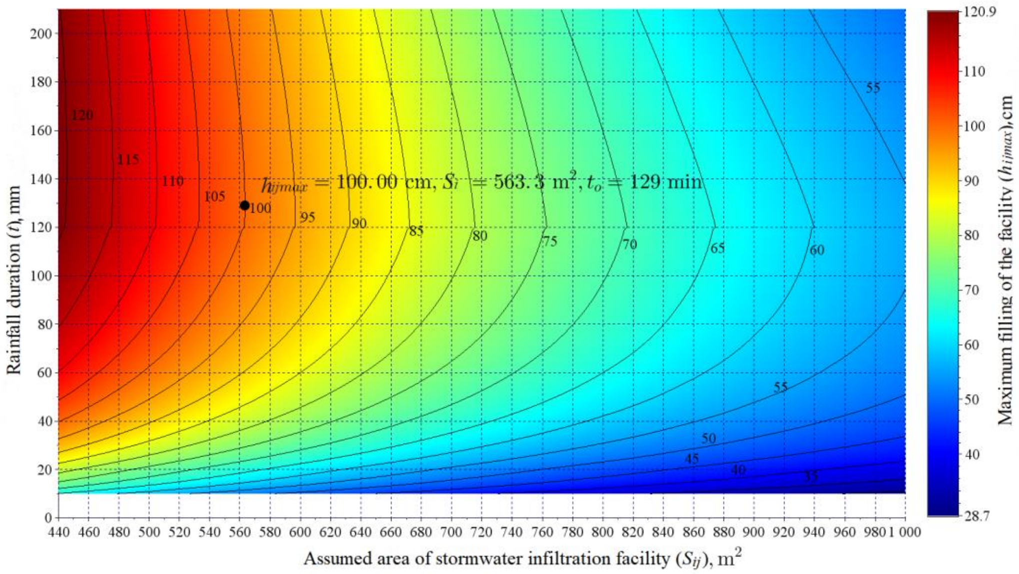


Figure 4. The maximum level of fill in an infiltration tank (h_{ijmax}) as a function of the duration of rainfall (t) and the bottom area of the facility (S_{ij}), determined for a randomly selected catchment (h_{ijmax}—maximum level of fill in the tank at a given area of its bottom; S_i—required area of the tank; t_o—critical rainfall duration).

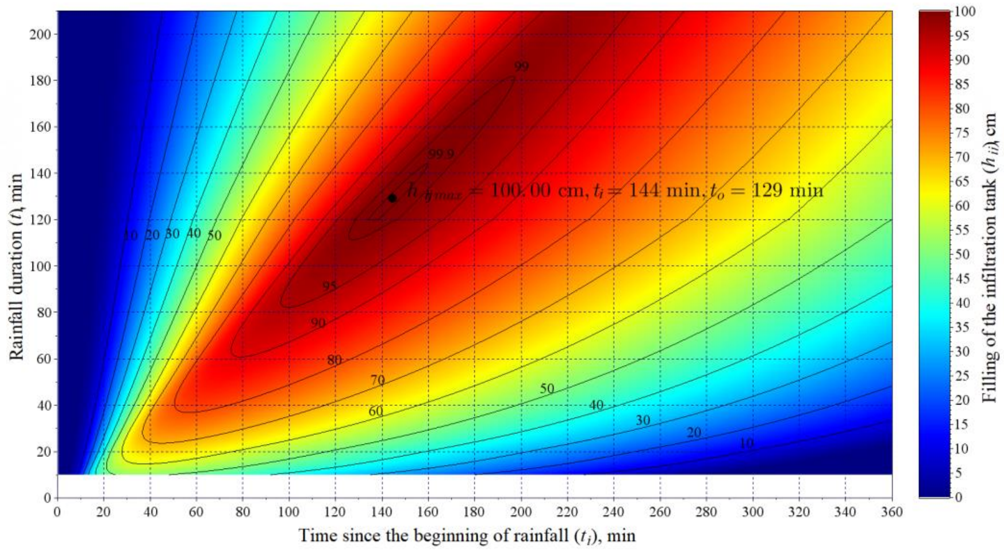


Figure 5. Infiltration tank fill level (h_{ij}) in time (t_i) depending on the duration of the rainfall (t), determined for its bottom area of S_i = 563.30 m^2 (h_{ijmax}—maximum fill level in the tank at a given area of its bottom; t_o—critical rainfall duration).

The combinations of the independent variables, along with the determined values of the required area of the stormwater infiltration facility (S_i), were then implemented into the Statistica software for sensitivity analysis. The parameters that were included in the research plan, as well as the longest part of the system (L_d) resulting from the adopted catchment layout and ranging from 33.2 to 2000.0 m, were defined as quantitative input variables. The type of soil within the catchment was considered a qualitative variable. In turn, the results of the hydrodynamic simulations (S_i) were defined as a quantitative output variable. Artificial neural networks (ANNs) were used as a tool and the research was carried out separately for each type of the facility and its level of water saturation. As a result, four artificial neural networks were obtained, on the basis of which the parameters whose influence on the final results achieved in the analysis turned out to be the greatest were determined. ANNs can be used wherever simple mathematical models are not applicable due to the complexity of the systems under consideration. This tool has also been widely used in stormwater management studies [59,60]. Multilayer perception (MLP) networks [58] were used in this research. It was assumed that test data would account for 70% of the total data, while teaching and validation data would each account for 15% each. This division is consistent with the reference values of the Statistica software package [58]. It was also assumed that individual activation functions could be described by any function. The ANNs with the lowest error values and the largest fit were selected from among the ANNs generated by the software. The selected networks were then checked on the example of randomly selected combinations of parameters in order to verify their validity.

2.5. Case Study

The final stage of the analysis was to verify the results of the research obtained using the example of a real urban catchment.

The study area is a small watershed, located in Kolbuszowa County, Subcarpathian Voivodeship, Poland (Figure 6). The total catchment area is 11.023 ha. The average annual rainfall is in the range of 600 to 640 mm. The slope of the catchment surface is variable, ranging from 1.30% to 3.10%. Elevation and slope data were obtained using the Digital Elevation Model (DEM) with a resolution of 1 m [61].

Figure 6. Location of the study area.

The catchment area is dominated by single-family residential development. A small part is covered with green areas. Data on the physical properties of the soil were obtained through field research. Nineteen boreholes were made to a depth of 2 m. The thickness of individual soil layers is presented in Table 1.

Table 1. Soil layers in the considered urban catchment area.

Type of Soil	Thickness [cm]	Depth [cm]
Organic Soil	20–30	0–30
Sandy Loam	40–70	20–90
Sand	>110	>70

At the infiltration basin site, three boreholes were drilled to a depth of 4 m each (Figure 7). The identified soil layers are summarized in Table 2.

Figure 7. Soil samples from an example borehole.

Table 2. Soil layers at the location of the infiltration facility.

Type of Soil	Profile 1		Profile 2		Profile 3	
	Thickness [cm]	Depth [cm]	Thickness [cm]	Depth [cm]	Thickness [cm]	Depth [cm]
Organic Soil	20	0–20	25	0–25	20	0–20
Sandy Loam	40	20–60	45	25–70	50	20–70
Sand	150	60–210	150	70–220	150	70–220
Loamy Sand	20	210–230	20	220–240	30	220–250
Sand	>170	230–240	>160	240–400	>150	20–400
Groundwater level		370		360		390

Throughout the catchment area, the topsoil is organic soil. Below that, the occurrence of sandy loam with a thickness of 40 to 70 cm was established. Under the sandy loam layer there are sands. The occurrence of a groundwater table to a depth of 2 m was not recorded.

Increasing the depth of the borehole at the infiltration facility site made it possible to identify a layer of loamy sand with a thickness of 20–30 cm and a depth of 210–250 cm. Furthermore, the groundwater table was recorded at 3.6 to 3.9 m.

Based on the analysis, the SWMM model (Figure 8) was parameterized. The model consists of 220 subcatchments with similar characteristics. The elevation of the drainage system was determined on the basis of the data presented in the Geoportal [61]. It consists of 224 conduits with a length of 7.2 to 138.7 m. The slope of the conduits ranges from 0.3% to 3.5%. They are laid at a depth of 1.63 to 2.62 m. The inflow channel to the infiltration basin is located at a depth of 2.20 m.

