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Modelling the impact of green infrastructure on potential sewer flooding in the city of Trebišov, Slovakia

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The paper analyses the results of water flow modelling in the urban drainage system of the city of Trebišov, Slovakia. The purpose of the work was to assess the risk of flooding in the urban area and its reduction using Green Infrastructure (GI). The complex hydraulic and hydrological modelling software MIKE+ was used in the research. Using the model of the city's urban drainage system, water flow simulations were carried out using short-term block rainfall events of varying intensity, lasting from 15 to 120 minutes and with return periods of 2 to 10 years. For each scenario, the number of flooded manholes was determined. As a result, areas where two types of GI could be implemented were identified and included in the surface runoff hydrological model. In this study, two types of GI were used: semipermeable pavements and green roofs. The stormwater flow was modelled under four scenarios: current status, implementation of semipermeable pavements, green roofs and their combination. The model results were compared to the current conditions.
It was found that the application of both types of GI could potentially reduce the number of flooded points by more than 30 % for short-term rainfall with a return period of two years. As the return period of the short-term rainfall increases, the number of flooded points decreases to an average value of 5%.

KEY WORDS: green infrastructure, urban drainage, climate change, adaptation measures, surface flooding, MIKE+

Introduction

In urbanised catchments, it is generally necessary to carry out activities similar to those in natural catchments. These include a variety of water management activities, such as regulating the hydrological regime of these areas, water supply, water drainage but also flood protection. In the case of urbanised catchments, the situation is more complex than in the case of natural catchments, because anthropogenic influences - buildings, paved surfaces, but also water management structures serving the drainage of urbanised areas (in particular the sewerage network) – also enter into the overall scheme of the hydrological regime of these catchments.
It is clear that the consequences of the expected climate change will also affect this area. The expected effects of climate change (rainfall patterns, droughts, etc.), especially the increase in short-term rainfall intensities, will cause significant changes in the water regime of urbanised catchments.
Urban drainage systems in Slovakia were designed and sized for rainfall intensities that were based approximately on data from years 1955–1985, based on the previous works (Šamaj and Valovič, 1973; Urcikán and Imriška, 1986). In the context of climate change, short-term rainfall intensities are expected to increase in the order of units to tens of percent (Onderka, 2024), and work published so far confirms this trend (Onderka et al., 2023; Onderka and Pecho, 2022; 2023).
Increased intensities of short-term rainfall events will lead to an increased number of adverse sewer network operating conditions, in particular sewer surcharge and flooding. These terms are defined in the technical standard STN EN 16323 (UNMS SR, 2014), where flooding is defined as a condition where the level of wastewater in the sewer network rises above ground level, and surcharge is a condition where wastewater in the sewer is flowing under pressure but has not yet reached ground level.
It is clear that flooding in an urbanised area can also occur for reasons other than insufficient capacity of the drainage system to drain safely stormwater flows, e.g. by flooding of parts of the area by high water levels in watercourses, or a combination of these causes. In addition, inadequate maintenance of the sewerage network or surface drainage elements (clogging of pipes, blockage of storm drains) may also cause flooding. The restoration of the river network in urbanised areas is also of great importance (Halajova et al., 2019).
There are two main options for reducing urban flooding: increasing the hydraulic capacity of the drainage system or reducing the flow of rainwater into the urban drainage system. The first option is associated with relatively high investment costs as well as various constraints resulting

from the construction of the urban drainage system (sewer network). In addition, such a solution can significantly worsen the situation in terms of water pollution, as the increased capacity of the drainage system accelerates and concentrates the runoff before it enters the waste water treatment plant (WWTP). Even today, due to the limited hydraulic capacity of the WWTP, the only way we can get rid of these large flows is at the cost of polluting the watercourses – by hydraulically diverting the untreated wastewater into the receiving water through the combined sewer overflows (CSO's).

