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Preventing extreme events in the urban environment using blue–Green infrastructure

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ABSTRACT

The presented paper draws attention to the need to adapt urban areas to the negative impacts of climate change, more precisely to the solution of extreme rainfalls and long dry periods. The topic of rainwater management is popular worldwide due to the worsening situation in the field of climate change. Extreme weather fluctuations and torrential rains stress the urban hydrological cycle. Adaptation measures are proposed that mitigate the impact of climate change in cities. These also include measures to retain water in the country. The paper focuses on drainage density analysis, runoff coefficients and impermeability analysis, and the selection of appropriate measures to reduce surface runoff.

KEYWORDS

drainage systems, non-stationary precipitation-runoff process, urbanization

1. INTRODUCTION

Urban sewage systems are negatively affected by climate change. Its consequences can be observed in Slovakia. An illustrative example is e. g., the year 2018, which was characterized by a devastating drought in almost the entire territory of Slovakia. The drought, lasting from April to the end of October, was interrupted only by short periods of rainfalls characterized by high intensity. It follows from the long-term observations of the Slovak Hydrometeorological Institute that the total amount of precipitation for this year was far below the value of the long-term average for 1989–2019 [1]. The impacts of climate change affect the operation and assessment of sewer networks. As a result of climate change, long periods of drought occur more often, alternating with extreme rain events, sometimes with heavy torrential rains. These can cause an increase in the discharge of mixed wastewater into the receiving water or an overload of sewer networks, resulting in urban floods. Climate change and its impact on sewage networks and wastewater removal from urbanized areas have been frequently discussed in recent years. Many studies focus on assessing the interaction of the consequences of climate change and urbanization on sewage networks. According to the research of Grum et al. [2], an increase in the values of the design parameters Intensity Duration Frequency (IDF) curves can lead to an increase in the average rainwater runoff by up to 17% [2]. Many studies demonstrate the necessity of changing the design concept of urban sewer networks. The conventional way of dealing with wastewater in cities was based on the fastest drainage from the urbanized area. This concept ensures the prevention of threats to human life and property, traffic restrictions, and the negative impact of these waters on the regime and quality of surface and underground waters. Sewer systems designed based on this concept have been characterized as hydraulically highly efficient. The disadvantage is that it does not consider the impact of the designed sewer networks and their facilities on the environment. Due to the changes in urban watersheds' hydrological and hydrogeological parameters, this concept has proven to be insufficient over time [3].

The modern concept of wastewater removal from an urbanized environment combines all the urban drainage system components into one integrated system. The system's basic components are the sewer network and its objects, the wastewater treatment plant, and the receiving water. The concept evaluates the mutual interaction of individual components and their interaction with the surrounding environment of the urbanized area [3]. Increasing the infiltration capacity has always been one of the primary methods of reducing surface runoff and minimizing its impacts [4]. In line with this idea, several urban stormwater management strategies have been designed and implemented in recent years. Examples of these measures include Water-Sensitive Urban Design (WSUD) in Australia, Sustainable Drainage Systems (SuDS) in the UK, Best Management Practices (BMP), and Low Impact Development (LID) in the USA [4].

2. MATERIAL AND METHODS

2.1. Study area

The selected area is part of the city of Trnava's combined sewer network, namely the sewer collector A's catchment area. This area has been the subject of a long-term study by the Department of Sanitary and Environmental Engineering, Faculty of Civil Engineering, Slovak University of Technology in Bratislava teams, evidenced publications of Wittmanová and Csóka [5, 6]. The catchment area of collector A extends on the left bank of the river Trnávka and consists of 23 urban districts. The catchment consists of one main collector and 11 secondary branches. Trnava is located east of the capital city and extends into the central part of the Trnava Hills. The most cadastral territory is dominated by Aeolian loess, forming a relatively homogeneous soil cover. The soil-forming substrate consists mainly of Würmian to Holocene sediments (loess and fluvial sediments), which also results from the geological survey for Hlboká Street in Trnava and map number 4: Substrate - geological conditions [7]. Figure 1 presents the location of Trnava and the selected study area.

2.2. Drainage density analysis

The density of the pipeline network is defined as the ratio of the pipeline's total length to the basin's area. It expresses the degree of density of the pipe network in the given catchment. A high value of the density of the pipe network means that there is a sufficiently long network per unit area in the catchment area, and thus the rainfall-runoff is removed more quickly [8].