Figure 8. Hydrodynamic model of the study catchment area.

Rainfall data from 1 January 2011 to 30 June 2022 (Figure 9) was obtained from a rain gauge located 2.6 km from the study catchment area [62]. Total rainfall during the study period was 7142.1 mm (621.05 mm per year).

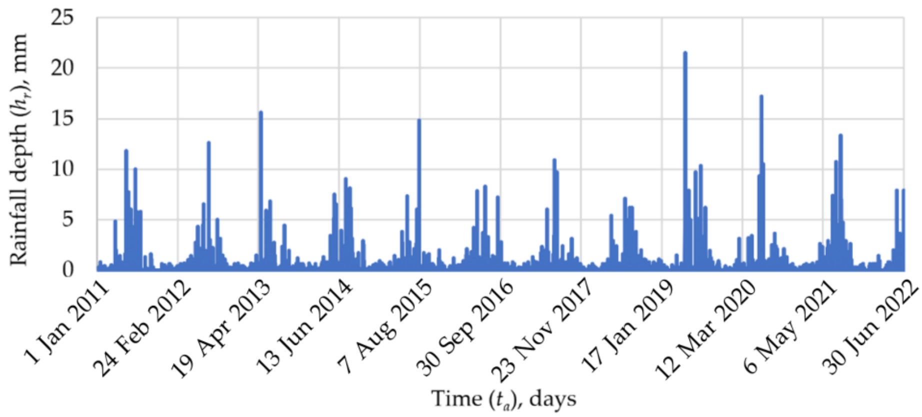
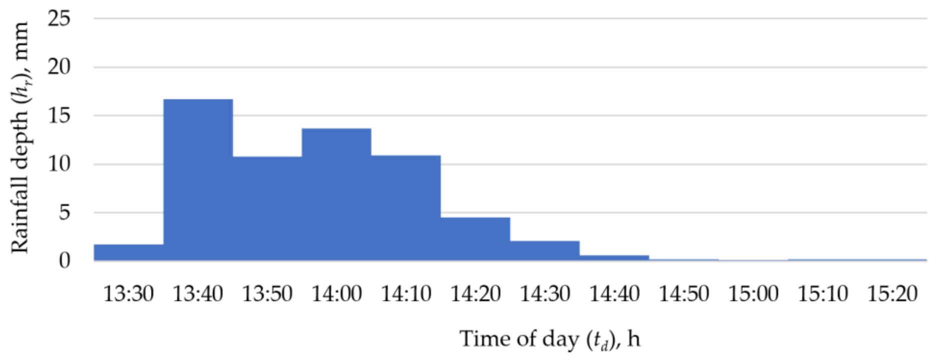
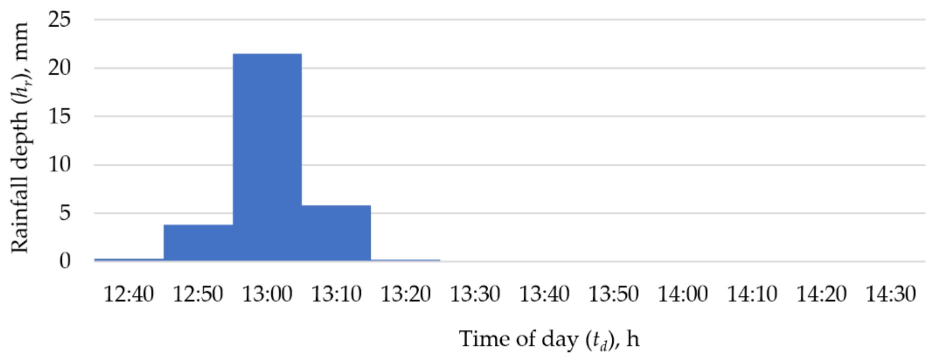


Figure 9. Rainfall depth at the KOLBUSZOWA 250210220 meteorological station with a 10 min time step (based on [62]).

A detailed analysis of the impact of a rainfall event on the hydraulic functioning of the infiltration facility was performed for three selected rainfall events with different probability of occurrence (Figure 10). According to the Bogdanowicz and Stachy model [50], the rainfall of 19th June, 2020 had a probability of occurrence of p = 0.00098. In less than 2 h, the rain gauge recorded a rainfall depth of h_r = 63.1 mm. In the case of the rainfall of 19th May, 2019, a depth of h_r = 31.1 mm was recorded, which means a probability of occurrence of p = 0.065. In contrast, on 8th August, 2019, rainfall occurred with a depth of h_r = 21.1 mm, having a probability of occurrence of p = 0.53.

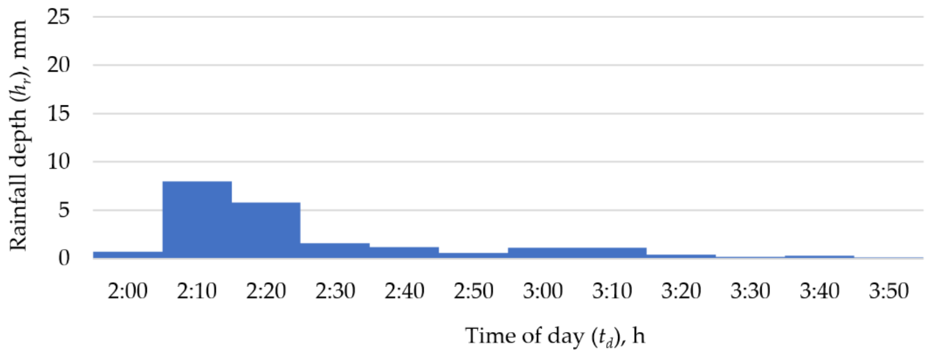


(**a**)



(**b**)

Figure 10. *Cont.*



(**c**)

Figure 10. Depth of the analyzed rainfall: (**a**) 19 June 2020—p = 0.00098; (**b**) 19 May 2019—p = 0.065; (**c**) 8 August 2019—p = 0.53.

To assess the impact of the selected parameters that characterize the catchment on the hydraulic functioning of the infiltration facility, three variants were analyzed:

- Variant 0—the parameters that characterize the catchment area were adopted according to the actual conditions. This was achieved by conducting local inspections, performing field surveys, using Geographic Information System (GIS) data, etc. An infiltration basin was designed in the lowest part of the catchment, assuming a rainfall probability of p = 0.5. The area of the square bottom of the facility was equal to 1892.25 m^2 (h_{imax} = 0.30 m);
- Variant 1—the selected parameters of Variant 0 (total catchment area, soil permeability, runoff coefficient, depth of depression storage, average surface slope and catchment roughness coefficient) were increased by 10% one by one. The change in each parameter was analyzed individually. The remaining variables took the same values as in Variant 0;
- Variant 2—the selected parameters of Variant 0 (the same as in Variant 1) were reduced by 10% one by one. The change in each parameter was analyzed individually. The remaining variables assumed the same values as in Variant 0.

3. Results

3.1. Hydrodynamic Simulations

As a result of the research carried out using SWMM 5.1 software, a set of data was obtained describing the required area of the stormwater infiltration facility (S_i). This parameter was chosen due to the fact that the surface area is one of the most sensitive elements of stormwater management best practice in most hydrological metrics [63]. The research indicated that both the total catchment area (A_c) and the permeability of the soil present in the catchment have a significant impact on the S_i value. Analyzing the data shown in Figures 11 and 12, it can be seen that in the case of sandy catchments, the value of S_i increases almost proportionally to the size of the reduced catchment area (A_z). This is due to the fact that the determined critical rainfall intensities turned out to be lower than the hydraulic conductivity of the loamy sand. As a result, all the stormwater that falls on the permeable part of the catchment seeped into the ground, while surface runoff was generated only within impervious surfaces. Thus, the results correspond to the often-accepted assumption [47,64] that the amount of stormwater delivered to drainage systems does not depend so much on the total area of the catchment (A_c), but rather on its reduced area (A_z). However, the results obtained for soils characterized by lower permeability contradict this assumption.