So we are currently trying to explore the second option: reducing the flow into the drainage system. There is a number of ways to achieve this goal: slowing and retaining rainwater at the surface, infiltrating it into the groundwater, increasing evapotranspiration, recycling and reusing rainwater, etc. Many of these measures aim to change the hydrological characteristics of the urbanised catchment to bring it closer to the hydrological characteristics of the natural catchment, both in terms of hydrological balance and runoff dynamics. By doing so, communities become more resilient and achieve environmental, social and economic benefits, as well as improving the micro-climate (Pokrývková et al., 2021).

The basic function of green infrastructure is to filter and absorb rainwater where it falls. In 2019, United States Congress passed the Water Infrastructure Improvement Act (US EPA, 2024b), which defines green infrastructure as "the range of measures that use plant or soil systems, permeable pavement or other permeable surfaces or substrates, stormwater harvest and reuse, or landscaping to store, infiltrate, or evapotranspirate stormwater and reduce flows to sewer systems or to surface waters".

Another definition is provided by the European Commission, which defines green infrastructure as strategically planned network of natural and semi-natural areas with other environmental features, designed and managed to deliver a wide range of ecosystem services, while also enhancing biodiversity." Such services include water purification, improving air quality, providing space for recreation and contributing to climate change mitigation and adaptation. (European Commision, 2024)

From a hydrological point of view, the role of green infrastructure is to reduce and delay stormwater runoff, i.e. to slow down flow and reduce the amount of stormwater entering the city's drainage system, which should be reflected in a reduction in the number of floods and the amount of pollution transported to receiving waters. In addition to the hydrological function, green infrastructure has other positive effects on the urban environment: cooling cities (preventing heat islands), increasing habitat diversity, creating recreational areas, etc.

The use of green infrastructure is also applied in legislation – the update of EC Directive 271/91/EEC (Council of the European Union, 1991) in Article 5 clearly requires to give preference to solutions based on green infrastructure in order to achieve the objectives set.

In this paper, we assess the impact of green infrastructure on changing the hydrological characteristics of an urban drainage system. We examine the impact of green infrastructure on the effectiveness of adaptation measures from a safety perspective - the incidence of flooding caused by insufficient capacity of the urban drainage system. We conducted the research as a study of the urbanised watershed of the city of Trebišov, on which we modelled several scenarios of adaptation measures based on the implementation of green infrastructure.

Material and methods

Trebišov, the centre of the southern Zemplín region, is situated in the south-western part of the East Slovak lowland. It lies at an altitude of 109 m, mostly on the right bank of the Trnávka stream, a tributary of the Ondava River. The town of Trebišov has 24 546 inhabitants, the population density is 350 persons per km^2, the total area of the town (including the suburbs/rural areas) is 70.159 km^2, the area of the part of the town we studied is 382.62 hectares.

In the town, there is a combined sewerage network of a single system, on which there are 1 pumping station and 2 CSO structures. In total, there are 1289 nodes (manholes) in the network, 320 of which are located on the territory of the surrounding municipalities (Nový

Fig. 1. The location of the town of Trebišov (WorldMeter, 2024).

Ruskov, Paričov), i.e. in the areas where the sewerage network is a separate system. No rainwater is drained from this part of the city drainage system; the flow in those parts of the network does not depend on precipitation. So only the nodes that are located on the sewer network of the combined system were evaluated, with their total number of 969 nodes.

The parameters of the catchment studied by us are as follows:

- Full catchment area 386.62 ha
- Area of impermeable surfaces 153.46 ha
- Reduced catchment area 148.32 ha
- Runoff coefficient 0.384
- Population 24 546 inhabitants
- Number of analysed nodes (manholes) 969
- Number of sub-catchments 645
- Length of sewer network 48 864 m
- Volume of the sewer network 18 320 m^3
- Specific length 1.99 m inh^{-1}
- Specific volume 0.746 m^3 inh^{-1}
- Specific length 126.38 m ha^{-1}
- Specific volume 47.38 m^3 ha^{-1}
- Population density 3.50 inh ha^{-1}