2.3. Analysis of build-up area, runoff coefficient and imperviousness

In the formation of surface runoff, an important role is played by the construction and land use, which significantly influences the runoff coefficient of the territory. When

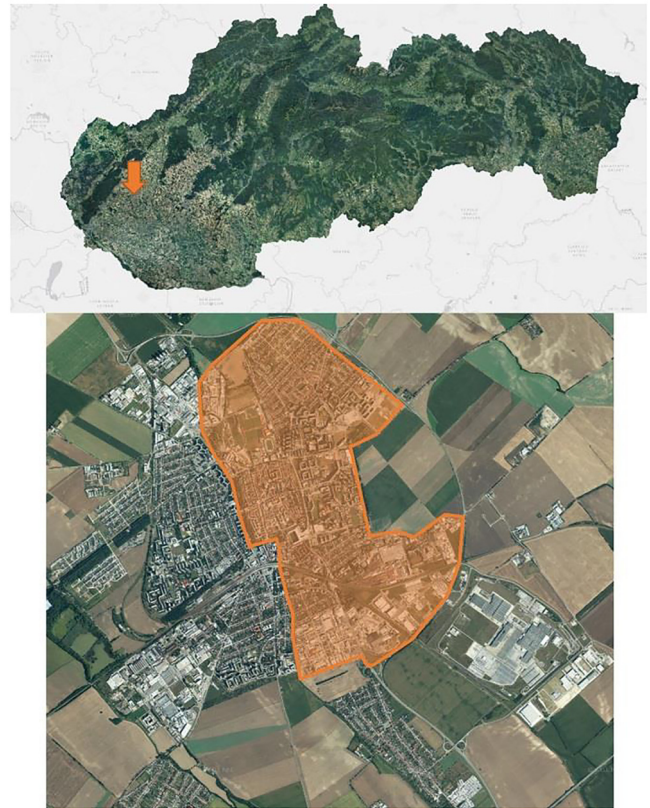


Fig. 1. The location of the study area

determining the sewerage catchments, it is necessary to consider the uniform type of build-up area in the entire catchment. The type of construction is specified based on map documents, satellite, and orthophoto images and a field survey.

For this study, to create some sample sub-catchments to determine the average values of impermeability was needed. The impermeability can be identified according to the runoff coefficient of the sample sub-catchments (Ψ_s),

$$\Psi_s = \sum_{i=1}^n \Psi_i S_i \left(\sum_{i=1}^n S_i \right)^{-1}, \quad (1)$$

where, S_i is the partial catchments with a uniform surface treatment; Ψ_i is the partial runoff coefficients corresponding to the type of surface and the catchment slope.

It follows from the formula that the runoff coefficient defines as a ratio of the volume of maximum rain flow, $Q_{\max}$ that flows out of an elementary area ΔS_s with the same surface treatment and the volume of precipitation fall currently to an elementary area, $q \Delta S_s \Delta t$, [9].

2.4. Measures to reduce the impact of extreme precipitation in the urban environment

The purpose of the rainwater management system is to create natural conditions for the drainage of rainwater from the urban environment, bringing the urban hydrological cycle closer to the natural cycle. It perceives the removal of

surface runoff into the sewer network as the last solution when other methods are no longer an option [10]. The priority in the proposal is to divert rainwater from the urbanized area so that it positively affects the urban environment to the greatest extent possible. However, the degree of impact depends on the current local conditions and legal regulations that specify the criteria for the qualitative and quantitative parameters of the discharged volume. Many studies describe the beneficial effect of integrated stormwater management facilities on human health and increasing the value of the real estate in each location [11]. The equipment selection for a rainwater management system is based on geological and hydrological conditions, the state of the receiving water, spatial arrangement, and architectural integration [12]. By incorporating these devices into the municipal drainage system, the goal is to minimize the runoff surface runoff through a combined sewer system, i.e., to reduce the peak flow in the sewer network and the reduced volume of wastewater to the recipient. Devices promoting evaporation, infiltration, and slow runoff are designed to reduce surface runoff. In general, a distinction is made between two basic categories of devices: decentralized and centralized [13]. Decentralized devices capture surface runoff at the place of its origin and thereby create conditions for the preservation of the natural hydrological cycle. These are surface and subsurface infiltration objects: green roofs, grassed areas, permeable reinforced areas (vegetation blocks), and trenches with grass, filter layer, perforated drainage pipes with gravel-sand filling, and infiltration trenches [12]. The second group consists of centralized facilities, representing a drainage system for larger groups of residential units. There can be included retention infiltration tanks and systems of depressions, and infiltration trenches [13]. Green roofs regulate runoff volume, improve air, and water quality, and promote energy savings for heating or air conditioning and cooling the building's interior spaces. Their primary advantage is the retention of rainwater from torrential rains and reducing and flattening of the tidal wave of rainwater in the sewage network. The design of green roofs in urbanized areas with a large percentage of paved areas changes the runoff coefficient, and the volume of surface runoff is reduced.