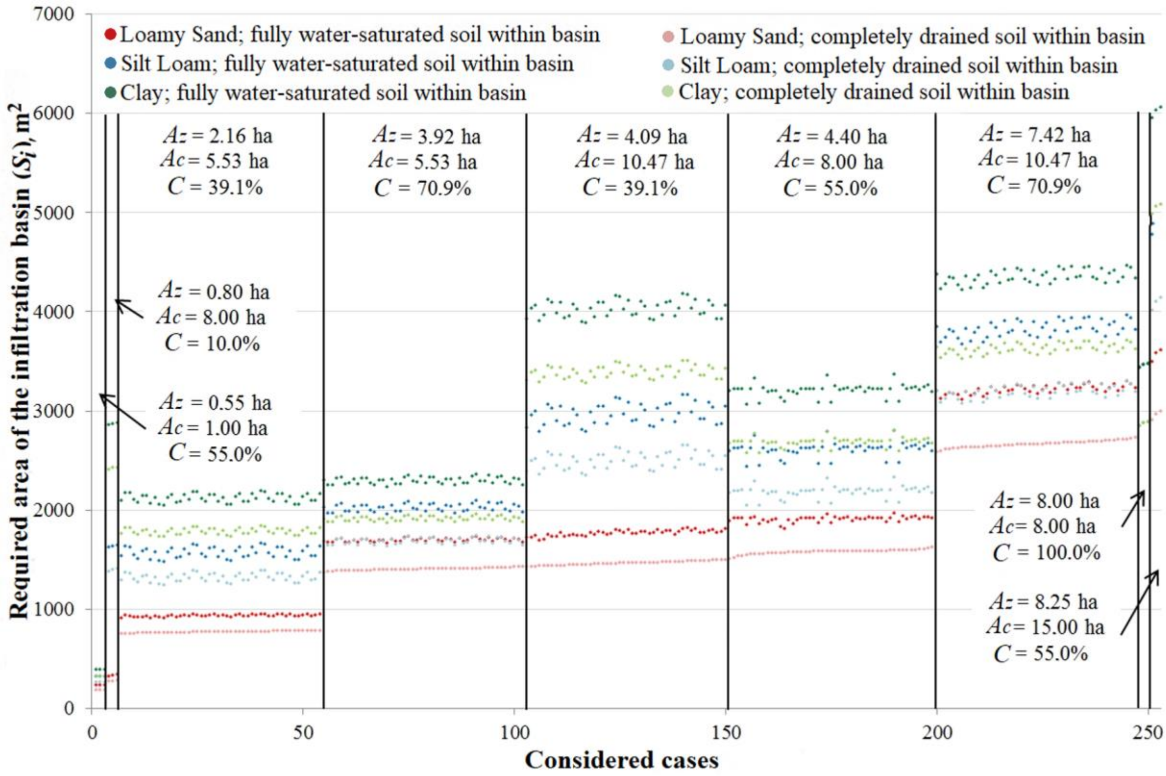


Figure 11. Results of the simulations carried out for the infiltration basin (A_z—reduced catchment area; A_c—total catchment area; C—runoff coefficient).

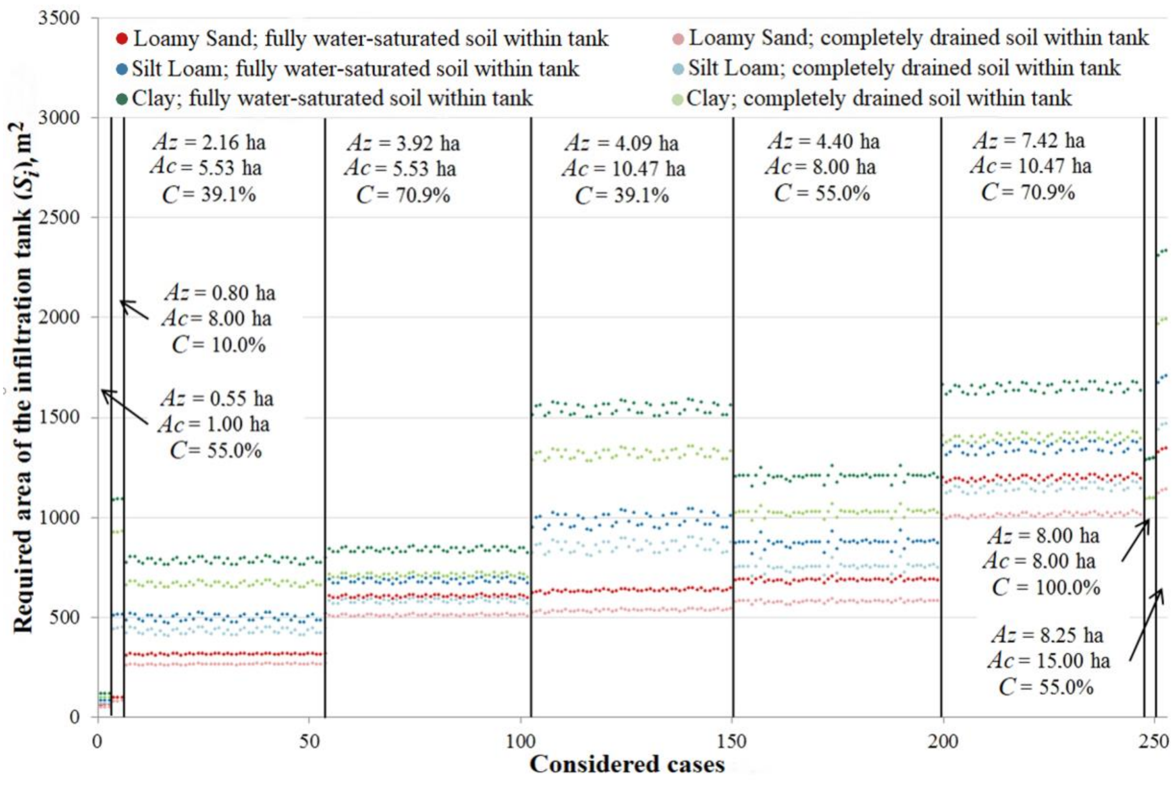


Figure 12. Results of the simulations carried out for the infiltration tank (A_z—reduced catchment area; A_c—total catchment area; C—runoff coefficient).

In the case of fully water-saturated silt loam, the required areas of the stormwater infiltration facilities (S_i) were on average more than 1.4 times larger than those for loamy sand. Slightly larger differences were observed for infiltration basins than for infiltration tanks. Additionally, the difference in the simulation results was marginally greater when the stormwater was discharged to completely drained facilities. This trend was also observed for catchments characterized by a minimum value of the runoff coefficient (C = 0.1). In this case, the determined S_i values were about five times higher than for loamy sand.

Even higher values of the required area of stormwater infiltration facilities (S_i) were obtained when assuming that there were clay soils within the catchment, the permeability of which at full water saturation is negligible. As a consequence, the vast majority of stormwater was discharged into the drainage system, and the reduced catchment area was no longer relevant. In the case of the system with the lowest degree of surface sealing, the determined value of S_i was almost nine times and more than eleven times higher than that obtained for loamy sand for infiltration basins and tanks, respectively. Conversely, the differences determined for other values of the runoff coefficient (C) fluctuated between 35 and 150%.

Based on hydrodynamic simulations, it was also found that the type of soil within the catchment directly influenced the changes in the required area of the stormwater infiltration facility (S_i) in relation to the maximum fill level of the facility. The ratio of the required bottom areas of infiltration basins and tanks turned out to be the smallest for fully water-saturated clay soils. The differences obtained in this situation were more similar, regardless of the values of the other parameters. Only when stormwater came from a one-hectare catchment did the ratio exceed 2.0. With larger total catchment areas (A_c), it was in the range of 1.53–1.63 and 1.57–1.75 for completely drained and fully water-saturated soils within the facilities, respectively. Slightly higher ratios of S_i values were obtained for sandy soils (on average 1.77 and 1.82). The highest, averaging 1.92 and 2.00, were recorded for silt loam. Therefore, these relationships do not arise directly from the permeability of the soil within the catchment. It should also be noted that the results were significantly more diversified, despite the fact that the highest value of the considered ratio, similar to clay soils, was obtained for the smallest of the studied catchments.

