Conceptual Hydrologic Design of Adaptation Measures in The City of Trnava

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Abstract

Climate change has been shown to necessitate adaptation measures in urban drainage systems. The increased intensity of rainfall necessitates greater hydraulic and storage capacity in such systems, thereby enabling more effective management of increased stormwater flows and volumes. In the absence of amendments to the prevailing concept of urban drainage in the Slovak Republic, the probability of flooding in urban areas due to increased rainfall intensity will remain high. This is because the current sewerage network cannot accommodate the increased demand. Moreover, climate change will result in increased pollution being transported from sewerage networks to surface waters (receiving waters) due to more frequent hydraulic overflows through combined sewer overflow structures. Furthermore, the larger volumes of such water will reach the receiving waters directly without any treatment. The present paper analyses the design of various adaptation measures for an urban catchment of the city of Trnava, with a focus on the legislative, hydraulic, and environmental aspects of urban stormwater management. The estimated required range and composition of adaptation measures, along with their effects on overall urban stormwater management, are described in terms of achieving the required goals. The results show that blue-green measures (such as blue-green infrastructure) alone cannot eliminate all the negative impacts of climate change. The findings indicate that, to the greatest extent possible, implementing blue-green infrastructure does not ensure the attainment of the objectives outlined in the recently adopted EU Directive 3019/2024. The analysis presented in the paper demonstrates that the extensive combined approach (blue-green and grey infrastructure, including stormwater tanks) is the only strategy capable of ensuring the requisite 2% of the annual pollution load is addressed, with the pollutants being conveyed directly to surface water through the CSO. A further significant issue is the technical versus financial effectiveness of the implemented measures, that is, determining the optimal solution to achieve the required parameters. It is likely to be a combination of green and grey infrastructure, with the proportions and extent of each type determining the total costs (investment plus maintenance). Nevertheless, it is assumed that such an optimal solution will be highly case-specific and must be determined for each individual case.

Keywords: *urban drainage, adaptation measures, combined sewer overflow, EU directive, Trnava*

1. Introduction

Climate change requires adaptation measures in urban drainage systems. Rising rainfall intensities demand increased hydraulic and storage capacities to handle larger stormwater volumes and peak flows. Without major changes to the current drainage approach in Slovakia, the risk of urban flooding from intense storms remains high, as the existing sewer infrastructure cannot fully accommodate increased runoff. Climate change is also likely to boost pollutant loads in discharges from sewer systems into receiving waters. More frequent overflows from combined sewer systems during heavy rain will release more untreated wastewater into surface waters, harming water quality.[1]

Two primary strategies address these challenges: expanding sewer network capacity or reducing stormwater inflows. Capacity expansion often requires major infrastructure upgrades, such as enlarging pipes, constructing retention facilities, or increasing existing stormwater storage, which can lead to significant construction, traffic disruptions, and high costs. Consequently, reducing inflows into the sewer system should be prioritised whenever feasible to prevent overloading and ensure effective stormwater conveyance. The second strategy involves managing stormwater at its source through local retention, disposal, or utilisation. Retention involves temporarily storing stormwater and releasing it into the sewer at a controlled rate that does not exceed the maximum limits set by authorities like municipalities or water utilities. Disposal methods include evaporation, infiltration, or discharge into local surface waters, thereby preventing stormwater from entering the sewer system.

In recent years, increasing attention has been given to nature-based solutions for stormwater retention and local management. These solutions often incorporate vegetation and natural processes that mimic the hydrological functions of natural catchments. Collectively, such measures are commonly referred to as blue–green infrastructure (BGI).

The growing importance of sustainable stormwater management is highlighted by recent changes to the European Union directive governing urban wastewater [2]. These updates mandate the development of integrated urban wastewater management plans outlining methods and procedures to meet the main stormwater management goals. These goals aim to lessen flood risks and reduce

the release of untreated wastewater pollutants into water bodies. To reach these targets, plans should include upgrading existing wastewater systems or building new infrastructure, such as additional stormwater detention and retention facilities.

When new infrastructure is needed, priority should be given to blue–green infrastructure solutions. Examples include retention ponds, constructed wetlands, permeable and semi-permeable surfaces, green roofs, and other nature-based options. Besides enhancing stormwater management, such infrastructure should also support biodiversity, ecosystem services, and water reuse initiatives.