3. RESULTS AND DISCUSSION

3.1. Drainage density analysis

The study catchment was divided into five characteristic sub-catchments (see Table 1). Sub-catchments were established based on the sewer network's hydro technical situation and the main collectors' location. The average degree of the drainage density was calculated based on the total length of the assessed sewer network and the catchment's total area. Its value is 9.6 km km^{-2} . Sub-catchment P1 includes the areas falling under catchments of collectors D, C, VD, and A9a. It is characterized as a densely populated and built-up area of the territory of interest. The build-up area can be

Table 1. Drainage density analysis

Sub-catchment	Area (km^2)	Length (km)	Drainage density (km/km^{-2})
P _{sum.}	6.8	65.9	9.6
P1	2.9	31.2	10.9
P2	1.0	11.0	11.5
P3	0.9	6.5	7.3
P4	1.0	5.8	5.7
P5	1.1	11.5	10.8

characterized as mixed. Part of the territory consists of family houses, part of a housing estate with a sports area, and part of paved parking areas and a shopping center. The degree of drainage density is 10.9 km km^{-2} . The P2 sub-catchment also has a high density of up to 11.5 km km^{-2} . It is situated in the historic center, which has impermeable surface. This sub-catchment includes the areas of I, II, V, and part of A branches. Sub-catchment P3 shows a lower drainage density. However, it should be noted that this catchment is situated in a residential area with extensive green areas. The lowest drainage density level is shown by sub-catchment P4 (5.7 km km^{-2}), which extends into the industrial area and the development of family houses. The P5 sub-catchment also has a high pipe network density of up to 10.8 km km^{-2} . The given area belongs to the catchment areas A and AN, and the development consists of apartments, family houses, and an industrial area.

3.2. Analysis of build-up area, runoff coefficient and imperviousness

The character of the building and surface treatment of the study area is very diverse. Therefore, the formation of seven sample sub-catchment was needed. There are characterized by six basic build-up areas: housing development (settlement), family housing, industrial and commercial areas, green areas (parks and playgrounds), historic core, traffic, and similar areas. The surface runoff calculation using the rational method includes the character of the surfaces as a runoff coefficient, which depends on the configuration of the terrain, the construction method, and the land type.

The analysis was carried out based on the provided background materials, which contained map documents, data from cadastral maps and a field inspection of the study area. The estimation of the average values of impermeability and the values of the average runoff coefficient for seven sample sub-catchments are shown in Table 2. The average imperviousness of the model sub-catchments, shown in Fig. 2 was determined based on the average runoff coefficients.

3.3. Design of green roof for the runoff coefficient reduction in highly urbanized areas

Based on the analysis of runoff coefficients and impermeability results, it can be concluded that the areas falling under the sample sub-catchments 4, 5, and 6 contribute the most significant volume of overflowed surface runoff to the sewer network.



Table 2. The average values of runoff coefficient (Ψ_s), and impermeability (I_m)

Sub-catchment no.	Ψ_s (–)	I_m (%)
1	0.51–0.57	35–45
2	0.57	45
3	0.36	10
4	0.78–0.72	80–70
5	0.78–0.66	80–60
6	0.84	90
7	0.60	50

There are mainly industrial buildings in the given areas, which offer the possibility of using objects for collecting and managing rainwater. The area of interest's geological subsoil is unsuitable for infiltration facilities. Therefore, it is necessary to take measures to increase the green areas in the area.

Table 3. Green roof layers

Layers	Thickness (mm)
Extensive green roof substrate	60
Geotextile geoNetex MB 200	<2
Foil DSE 20	20
Geotextile geoNetex MB 300	<2
Asphalt foil Plant E	<5
Rockwool ISOVER T 10	100
Rockwool ISOVER T 14	140
Vapour barrier Bauder EVA 35	<1
Pack from graded aggregate fr. 16/32	60
Σ	390

One possibility is the design of green roofs on industrial buildings. After extensive research, the green roof construction for the area is shown in Table 3.