The analysis of the results also showed that for both infiltration basins and tanks, the initial deficit within the facility had a significant impact on the final results of the simulations. The required area of the infiltration basins (S_i) turned out to be almost 20% higher on average when the facility was fully water-saturated than when it was fully drained. In the case of infiltration tanks, these values were slightly lower; however, they still exceeded 17.5% on average. It is worth mentioning that the absolute differences between the simulation results increased with decreasing permeability of the soil within the catchment, and the reduced area of the catchment increased. This is a consequence of the increase in the amount of stormwater entering the facility. Therefore, it is important to consider the method of land development in its surroundings at the design stage of the stormwater infiltration system. It is also essential to adopt an appropriate level of security, whose premise will be to provide the required degree of protection at the relatively lowest cost.

Recognizing the relations between the other parameters and the required area of the stormwater infiltration facilities was not possible at this stage. For this reason, the Artificial Neural Networks module available in Statistica software was used, the application of which made it possible to indicate the relationships between them.

3.2. Global Sensitivity Analysis

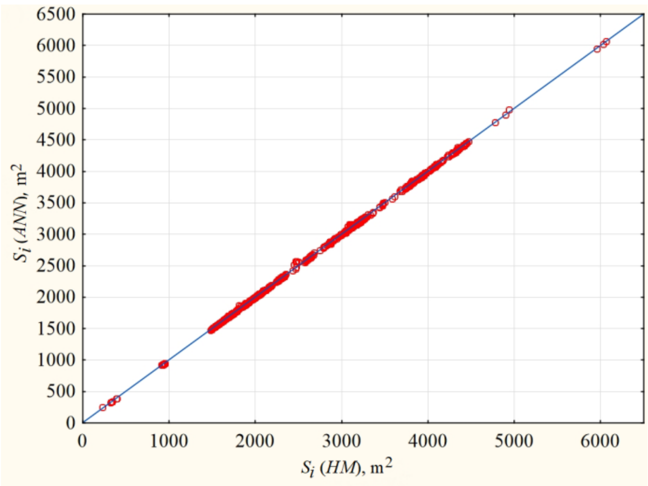
The results of the hydrodynamic simulations were implemented in the Statistica software. According to the adopted research methodology, four sets of artificial neural networks were generated to describe the connections that occur between the parameters of the drainage systems. On the basis of these, a global sensitivity analysis was conducted. The numerical values assigned to the independent variables denote their influence on the value of the dependent variable (S_i). The higher the value assigned to the parameter, the greater its importance for the final results of the analysis. This approach to assessing the impact of individual parameters on the value of the dependent variable is recommended, among others, by Kajewska-Szkudlarek [65] and Kruk and Fudała [66]. Table 3 summarizes the global sensitivity analysis results obtained for the selected ANNs. The choice of specific artificial neural networks was dictated by the degree of matching between the S_i values generated by individual ANNs and those obtained from hydrodynamic simulations (Figure 13), and additionally for randomly selected combinations of input parameters.

Table 3. Summary of the results of the global sensitivity analysis (ANNs—artificial neural networks; MLP—multilayer perception network, other designations as in Figure 2).

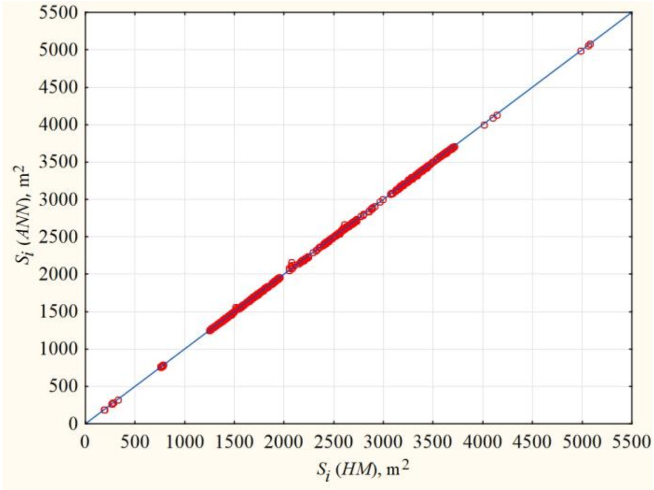
ANNs	Activation Functions	Case	A_c	Type of Soil	C	h_d	L_d	i_s	L_c	i_c	n_c	n_s
MLP 12-9-1	tanh, exponential	Infiltration basin; fully water-saturated soil	4523.3	3486.0	1010.6	14.2	5.5	3.3	2.1	1.2	1.2	1.1
MLP 12-8-1	tanh, linear	Infiltration basin; completely drained soil	5481.4	4468.5	1195.6	14.3	6.0	4.0	2.2	1.3	1.2	1.1
MLP 12-8-1	logistic, linear	Infiltration tank; fully water-saturated soil	11237.9	9869.5	2688.5	28.7	3.8	3.3	2.1	1.2	1.1	1.1
MLP 12-5-1	logistic, linear	Infiltration tank; completely drained soil	7752.8	6832.3	1789.2	17.5	3.7	2.8	1.8	1.2	1.1	1.1

Based on this analysis, it was found that the ranking of the influence of the input parameters on the required area of the stormwater infiltration facility (S_i) was the same in each case, regardless of the type of facility (infiltration basin, infiltration tank) and its degree of water saturation.

The highest numerical values, corresponding to the importance of the variable, were assigned to the total catchment area (A_c). Slightly lower values, by about 12% on average for infiltration tanks and almost 21% for basins, were obtained with the type of soil within the catchment area. This confirms that the impact of this parameter is very significant; however, it is more noticeable for facilities with higher designed fill levels. The runoff coefficient (C) ranked only third, and the numerical values assigned to it turned out to be more than four times lower than those. Therefore, these results demonstrate the lack of a proper approach to the design of drainage systems in Poland. Admittedly, the size of the reduced catchment area (A_z) is considered when calculating the required size of the infiltration facilities, but the type of soil within the catchment area from which stormwater flows is usually not included in the analysis.



(**a**)



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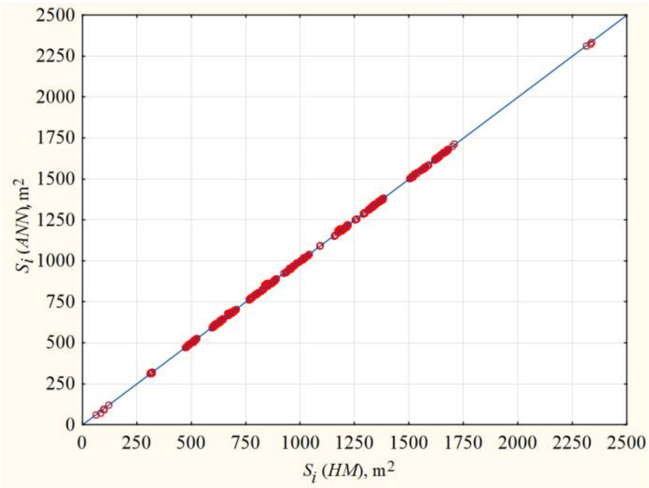

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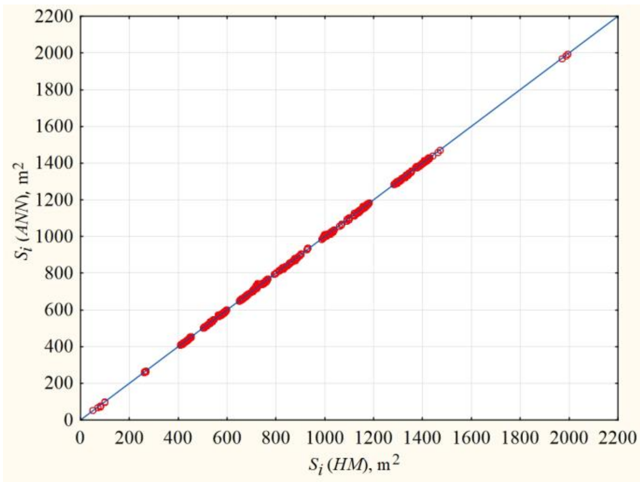


(**d**)

Figure 13. Comparison of the required area of the stormwater infiltration facility (S_i) generated from the artificial neural network (ANN) and obtained from hydrodynamic simulations (HM): (**a**) infiltration basin, fully water saturated; (**b**) infiltration basin, completely drained; (**c**) infiltration tank, fully water saturated; (**d**) infiltration tank, completely drained.