For the overall runoff modelling from the urbanised area of the town of Trebišov, the model MIKE+ was used. MIKE+ is a simulation software package for modelling stormwater and wastewater systems, including surface runoff and pipe flows. The collection system modelling is based on US EPA SWMM (US EPA, 2024a)) engine with additional functions of DHI's multi-core MIKE 1 engine. The current version of MIKE+ allows the simulation of subcritical and supercritical flow conditions in partial, full and pressurised pipe networks. A combination of time-area unit hydrograph and kinematic wave methods was used for calculations, in MIKE+ the second one is also used for green infrastructure analysis. Platform also allows various green infrastructure practices to be modelled at both the hydrological screening and detailed hydraulic levels to assess their impact. An advantage is the universal database platform for all models of the DHI group, which allows the interconnection of different models (e.g. urban collection systems and river models, both for hydraulic and water quality modelling) (DHI, 2024).

The data for modelling the runoff from the urbanised area of the town of Trebišov for this study were provided by Východoslovenská vodárenská spoločnosť, a.s. (VVS, a.s., East Slovak Water Utility, JSCo.) and DHI Slovakia, Ltd.. The data provided forms a comprehensive hydrological model that was calibrated during the hydraulic assessment of the wastewater system, which was based on measurements at seven points throughout the city. The resulting model was slightly modified, in consultation with experts from DHI Slovakia, Ltd., some errors in the model were corrected and, based on our own research, more detailed modelling of sub-catchments with prospects for green infrastructure development was included in the model. This included the addition of information on the surface slope and surface permeability parameters, which are required in MIKE+ to apply the kinematic wave equations.

On the MIKE+ platform, green infrastructure is implemented by specifying its parameters, the extent of implementation within each catchment, and the catchment area of each element. The parameters include hydraulic conductivity, drainage mat thickness,