The effects of discharges from combined sewer overflows (CSOs) on the ecological health of receiving waters are complex and vary significantly by location, depending on local conditions. Traditional assessment methods usually estimate the annual pollutant load released into these waters but do not fully account for the impact of individual rainfall events or the frequency and duration of CSO discharges. Even sophisticated rainfall–runoff models can face significant uncertainty due to variability in their parameter values and rainfall patterns. This is especially true in larger catchments, where rainfall can vary greatly across different areas, and in sewer systems, where runoff and wastewater flows are affected by many local and time-dependent factors. Current assessment methods can measure key CSO performance indicators, such as the total annual pollutant load, total overflow volume, number of CSO events, and the combined duration of CSO events throughout the year. However, the main research question of this study is how effective green infrastructure is at reducing or completely preventing the negative effects of CSO discharges on receiving waters. These impacts are often assessed by changes in flood risk and decreases in pollutant loads transferred through CSO structures into receiving waters.

This research focuses on how green infrastructure affects the pollutant loads released through combined sewer overflows into receiving waters. It is a key performance indicator in the EU urban wastewater framework, which sets up a non-binding goal that pollutant discharges via CSOs should not surpass 2% of the annual total pollutant load sent to wastewater treatment plants. This indicator uses an emission-based mass balance approach, but a precise methodology and calculation steps for evaluating it have not yet been officially defined.

2. Methods

Trnava is a regional city in western Slovakia, approximately 50 km northeast of Bratislava, the country's capital (Figure 1). It is the administrative centre of the Trnava Region and one of the oldest urban settlements in Slovakia, with a rich historical and cultural heritage. The city has a population of about 65,000 inhabitants. Trnava lies in the Danubian Lowland, characterised by predominantly flat terrain and a temperate continental climate. Due to its urban development and increasing climate-related challenges, Trnava represents a relevant case study for investigating sustainable urban stormwater management practices.

The first step was to analyse the land cover within the city of Trnava's borders. Using QGIS and OpenStreetMap, we identified the total catchment area and the individual land cover types within the city limits of Trnava. The defined areas are shown in Figure 3.