The next position in the ranking was occupied by the depth of depression storage (h_d). However, the effect of this variable on the required area of the stormwater infiltration facility (S_i) can be considered negligible. This is because the numerical values assigned to it are several hundred times lower than those obtained by the A_c variable.

In contrast, the values assigned to the other input parameters, i.e., the longest part of the system (L_d), average catchment surface slope (i_s), catchment load (L_c), average slope of the conduits bottom (i_c), catchment roughness coefficient (n_c) and number of subcatchments (n_s), did not exceed 6. 0, and in most cases only slightly exceeded 1.0. When comparing them with the values assigned to the A_c variable, which ranged from a few to several thousand, it can be assumed that the significance of these parameters for the final results of the analysis was negligibly small.

The results shown in Figure 13 demonstrate a significant match between the S_i values generated from the selected ANNs and those obtained from the hydrodynamic simulations carried out in SWMM 5.1. In regard to the combinations of parameters that were included in the construction of models in Statistica software, the differences between the two values usually did not exceed 1.0%, and only in the case of a few catchments did they reach values of several percent. Furthermore, considering the results for randomly selected combinations of input parameters (Appendix B), it can be seen that the differences between the results obtained from ANNs and hydrodynamic simulations did not exceed a few percent.

As mentioned in the Introduction, the commonly used methodology for designing stormwater infiltration facilities in Poland is based solely on the total catchment area (A_c) and the runoff coefficient (C), while the type of soil within the catchment is mostly ignored. Meanwhile, research has shown that this parameter has a greater influence on the size of the stormwater infiltration facility than the value of the runoff coefficient. Considering that the implementation of infiltration facilities is one of the most favorable ways to manage stormwater from residential catchment areas, their proper design, ensuring long-term operation, should be a goal for every investor. However, this will not be possible without considering a key parameter, the type of soil present within the catchment area.

3.3. Case Study Analysis

First, the variability in the stormwater fill level in the infiltration facility of Variant 0 was analyzed for the period from 1st January 2011 to 30th June 2022 (Figure 14). In fact, overflow risk is one of the design parameters that characterize the risk-based approach to the design of infiltration basins [67]. According to the hydrodynamic simulations, 11 rainfall events resulted in a fill level higher than the assumed designed fill level of 0.3 m. During the analyzed period of time (4199 days), the stormwater infiltration facility had a fill level above a value of 0.3 m for 1.354 days (1950 min).

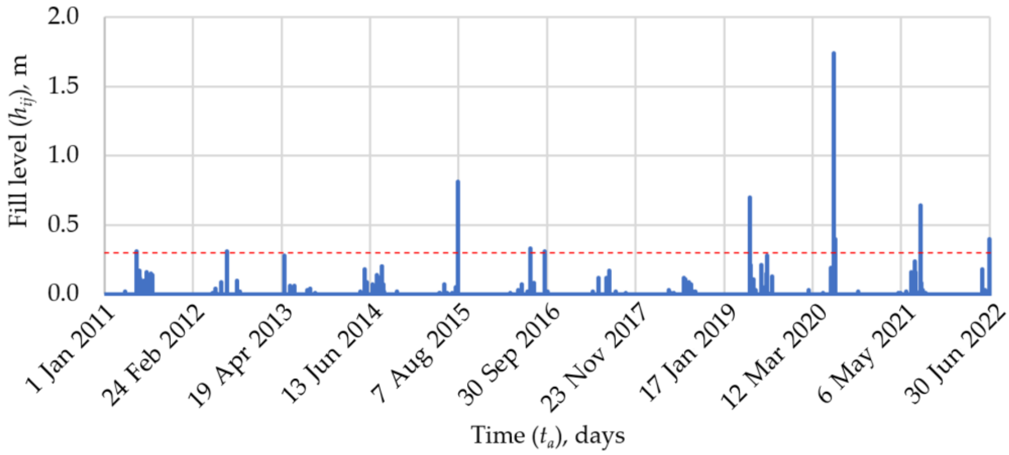


Figure 14. Stormwater fill level in the infiltration facility (blue line—actual fill level; red line—designed fill level).

As part of the research, the impact of changing the values of the selected parameters characterizing the catchment area on the fill level in the infiltration facility was assessed. As mentioned in the Materials and Methods section, the research assumed that the baseline values of the selected parameters will change within a range of $\pm$ 10%. The results of the hydrodynamic simulations are presented in Figures 15 and 16 and in Appendix C.

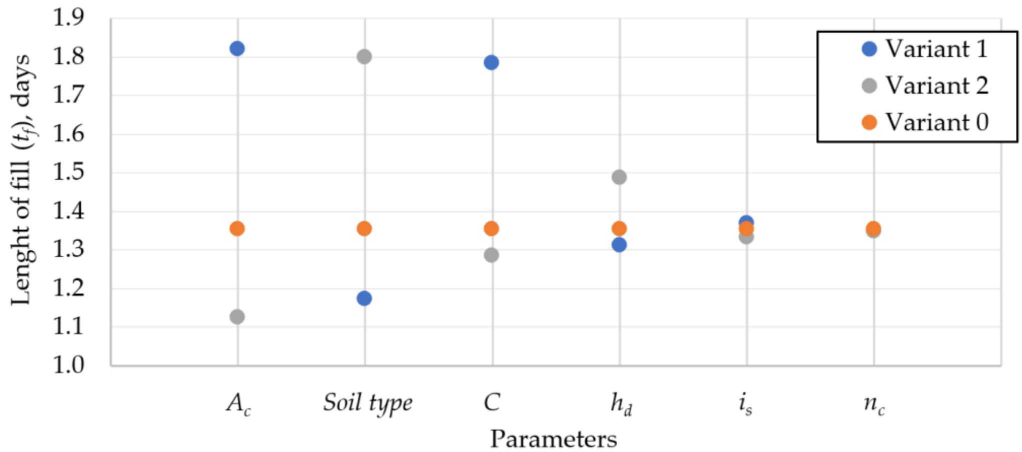


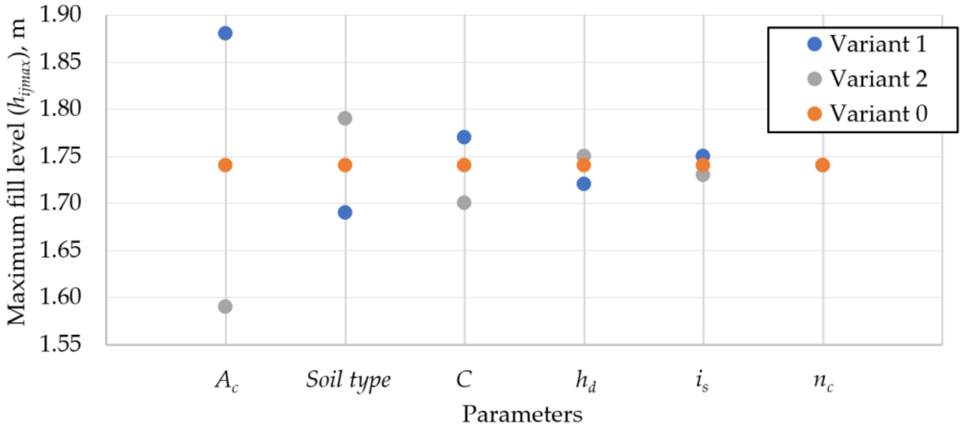
Figure 15. The length of fill of the infiltration facility above the value of h_{imax} = 0.3 m in the period from 1 January 2011 to 30 June 2022 (designations as in Figure 2).

The results of this analysis are consistent with the connections established for the model catchments. The greatest difference in the maximum fill level of the stormwater infiltration facility and the length of fill above the design height of 0.3 m was obtained when the total catchment area was changed. On the other hand, the smallest difference in the studied parameters was determined when the value of the roughness coefficient of the catchment (n_c) was changed.