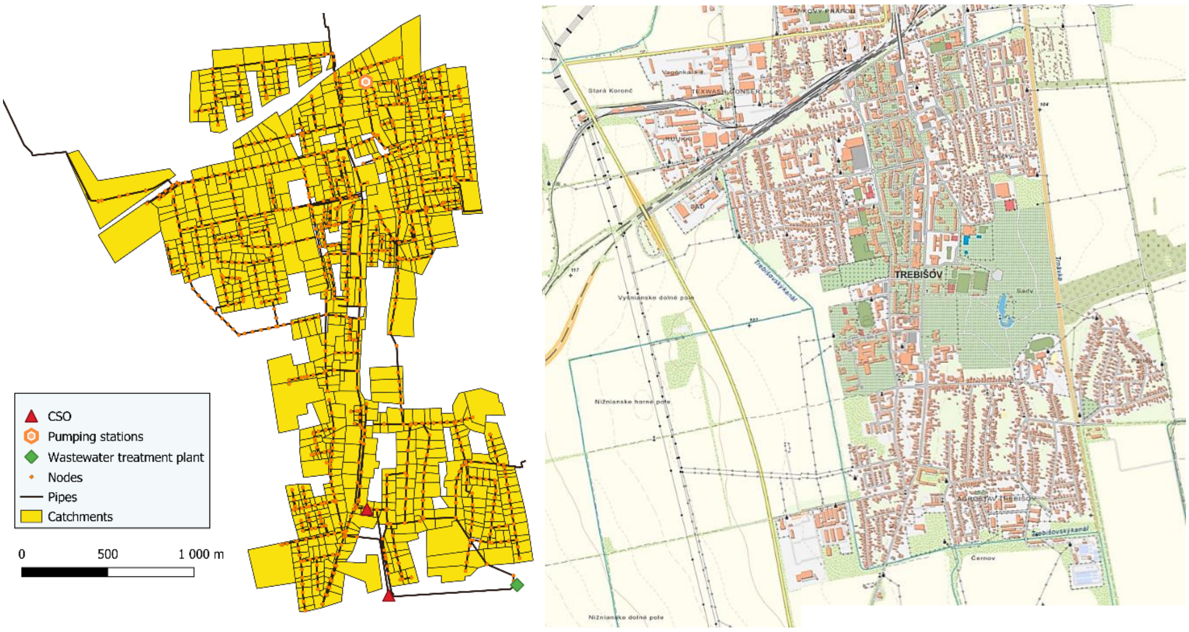

Fig. 2. Schematic layouts of the sewerage network of the town of Trebišov and the map of the city (GKU Bratislava, 2024).

water permeability, starting water level, clogging factor, drainage outlet and others. The parameters were determined using manuals and building codes of both Slovakia and the neighbouring Czech Republic (Balko et al., 2017; Hudeková et al., 2018; JV PROJEKT VH s.r.o, 2018)

For the purpose of this study, we used the intensities of short-term block rainfall according to the publication (Urcikán and Imriška, 1986), which was also adopted by the currently valid Slovak technical standard (UNMS SR, 2016). The values of these rainfall intensities for the individual return periods and durations of the block rains are presented in Table 1, the rainfall depth is presented in Table 2.

We have tried to define the extent of green infrastructure realistically, i.e. in terms of current economic, legislative and technical possibilities. From the available options, we considered it realistic to include green roofs and semi-permeable surfaces in the overall drainage system of the city. Other elements of green infrastructure are only sporadic in the Slovak Republic, and further could also be tied to chosen two types of structures (for example, rainwater barrels). When creating the scenario with green roofs, we took into account the fact that so far they have been designed and implemented mainly on larger and more public or industrial buildings, rather than on residential buildings. They are practically non-existent on existing single-family houses, whose owners prefer other rainwater infrastructure, if necessary. Exceptions are new single-family houses and mainly new residential projects, where green roofs or other water retention measures with green infrastructure elements are very often proposed. The implementation of green roofs on older buildings can also be problematic in terms of structural load capacity. Problematic can be also the infiltration capacity and potential erosion on some types of green roofs (Danáčová et al., 2022). For this reasons, extensive green roofs with relatively low water retention capacity were considered for older buildings. For single-family houses, only minimal runoff from roofs was considered, as the current Water Supply and Sewerage Act (442/2002 Coll., 2002) requires payment for the drainage of rainwater runoff (service provided by the Water Utility). As a result, more or less all single-family houses have disconnected their roofs and paved areas from the urban drainage system.

The second element of green infrastructure – semi-permeable surfaces - also has some technical limitations. Often these are technical problems arising from collisions with other technical infrastructure (e.g. utility networks). In addition, this type of surface should not be designed in park lots with high traffic loads. In these cases, paved areas should be used, or rainwater is better to be drained into surface retention basins or bioswales. However, these systems are more maintenance intensive.

For the purposes of this study, we considered four different development scenarios, including current conditions; their general description is provided in Table 3.

For the hydraulic evaluation of the effectiveness of the green measures, we chose the number of flooded manholes and the number of surcharged manholes as criteria. We consider surcharged manholes to be those where the maximum water level is less than 1 m below ground level. Under such hydraulic conditions in the sewer network, there is a real risk of property damage due to flooding of basements, cellars and lower lying areas.

Results

The results of the simulations of the runoff from the urbanised area of Trebišov are presented in Table 4 and Table 5.