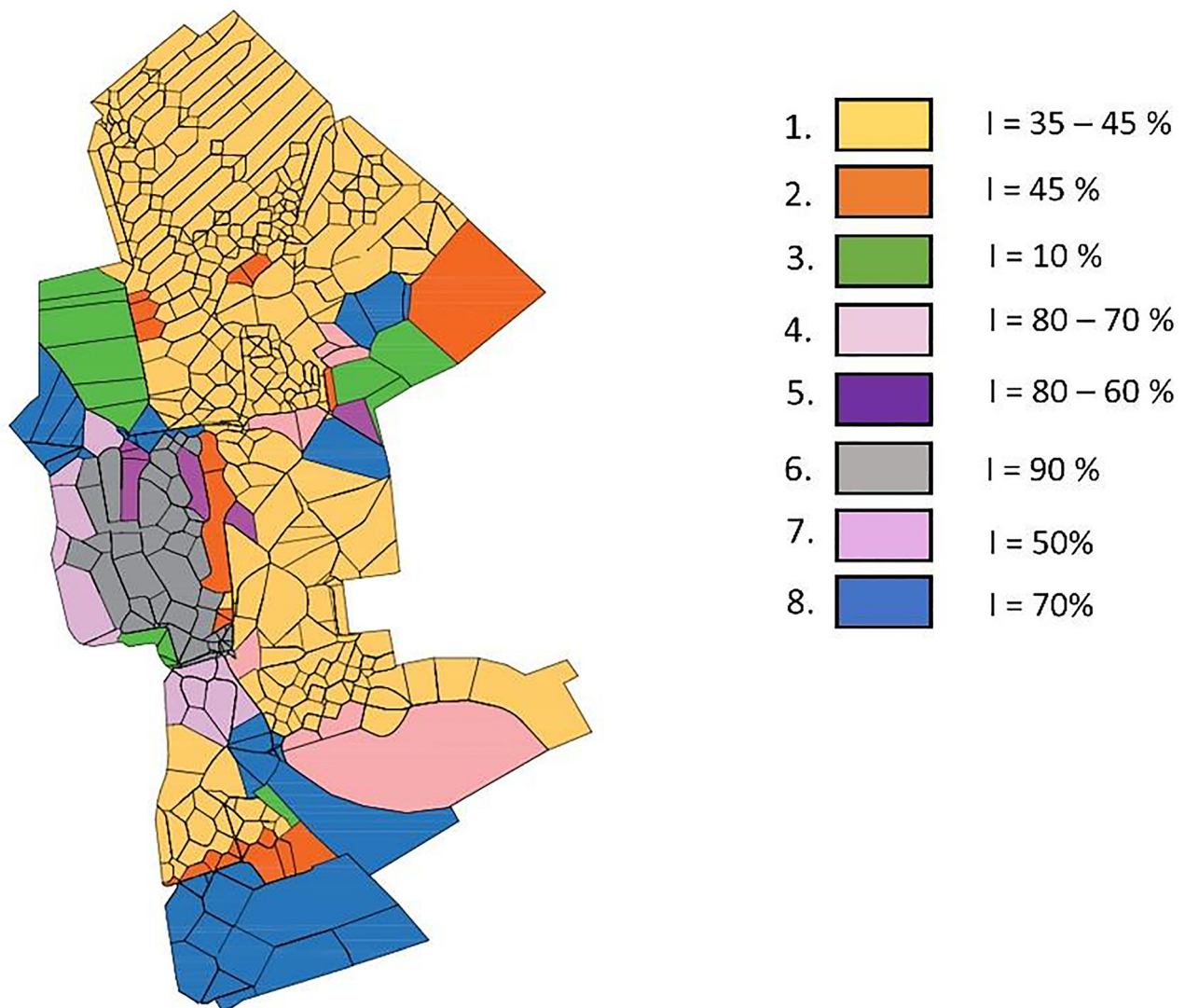


Fig. 2. Study area's average impermeability values, 1) Family houses ($I = 35\text{--}45\%$), 2) Housing estate (multi-story apartment houses) ($I = 45\%$), 3) Parks, cemeteries, green areas ($I = 10\%$); 4) Industrial areas ($I = 80\text{--}70\%$); 5) Business zone ($I = 80\text{--}60\%$); 6) Historical center (multifunctional houses, apartment houses, $I = 90\%$); Mixed zone (multifunctional houses, apartment houses, city walls with adjacent greenery, $I = 50\%$)

When applying green roofs to the roofs of industrial buildings, there will be a change in the permeability and runoff coefficient value of the sub-catchment. If the value of the runoff coefficient is reduced from 0.78 to 0.6 on a sample area of 1 ha, a 40% reduction in surface runoff is expected.