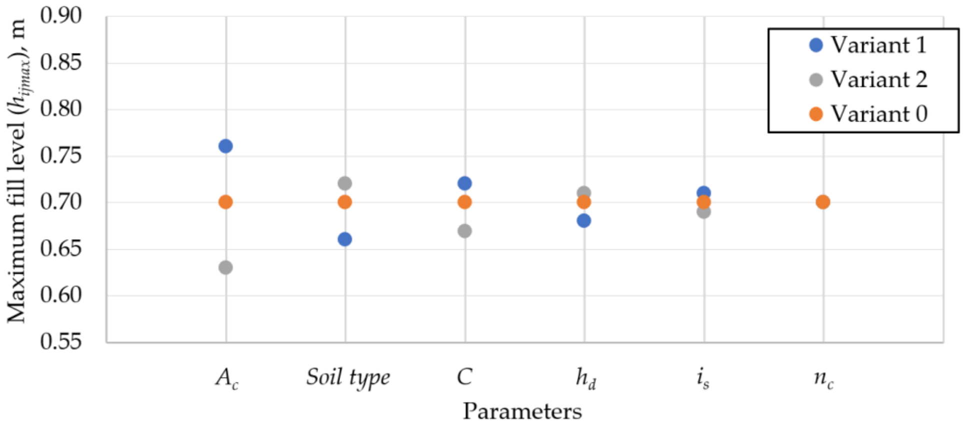
This study shows that the parameters affecting the formation of the fill level above the designed level are the total catchment area (A_c), soil type and the value of runoff coefficient (C). It was noticed that an increase in the values of the above parameters by 10% resulted in an increase in the number of rainfall events required cause the infiltration facility's designed fill level to be exceeded. In the case of the analyzed urban catchment, this was an increase from 11 to 12 rainfall events. Increasing the total catchment area (A_c) by 10% resulted in an increase in the maximum level of fill of the stormwater infiltration facility by 8.05 to 9.96%. In contrast, a 10% decrease in A_c resulted in a decrease in h_{ijmax} of approximately 8.62 to 10.33%. When the value of the roughness coefficient of the catchment (n_c) changed within a range of ±10%, there was no change in the maximum fill level of the infiltration facility and the length of its fill above the designed level of 0.3 m.

It should be noted that the degree of influence of the runoff coefficient (C) depends on the total depth of rainfall. It was found that, with increasing depth of rainfall, the effect of the C parameter on the maximum fill level of the stormwater infiltration facility decreased. For the rainfall of 19th June, 2020, which was characterized by a depth of 63.1 mm, a 10% change in the runoff coefficient (C) resulted in a 2.30% change in the maximum fill level. On the other hand, for a rainfall of 21.1 mm (8th August, 2019) a change in the maximum fill level by 7.35% was recorded. This is probably due to the fact that increasing the depth of rainfall results in increased runoff from green areas.

This research omitted changes in the catchment load (L_c), the number of subcatchments (n_s), and the slope of the bottom of the conduits (i_c). This is due to the fact that the research was performed on the existing drainage system. Its modification could result in the need for significant capital expenditure and traffic obstructions, thus resulting in increased social unrest.



(**a**)



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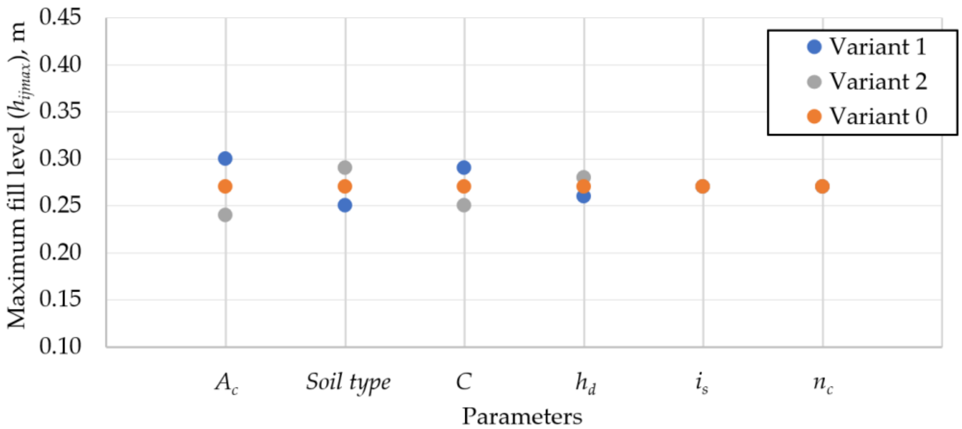

(**c**)

Figure 16. Maximum level of fill in the stormwater infiltration facility: (**a**) 19 June, 2020—p = 0.00098; (**b**) 19 May, 2019—p = 0.065; (**c**) 8 August, 2019—p = 0.53 (designations as in Figure 2).

4. Discussion

4.1. Practical Application

The application of infiltration basins and tanks is one of the most advantageous methods of stormwater management. The use of these facilities can help reduce the adverse phenomena that occur in storm water receivers. It may also contribute to supplying groundwater resources and increasing biodiversity in urban areas. However, the success of infiltration basins and tanks depends on local conditions and the availability of land for development [33,34]. It is also important to precisely determine the required area of the stormwater infiltration facility. To make this possible, it is necessary to carefully analyze all the parameters that may determine the size of this facility.

The research shows that when designing stormwater infiltration facilities, the total catchment area, soil type, and runoff coefficient should be determined with special care. This connection was confirmed in studies of bioretention cells working in real conditions [68]. The total catchment area and the runoff coefficient also play an important role in the dimensioning of retention reservoirs. Pochwat [47] showed that the reduced catchment area is one of the factors that has the greatest impact on the functioning of such facilities. Therefore, it can be assumed that these parameters should be determined with careful consideration when designing all the elements of the drainage infrastructure. If a numerical terrain model and satellite images are used, the extent of the catchment area and its management can be determined with a high degree of accuracy. Currently, the use of DEM is one of the primary sources of information when developing hydrodynamic models [69]. Based on the DEM, it is possible to extract geomorphological and hydrological data, such as slope, stream network, watershed delineation, flow direction or accumulation patch [70].

As mentioned above, the results of the analysis also indicate the need to consider the type of soil within the catchment area when designing stormwater infiltration facilities. On the basis of the authors' expertise, it is known that the biggest problem is access to data characterizing the soil. To obtain a good representation of the spatial variability of the soil, it is necessary to drill an adequate number of boreholes. This is particularly cumbersome in the case of catchments with large areas. Although detailed studies of the physical properties of the soil within the catchment area are time-consuming and sometimes involve significant financial outlays, they are considered necessary for the construction of a reliable hydrodynamic model. This is especially true when there are no historical data on stormwater flows in the drainage system or streams. Other authors have already pointed out the need to accurately determine the physical properties of the soil when designing drainage systems [71]. Batalini de Macedo et al. [72] indicated that the type of soil within the catchment area determines the volume of inflow to LID facilities. Nguyen et al. [73] further emphasized that during flash floods, stormwater infiltration is the most important loss in water balance. Therefore, a good understanding of this process is crucial for representing runoff losses.

It should also be noted that the amount of runoff from green spaces depends on the amount of rainfall. Thus, the impact of the runoff coefficient on the operation of the drainage infrastructure varies depending on the characteristics of the rainfall. The influence of rainfall intensity and duration on the sensitivity of parameters that characterize infiltration facilities was also confirmed by Xu et al. [74] on the example of urban green land. Considering that the formation of surface runoff within permeable surfaces depends on the hydraulic conductivity of the soil, precise determination of the physical properties of the soil should be a priority.

The importance of the other parameters characterizing the catchment area proved to be far less significant. However, this does not mean that these parameters can be completely ignored. It only suggests that a slight deviation in their values from the actual values will not result in significant changes in the facility size at which increased flood risk might occur.

The analysis on the real urban catchment also shows that the change in the probability of rainfall, and thus its height, does not change the established hierarchy of significance of the studied parameters. The relations that were obtained for the model catchments were confirmed even with extreme rainfall, which had a probability of $p = 0.00098$. Considering that many regions of the world are experiencing an increase in extreme rainfall events [75,76], this finding is particularly significant and confirms that the results of the analysis can be applied not only to Poland, but also to other regions of the world.

4.2. Limitations and Further Research

A limitation of this research is that other types of soil were not included in the analysis. Therefore, the next stage of the research will be to analyze the hydraulic performance of infiltration facilities in catchments characterized by different soil and water conditions. The effect of the spatial variability of the catchment on the required area of stormwater infiltration facilities will also be investigated. This is because the drainage infrastructure is sensitive not only to the value of soil input data, but also to the spatial explicitness of these data. This is confirmed by the research of Hossain Anni et al. [77] with regard to the flood simulation predictions.