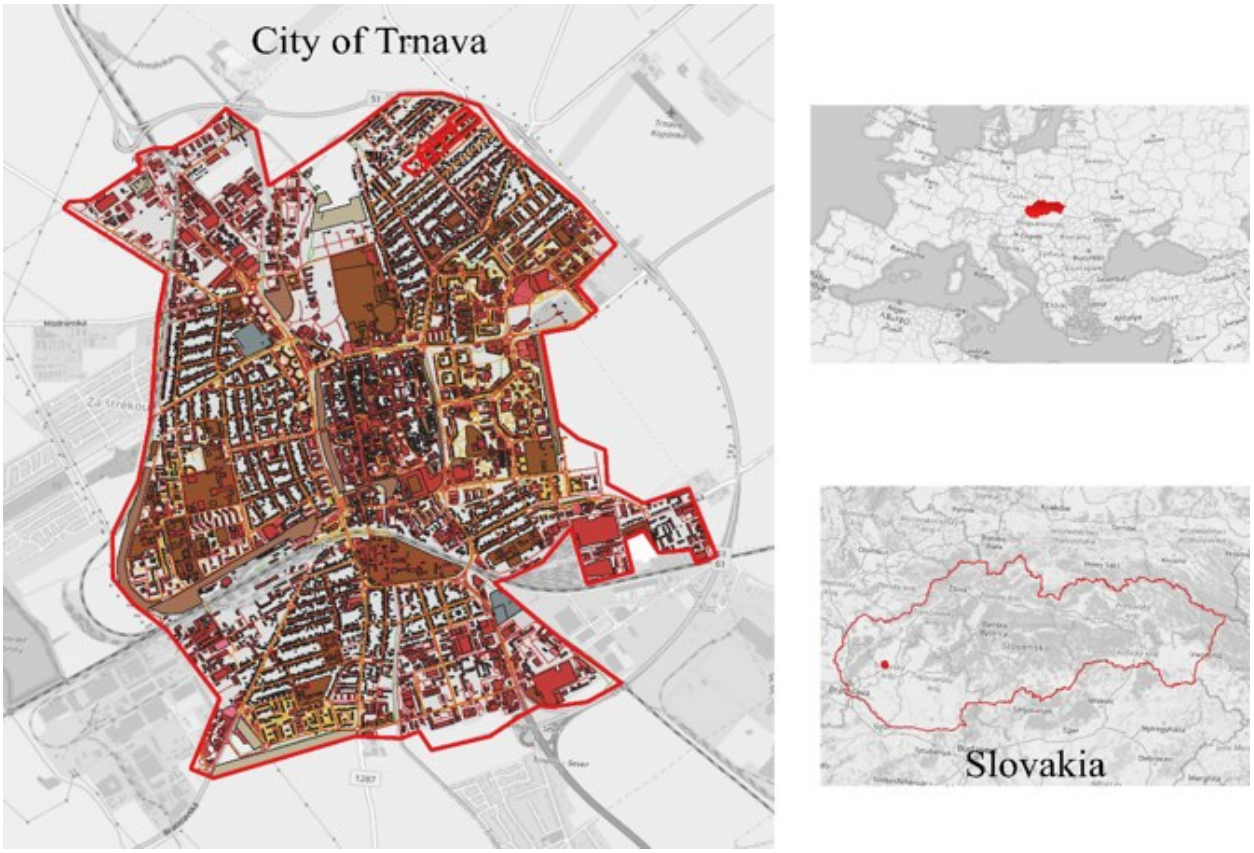

Fig. 1. Layout map of the city of Trnava

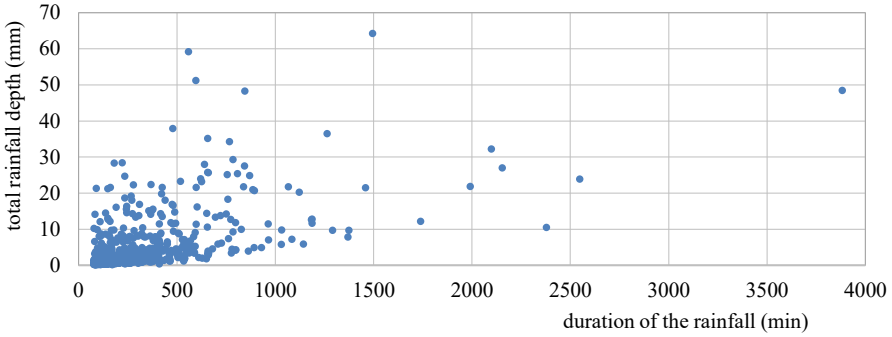

Fig. 2. Rainfalls in Trnava city (6.6 -year rain gauge records)

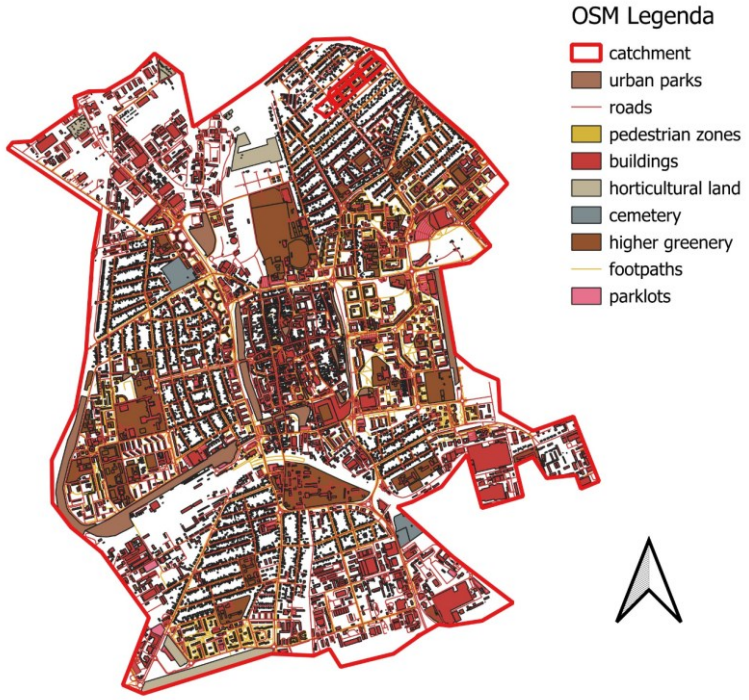

Fig. 3. Surface areas classification in Trnava city

We considered the areas of these zones, their percentage shares, as well as the hydrological parameters—surface waterlogging values and runoff coefficients for both the existing and proposed blue-green infrastructure—as shown in Table 1