Discussion

It is necessary to begin the discussion by addressing the uncertainties that may have influenced the results of this study. The first uncertainty is the reliability of

Table 1. Intensity of short-term rainfalls with different periodicity (return periods) in the town of Trebišov in l s^{-1} ha^{-1}

Periodicity / return period in years	Duration of rainfall partitions in minutes				
	15	30	60	90	120
0.5 / 2	178	118	72	52	41
0.2 / 5	224	157	100	73	58
0.1 / 10	263	187	118	88	72

Table 2. Rainfall depth of short-term rainfalls with different periodicity (return periods) in the town of Trebišov in mm

Periodicity / return period in years	Duration of rainfall partitions in minutes				
	15	30	60	90	120
0.5 / 2	16.02	21.24	25.92	28.08	29.52
0.2 / 5	20.16	28.26	36	39.42	41.76
0.1 / 10	23.67	33.66	42.48	47.52	51.84

Table 3. General description of compared scenarios of green infrastructure development

N of scenario	Description	Affected area [ha]	Affected area [% of total]
1	Current conditions	-	-
2	Building with area larger than 1000 m^2 are covered with green roofs	10.68	2.59
3	Identified paved areas, park lots, transformed to permeable pavement	8.75	2.29
4	Combination of scenarios 2 and 3	19.43	4.88

Table 4. Number of flooded nodes as a function of rainfall return period

Rain duration	2 years		5 years		10 years	
	Current conditions	Combined	Current conditions	Combined	Current conditions	Combined
15 minutes	38	18	94	67	167	142
30 minutes	74	40	170	148	238	224
60 minutes	69	49	169	153	226	211
90 minutes	52	34	141	126	190	179
120 minutes	38	31	104	76	172	160

Table 5. Number of flooded and surcharged points as a function of rainfall return period

Rain duration	2 years		5 years		10 years	
	Current conditions	Combined	Current conditions	Combined	Current conditions	Combined
15 minutes	199	134	392	346	475	469
30 minutes	320	262	415	408	554	529
60 minutes	305	262	440	401	556	536
90 minutes	250	212	355	338	513	485
120 minutes	202	170	314	304	441	413

the sewer network, catchment and object data used and the possible uncertainty in the model calibration. The model calibration was performed in the crucial points of the system, as mentioned in the previous chapter, but the results might not fully correlate with every particular parts of the overall urban catchment.

As mentioned above, the set-up and calibration of the hydraulic model was approved by the operator of the sewerage network in the town of Trebišov (VVS, a.s.). The aim of this study is to quantify the impact of green infrastructure, i.e. to assess its effect compared to the status quo. The modelling of the different scenarios and alternatives was carried out using the same data (except for the addition of green infrastructure), so possible errors in the data would have little effect on the quantification of the green infrastructure impact.

The second uncertainty is the use of block rainfall, which is a simplification of reality and its occurrence in the actual catchment is not realistic. Again, it should be noted that this study was concerned with assessing the effectiveness of green infrastructure under a wider range of boundary conditions, including relatively extreme conditions such as rainfall with a return period of 5 or 10 years. Using real rainfall records, it would be uncertain whether such extreme conditions occurred in the rainfall series used. However, we agree that it is also necessary to investigate the behaviour of the urban drainage system under realistic conditions, so we plan to analyse urban drainage systems using real (historical) rain gauge records in the future.

In this context, it is worth to mention another fact – we applied the block rainfall uniformly over the whole catchment, which is a considerable simplification of reality. In the case of the town of Trebišov, this is a relatively small area (about 1.5 x 3.5 km), so it can be assumed that this error will not be large. In the case of larger cities, the spatial non-uniformity of the rainfall must also be taken into account.

Another uncertainty is the identification of possible areas for the implementation of green infrastructure in the town of Trebišov. The exact identification of possible areas requires a detailed local survey, which is far beyond the scope and time requirements of the authors of this study.

Uncertainties include the accuracy of the hydrological/hydraulic model and the behaviour of the network under extreme conditions. When evaluating the model results, we noticed that for some of the modelled alternatives, a relatively large number of manholes were classified as only surcharged, with water levels at these network nodes at ground level or at a minimal depth below ground level. It might be the result of numerical oscillations (numerical errors) in the model resulting from the modelling of extreme conditions in the sewer network (pressure flow in the sewer network and the approximation of the flow with the free surface, e.g. Preismann's slot (Yen, 1986)). This explains the somewhat irregular shape of the resulting curves (see Fig. 3 and Fig. 4).