It should also be noted that the research was carried out for strictly defined parameters of the infiltration facilities. Therefore, in the next stage of the research it is planned to evaluate the impact of changes in the geometry of the facility and the type of soil within it on the final results of the analysis.

5. Conclusions

This paper evaluated the influence of parameters that characterize the catchment on the required area of a stormwater infiltration facility. The results of the model studies were further confirmed on a real urban catchment, for which the hydraulic performance of the infiltration facility was analyzed. The study confirmed that the key significance in the design of drainage infrastructure, including infiltration facilities, has the total catchment area, the type of soil within it and the value of the runoff coefficient. The importance of the other parameters that characterize the catchment was noticeably lower. Their slight inconsistency with actual conditions did not result in significant changes in the facility size at which increased flood risk might occur. However, this does not mean that the values of these parameters can be adopted indiscriminately, without careful analysis of the characteristics of the catchment area.

Considering that only homogeneous catchments were considered in the study, future research will focus on the analysis of the impact of spatial variability of the catchment on the required area of stormwater infiltration facilities. In addition, the impact of the parameters that characterize the infiltration facility on its required capacity will be assessed.

These results should be considered when using SWMM software to design drainage infrastructure, mainly infiltration facilities. They will be particularly useful in the development of hydrodynamic models in the absence of comprehensive data characterizing the catchment. Designers can also use them to initially identify the required capacity of infiltration facilities. Furthermore, the findings of this analysis may help young scientists in their research as they contribute to a better understanding of the knowledge structure in stormwater management. Together with the findings of other researchers and people involved in promoting the idea of sustainable stormwater management, this paper may contribute to the further development of stormwater infiltration systems.

Author Contributions: Conceptualization, S.K.-O. and M.S.; methodology, S.K.-O. and M.S.; software, S.K.-O. and M.S.; validation, S.K.-O.; formal analysis, S.K.-O.; investigation, S.K.-O. and M.S.; writing—original draft preparation, S.K.-O. and M.S.; writing—review and editing, S.K.-O.; visualization, S.K.-O. and M.S.; supervision, D.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Rainfall data are available at: https://danepubliczne.imgw.pl/ (accessed on 30 September 2022). GIS data are available at: https://www.geoportal.gov.pl/uslugi/usluga-przegladania-wms (accessed on 30 September 2022).

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1 presents the research plan, including the values of the input parameters.

Table A1. Research plan including the values of the input parameters (designations as in Figure 2).

A_c ha	L_c ha/km	n_s No.	C %	i_c ‰	h_d mm	i_s ‰	n_c s/m$^{1/3}$
5.53	6.6	10	39.1	0.4	2.13	3.5	0.015
5.53	6.6	10	70.9	0.4	1.68	2.0	0.020
5.53	6.6	21	39.1	0.7	2.13	2.0	0.020
5.53	6.6	21	70.9	0.7	1.68	3.5	0.015
5.53	8.4	10	39.1	0.4	1.68	2.0	0.015
5.53	8.4	10	70.9	0.4	2.13	3.5	0.020
5.53	8.4	21	39.1	0.7	1.68	3.5	0.020
5.53	8.4	21	70.9	0.7	2.13	2.0	0.015
10.47	6.6	10	39.1	0.7	2.13	2.0	0.015
10.47	6.6	10	70.9	0.7	1.68	3.5	0.020
10.47	6.6	21	39.1	0.4	2.13	3.5	0.020
10.47	6.6	21	70.9	0.4	1.68	2.0	0.015
10.47	8.4	10	39.1	0.7	1.68	3.5	0.015
10.47	8.4	10	70.9	0.7	2.13	2.0	0.020
10.47	8.4	21	39.1	0.4	1.68	2.0	0.020
10.47	8.4	21	70.9	0.4	2.13	3.5	0.015
8.00	7.5	16	55.0	0.6	1.91	2.8	0.018
5.53	6.6	10	39.1	0.7	1.68	3.5	0.015
5.53	6.6	10	70.9	0.7	2.13	2.0	0.020
5.53	6.6	21	39.1	0.4	1.68	2.0	0.020
5.53	6.6	21	70.9	0.4	2.13	3.5	0.015
5.53	8.4	10	39.1	0.7	2.13	2.0	0.015
5.53	8.4	10	70.9	0.7	1.68	3.5	0.020
5.53	8.4	21	39.1	0.4	2.13	3.5	0.020
5.53	8.4	21	70.9	0.4	1.68	2.0	0.015
10.47	6.6	10	39.1	0.4	1.68	2.0	0.015
10.47	6.6	10	70.9	0.4	2.13	3.5	0.020
10.47	6.6	21	39.1	0.7	1.68	3.5	0.020
10.47	6.6	21	70.9	0.7	2.13	2.0	0.015
10.47	8.4	10	39.1	0.4	2.13	3.5	0.015
10.47	8.4	10	70.9	0.4	1.68	2.0	0.020
10.47	8.4	21	39.1	0.7	2.13	2.0	0.020
10.47	8.4	21	70.9	0.7	1.68	3.5	0.015
8.00	7.5	16	55.0	0.6	1.91	2.8	0.018
5.53	6.6	10	39.1	0.4	1.68	3.5	0.020
5.53	6.6	10	70.9	0.4	2.13	2.0	0.015
5.53	6.6	21	39.1	0.7	1.68	2.0	0.015
5.53	6.6	21	70.9	0.7	2.13	3.5	0.020
5.53	8.4	10	39.1	0.4	2.13	2.0	0.020
5.53	8.4	10	70.9	0.4	1.68	3.5	0.015
5.53	8.4	21	39.1	0.7	2.13	3.5	0.015
5.53	8.4	21	70.9	0.7	1.68	2.0	0.020
10.47	6.6	10	39.1	0.7	1.68	2.0	0.020
10.47	6.6	10	70.9	0.7	2.13	3.5	0.015
10.47	6.6	21	39.1	0.4	1.68	3.5	0.015
10.47	6.6	21	70.9	0.4	2.13	2.0	0.020
10.47	8.4	10	39.1	0.7	2.13	3.5	0.020
10.47	8.4	10	70.9	0.7	1.68	2.0	0.015
10.47	8.4	21	39.1	0.4	2.13	2.0	0.015
10.47	8.4	21	70.9	0.4	1.68	3.5	0.020
8.00	7.5	16	55.0	0.6	1.91	2.8	0.018

Table A1. *Cont.*

A_c ha	L_c ha/km	n_s No.	C %	i_c ‰	h_d mm	i_s ‰	n_c s/m$^{1/3}$
5.53	6.6	10	39.1	0.7	2.13	3.5	0.020
5.53	6.6	10	70.9	0.7	1.68	2.0	0.015
5.53	6.6	21	39.1	0.4	2.13	2.0	0.015
5.53	6.6	21	70.9	0.4	1.68	3.5	0.020
5.53	8.4	10	39.1	0.7	1.68	2.0	0.020
5.53	8.4	10	70.9	0.7	2.13	3.5	0.015
5.53	8.4	21	39.1	0.4	1.68	3.5	0.015
5.53	8.4	21	70.9	0.4	2.13	2.0	0.020
10.47	6.6	10	39.1	0.4	2.13	2.0	0.020
10.47	6.6	10	70.9	0.4	1.68	3.5	0.015
10.47	6.6	21	39.1	0.7	2.13	3.5	0.015
10.47	6.6	21	70.9	0.7	1.68	2.0	0.020
10.47	8.4	10	39.1	0.4	1.68	3.5	0.020
10.47	8.4	10	70.9	0.4	2.13	2.0	0.015
10.47	8.4	21	39.1	0.7	1.68	2.0	0.015
10.47	8.4	21	70.9	0.7	2.13	3.5	0.020
8.00	7.5	16	55.0	0.6	1.91	2.8	0.018
1.00	7.5	16	55.0	0.6	1.91	2.8	0.018
15.00	7.5	16	55.0	0.6	1.91	2.8	0.018
8.00	5.0	16	55.0	0.6	1.91	2.8	0.018
8.00	10.0	16	55.0	0.6	1.91	2.8	0.018
8.00	7.5	1	55.0	0.6	1.91	2.8	0.018
8.00	7.5	30	55.0	0.6	1.91	2.8	0.018
8.00	7.5	16	10.0	0.6	1.91	2.8	0.018
8.00	7.5	16	100.0	0.6	1.91	2.8	0.018
8.00	7.5	16	55.0	0.1	1.91	2.8	0.018
8.00	7.5	16	55.0	1.0	1.91	2.8	0.018
8.00	7.5	16	55.0	0.6	1.27	2.8	0.018
8.00	7.5	16	55.0	0.6	2.54	2.8	0.018
8.00	7.5	16	55.0	0.6	1.91	0.5	0.018
8.00	7.5	16	55.0	0.6	1.91	5.0	0.018
8.00	7.5	16	55.0	0.6	1.91	2.8	0.011
8.00	7.5	16	55.0	0.6	1.91	2.8	0.024
8.00	7.5	16	55.0	0.6	1.91	2.8	0.018

Appendix B

Tables A2–A5 present a comparison of the results generated for a random combination of input parameters from artificial neural networks and hydrodynamic simulations.