4. DISCUSSION

The topic of rainwater management is popular worldwide due to the worsening situation in the field of climate change. Extreme weather fluctuations and torrential rains stress the urban hydrological cycle. Adaptation measures are proposed to mitigate climate change's impact on cities. These also include measures to retain water in the country.

Several authors deal with the proposal of measures to reduce surface runoff from urbanized areas. The publication Csicsaiová et al. [14] compares the effectiveness of infiltration wells and infiltration trenches. Green roofs help reduce the runoff coefficient and retain water in the landscape. During the reconstruction of industrial areas in the future, consider the construction of green roofs, which could significantly affect the runoff coefficient and reduce the volume of surface runoff drained into the sewer network. Many projects supporting the adaptation of urbanized areas to climate change are currently being developed.

Compared to Slovakia, the Czech Republic is more developed in building elements to reduce surface runoff. In addition to the elements and objects of the blue-green infrastructure, it works extensively on the revitalization of water courses and areas in urban zones. The government with researchers created a manual, which defines the principles of designing and dimensioning objects to reduce surface runoff in urban zones. As part of it, the reconstruction of the existing parking lot in Prague on Čílkova Street was proposed. The proposal involved draining the rainwater from the reinforced surfaces into two cascading trenches [15]. The RainDrop project, which contributed to the restoration of the drainage system of the Municipal House of Culture in Karvina, was also a great success. Drainage grooves were designed to drain rainwater, which collects runoff from roofs and paved surfaces. From them, the regulated drain is diverted to the sewer network. Retention ditches and infiltration ditches with retention tanks that capture and retain rainwater from the roofs of buildings were also applied on the campus of Masaryk University in Bohunice [16]. To support the country's sustainable development, the separation, and regulation of surface runoff in urban basins is also being approached within Slovakia, thereby reducing the load on the sewer system and the recipient during extreme rain events. As part of the Interreg Lumat project [17], a recreational area was revitalized in the city of Trnava to collect rainwater and retain water in the landscape. In addition to revitalization, rainwater harvesting measures are gradually coming to the fore. The city of Prešov is also a good example; it developed project after project intending to improve the environment

and create prerequisites for efficient and sustainable use of the area of interest [18]. In recent years, rainwater management facilities and equipment have been extensively applied to urban drainage systems. Most often, this involves the construction of retention tanks and infiltration facilities near large shopping centers and parking lots. Only recently, Bratislava presented a renewal project called "Living Cities" to bring life back to the public spaces of well-known areas. The reinforced areas of many well-known areas will undergo revitalization, emphasizing mitigating the impact of climate change, i.e., it should contain elements of blue-green infrastructure. The effect of reducing the surface runoff of these devices is proven. The question remains, however, to what extent these devices affect already applied objects on the flows in sewer networks, and what percentage of areas in the urbanized area is advantageous to connect to these devices to achieve effective results. The answer to this question could be provided by mathematical models, which will play a major role in restoring sewer networks in the future.

5. CONCLUSION

The aim of this paper was to draw attention to the need to adapt urban areas to the negative impacts of climate change, specifically to address extreme rainfalls and extended dry periods. For this purpose, the introduction of measures supporting rainwater management and the reduction of surface runoff through the sewer network is currently being supported. In the study area, negative phenomena caused by climate change have been observed for a long time. After extensive analysis of the study area, the density of the pipeline network was evaluated. The analysis proved that the density of the pipe network is sufficient. Subsequently, the analysis of runoff coefficients revealed problem areas where the formation of surface runoff is higher. In these areas, it is necessary to step up the introduction of adaptation measures. The area of interest's geological subsoil is unsuitable for infiltration facilities. Therefore, it is necessary to take measures to increase the green areas in the area. One possibility is the design of green roofs on industrial buildings. Green roofs help reduce the runoff coefficient and retain water in the landscape. During the reconstruction of industrial areas in the future, consider the construction of green roofs, which could significantly affect the runoff coefficient and reduce the volume of surface runoff drained into the sewer network.

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