This irregular shape of the curves may be caused by another factor. As shown in earlier work by Fuchs (Fuchs, 1987), the actual periodicity of sewer flooding / surcharging and the periodicity of design rainfall are not statistically significantly correlated. It should also be noted that the cited work concludes that there is no statistically significant correlation between the *actual periodicity of surcharging (flooding)* of the sewer network and the *design rainfall* for which the sewer network was designed. We believe that a similar relationship exists between the block rainfall we used and the model results for network node flooding / surcharging in an urban drainage system. This may be due, for example, to different initial conditions at the beginning of the rainfall (saturation, wetting of the catchment surface), but also to the function of the structures in the sewer system (CSO's, pumping stations, storage tanks), non-linear dependencies between the surface travel time and the intensity of the rainfall, as well as the depth of the sewer network bedding, which has a significant influence on the flow velocity under conditions of pressurised water flow in the sewer network.

In Table 4, we present the number of flooded nodes in the network, while Table 5 shows the number of flooded and surcharged nodes. The results from Table 4 are presented graphically in Fig. 3.

Fig. 4 shows the percentage reduction in flooded and surcharged network nodes compared to the current conditions. As can be seen from this figure, the greatest reduction is for rainfall events with a short return period (2 years), approximately 15–30%. As the return period increases, the effectiveness of green infrastructure in reducing flooding and surcharging in the urban drainage system decreases and is approximately 2–15% for a rainfall event with a return period of 5 years and 2–6% for a rainfall event with a return period of 10 years. As can be seen on Fig. 3, the greatest numbers of flooded and surcharged manholes occur during rainfall durations

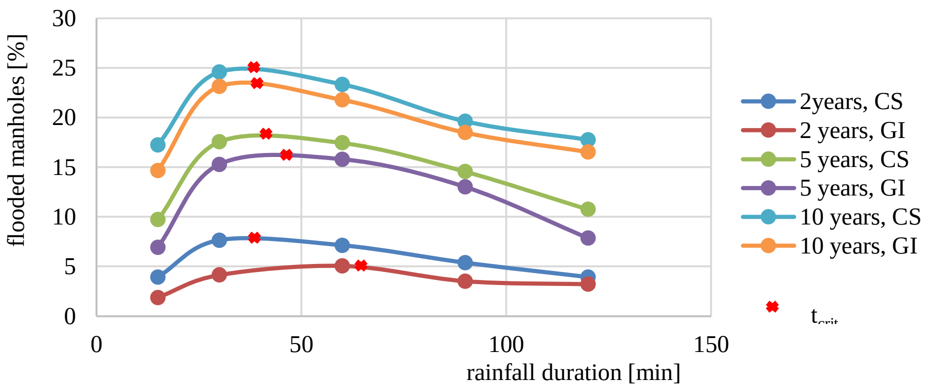

Fig. 3. Number of flooded nodes as a % of the total number of nodes in the studied alternatives (CS – Current Status, GI – Green Infrastructure, t_{crit} – estimated critical time / time of concentration).

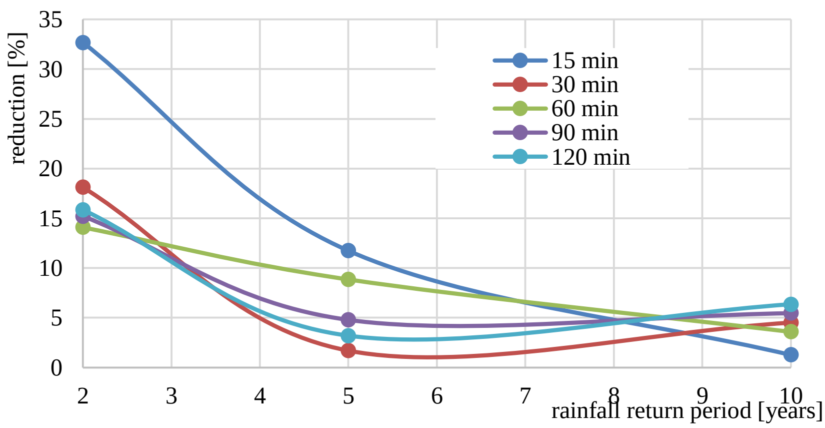

Fig. 4. Decrease in flooded and surcharged nodes with green infrastructure, expressed as a percentage of the total number of surcharged and flooded nodes in the current status alternative.