Table A2. Comparison of the required areas of the fully water-saturated infiltration basin (S_i) generated for a random combination of input parameters from the MLP 12-9-1 artificial neural network (ANN) and those obtained from hydrodynamic simulations (HM) (designations as in Figure 2).

A_c ha	L_c ha/km	n_s No.	C %	i_c ‰	h_d mm	i_s ‰	n_c s/m$^{1/3}$	L_{max} m	Type of Soil	S_i (HM) m^2	S_i (ANN) m^2	ΔS_i %
10.8	9.2	9	32.2	0.7	1.74	3.9	0.012	521.6	silt loam	2957.25	2923.27	–1.15
5.5	8.7	26	93.3	0.3	1.78	1.0	0.023	315.9	loamy sand	2149.40	2146.04	–0.16
10.9	9.4	1	94.0	0.2	1.68	1.6	0.014	1159.6	silt loam	4290.85	4379.69	2.07
11.7	5.7	21	58.4	0.2	2.03	3.7	0.018	1074.7	loamy sand	2910.40	3026.96	4.00
5.6	6.6	18	16.2	0.6	2.43	4.9	0.012	847.8	clay	1982.50	1962.13	–1.03

Table A3. Comparison of the required areas of the completely drained infiltration basin (S_i) generated for a random combination of input parameters from the MLP 12-8-1 artificial neural network (ANN) and those obtained from the hydrodynamic simulations (HM) (designations as in Figure 2).

A_c ha	L_c ha/km	n_s No.	C %	i_c ‰	h_d mm	i_s ‰	n_c s/m$^{1/3}$	L_{max} m	Type of Soil	S_i (HM) m^2	S_i (ANN) m^2	ΔS_i %
9.1	5.7	18	55.9	0.7	2.40	4.2	0.011	521.2	loamy sand	1802.80	1795.83	–0.39
1.4	5.8	28	59.7	0.3	2.03	3.4	0.013	1687.4	loamy sand	713.05	758.81	6.42
13.5	9.1	10	36.2	0.3	1.74	3.5	0.018	1221.0	clay	3742.10	3607.47	–3.60
5.1	8.4	6	36.7	0.8	1.35	3.7	0.015	855.0	silt loam	1580.35	1653.68	4.64
12.9	7.7	25	91.9	0.3	1.78	1.4	0.013	156.25	loamy sand	304.10	323.50	6.38

Table A4. Comparison of the required areas of the fully water-saturated infiltration tank (S_i) generated for a random combination of input parameters from the MLP 12-8-1 (ANN) artificial neural network (ANN) and those obtained from the hydrodynamic simulations (HM) (designations as in Figure 2).

A_c ha	L_c ha/km	n_s No.	C %	i_c ‰	h_d mm	i_s ‰	n_c s/m$^{1/3}$	L_{max} m	Type of Soil	S_i (HM) m^2	S_i (ANN) m^2	ΔS_i %
9.1	5.7	18	55.9	0.7	2.40	4.2	0.011	887.0	clay	1354.30	1366.98	0.94
1.4	5.8	28	59.7	0.3	2.03	3.4	0.013	129.0	silt loam	130.80	133.84	2.33
13.5	9.1	10	36.2	0.3	1.74	3.5	0.018	1483.5	loamy sand	760.80	776.79	2.10
5.1	8.4	6	36.7	0.8	1.35	3.7	0.015	607.2	silt loam	482.95	486.88	0.81
12.9	7.7	25	91.9	0.3	1.78	1.4	0.013	402.0	clay	2128.70	2032.74	–4.51

Table A5. Comparison of the required areas of the completely drained infiltration tank (S_i) generated for a random combination of input parameters from the MLP 12-5-1 (ANN) artificial neural network (ANN) and those obtained from the hydrodynamic simulations (HM) (designations as in Figure 2).

A_c ha	L_c ha/km	n_s No.	C %	i_c ‰	h_d mm	i_s ‰	n_c s/m$^{1/3}$	L_{max} m	Type of Soil	S_i (HM) m^2	S_i (ANN) m^2	ΔS_i %
2.8	9.4	4	97.1	0.3	1.72	0.7	0.022	223.5	clay	340.80	337.54	0.95
4.4	7.9	27	67.6	0.9	2.49	2.0	0.017	494.4	loamy sand	369.15	372.36	0.87
4.1	7.6	15	30.0	0.1	2.36	1.8	0.020	216.0	loamy sand	132.55	131.68	–0.65
3.0	8.4	21	60.1	0.4	2.22	0.9	0.016	323.0	loamy sand	210.15	214.44	2.04
2.2	5.1	13	66.5	1.0	2.24	4.9	0.012	165.9	silt loam	198.80	212.76	7.02

Appendix C

Tables A6 and A7 present the results of hydrodynamic simulations of the analyzed urban catchment.

Table A6. The length of fill of the infiltration facility above the value of h_{imax} = 0.3 m in the period from 1 January 2011 to 30 June 2022 (designations as in Figure 2).

Length of fill of the infiltration facility above the level of h_{imax} = 0.3 m (days)						
	A_c	*Soil type*	C	h_d	i_s	n_c
Variant 1	1.82	1.17	1.78	1.31	1.37	1.35
Variant 0				1.35		
Variant 2	1.13	1.80	1.28	1.49	1.33	1.35
Percentage change in the length of fill above the level of h_{imax} = 0.3 m compared to Variant 0						
Variant 1	34.36	–13.33	31.79	–3.08	1.03	0.00
Variant 2	–16.92	32.82	–5.13	9.74	–1.54	0.00

Table A7. Maximum fill level of the infiltration facility (designations as in Figure 2).

Maximum Fill Level of the Infiltration Facility (m)						
	A_c	*Soil Type*	C	h_d	i_s	n_c
Rainfall on 19 June 2020						
Variant 1	1.88	1.70	1.75	1.73	1.74	1.74
Variant 0	1.74	1.74	1.74	1.74	1.74	1.74
Variant 2	1.59	1.77	1.72	1.75	1.74	1.74
Percentage change in the maximum fill level of the infiltration facility (h_{ijmax})						
Variant 1	8.05	–2.30	0.57	–0.57	0.00	0.00
Variant 2	–8.62	1.72	–1.15	0.57	0.00	0.00
Rainfall on 19 May 2019						
Variant 1	0.76	0.66	0.72	0.68	0.71	0.70
Variant 0	0.70	0.70	0.70	0.70	0.70	0.70
Variant 2	0.63	0.72	0.67	0.71	0.69	0.70
Percentage change in the maximum fill level of the infiltration facility (h_{ijmax})						
Variant 1	8.57	–5.71	2.86	–2.86	1.14	0.00
Variant 2	–9.84	2.89	–4.29	1.43	–1.28	0.00
Rainfall on 8 August 2019						
Variant 1	0.30	0.25	0.29	0.26	0.27	0.27
Variant 0	0.27	0.27	0.27	0.27	0.27	0.27
Variant 2	0.24	0.29	0.25	0.28	0.27	0.27
Percentage change in the maximum fill level of the infiltration facility (h_{ijmax})						
Variant 1	9.96	–7.35	6.64	–2.78	0.00	0.00
Variant 2	–10.33	7.04	–7.01	2.96	0.00	0.00

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