of approximately 30–60 minutes. This is related to the travel time (critical time) of the catchment, which, based on these results, is estimated to be 30–60 minutes. The critical time (time of concentration) is not constant, but varies according to the intensity of the rain. The role of green infrastructure is to slow down the overall runoff, in particular, the surface runoff time and consequently the runoff concentration in the drainage network. By extending the runoff time, a lower hydraulic load on the city's drainage system is achieved. This trend is clearly evident for the 2-year return period storm (see Fig. 3), where an increase in travel time from 35 to 60 minutes is observed, i.e. a delay in peak runoff of 25 minutes; for the 5-year return period storm, the estimated increase of the travel time is approximately 5 minutes; for the 10-year return period storm, we estimate the runoff delay to be approximately 1 minute.

Conclusion

In this study, we analyse and evaluate the effectiveness of implementing green infrastructure as a means of reducing the risk of flooding or surcharging the urban drainage system.

As can be seen from the description of uncertainties in the previous chapter, the behaviour of urban drainage systems is generally non-linear and the relationship between cause (block rain) and effect (surcharging, flooding) is not reliably demonstrated (Fuchs, 1987). It should therefore be noted that the assessment of urban drainage systems is highly individual and the results depend on the specific site and local conditions. In addition, the transferability and generalisation of the results may be problematic in the case of cities with specific conditions. Therefore, an individual assessment or study should always be carried out. It should take into account the local conditions, such as surface runoff and the hydraulic capacity of the drainage system (sewer network).

As can be seen from the results of the model study of the city of Trebišov, the effectiveness of the implementation of green infrastructure in reducing the number of flooded or surcharged manholes is approximately 15-30% for rainfall events with a short return period (2 years). As the return period increases, the effectiveness of green infrastructure in reducing flooding and surcharging of the urban drainage system decreases and is approximately 2–15% for a rainfall event with a return period of 5 years and 2–6% for a rainfall event with a return period of 10 years.

Based on the above, it can be concluded that green infrastructure is particularly effective in protecting the urban area from flooding during low intensity rainfall events, but relatively ineffective during high intensity rainfall events (storms, torrential rain). An undeniable benefit of implementing green infrastructure is that it reduces the number (frequency) of flooding events for rainfall events with low return period.

It is reasonable to assume that this effectiveness would be higher if green infrastructure were implemented on a large scale. We believe that large-scale implementation of green infrastructure would require disproportionately high financial costs and it is questionable whether such a high investment would be proportionate to the effect.

Therefore, in the future we plan to focus on the question of the financial efficiency of implementing green infrastructure compared to other traditional solutions (e.g. grey infrastructure). The option of adding a certain amount of green infrastructure to determine its most optimal extent and changing the parameters is also being considered. The impact of green infrastructure on current environmental problems, such as combined system overflows (CSO's) from urban drainage systems and increased rainfall intensity due to climate change (Bara et al., 2013), also needs to be addressed. As mentioned above, the results of studies are always individual, so we plan to conduct several studies in different locations to achieve a greater degree of generalisation and representativeness of the results.

The study concludes that the effect of green infrastructure on flood protection in urban areas is relatively small in case of rainfall events with high intensities. Despite of this we believe that green infrastructure has an indispensable role in urban areas (ecosystem functions) and its implementation should be promoted to an economically and technically reasonable extent in combination with other measures (e.g. grey infrastructure).

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