Tab. 1: Values of hydrological parameters for the Trnava urban catchment

Surface type	area	proportion of area	Current status		Green infrastructure	
			Runoff coefficient	retention	Runoff coefficient	retention
	ha	%	-	mm	-	mm
Connected roofs	195.86	14.4	0.9	1.5	0.3	20[a]
Residential roofs (potentially able to disconnect)	54.33	4.0	0.9			
Roads	103.33	7.6	0.9	2	0.9	2
Connected sidewalks	19.35	1.4	0.9	2	0.3	30[a]
Squares, pedestrian zones	3.13	0.2	0.9	2	0.3	3
Parking lots	46.40	3.4	0.9	2	0.3	3
Greenery	36.58	2.7	0.05	4	0.05	4
Other green areas	905.03	66.4	0.05	4	0.05	4

[a] Additional retention volume, created by BGI, is incorporated

When identifying these areas, we assumed that plots up to 150 m² consist mainly of single-family homes, which have a high potential for disconnection from the sewer system. The rest (i.e., roofs larger than 150 m²) will likely be impossible to disconnect from the sewer system, but they are suitable for green roofs. We also assumed that approximately half of the city's sidewalks are located in green areas and that runoff from them into the sewer system is minimal. The other half of the sidewalks could potentially

be disconnected from the sewer system (if there are green areas nearby). Still, some sidewalks are practically impossible to disconnect (especially in the city centre).

For BGI areas (elements) defined in this way, we examined their effects on overflow volume through combined sewer overflows (CSOs) and on the amount of pollutants transported to receiving water bodies.

An alternative to BGI is the construction of grey infrastructure—in this case, stormwater retention tanks. We defined the volume of these tanks as the specific volume per unit of reduced area (runoff-active area: total area multiplied by the runoff coefficient).

For hydrological calculations, a simplified balance method was used, as outlined in the NATO Advanced Science Institute (ASI) series in Harrachov in 1996 [3]. Although this method has its limitations, it provides an accessible and logical way to assess factors affecting urban drainage systems, including stormwater tanks (SWT) and wastewater treatment plants. It also enables quick and easy re-evaluation of various water retention scenarios, including green infrastructure, within an urban catchment.

The core idea of this approach is to directly compare the rainfall volume in the catchment with its available retention volume, accounting for hydrological losses and the retention capacity of particular drainage system components. Each rainfall event is characterised by its duration and total precipitation depth, leading to a scatter plot as shown in Figure 2. Starting with total precipitation depth, characterised by depth and duration, we gradually deduct hydrological losses, such as surface wetting/retention, infiltration, and interception.

In the subsequent stage of the analysis, the retention capacity of the sewer network and the connected infrastructure (BGI + grey infrastructure) was deducted from the total rainfall depth. The two aforementioned components were then converted into proportions of the rainfall depth using the relationship.

$$\boldsymbol{h = \frac{V}{A_{red}}} \tag{1}$$

Where
h is the corresponding volume retention (sewer system, storage tank), expressed as rainfall depth (m),
V is the retention volume (m^3) and
A_{red} is the reduced catchment area (m^2), i.e. total catchment area multiplied by runoff coefficient ($A_{red} = A \cdot \varphi$)

The dynamic part of the system's volume balance—specifically, the volume drawn from the urban drainage system by the Waste Water Treatment Plant (WWTP), or simply, the volume that flows out towards the WWTP—can be expressed as follows:

$$\boldsymbol{h_{WWTP} = \frac{Q_{WWTP} . t}{A_{red}}} \tag{2}$$

Where
h is the corresponding outflow volume for time t, expressed as depth (m/min),
Q_{WWTP} is the flow rate of the wastewater flowing out of the urban drainage system (towards the WWTP)
t is the rainfall duration time (min).

The CSO volume can be calculated either graphically or numerically, using basic spreadsheet software. The applicable relationship is given by Eq. 3:

$$\boldsymbol{h_{CSO} = h_{HL} - h_S - \sum h - h_{WWTP} . t} \tag{3}$$

Where
h_{CSO} is the CSO outflow volume, expressed as depth (m),
h_{HL} are the total hydrologic losses (surface wetting losses + BGI retention) on the urban catchment (m),
Σh is the sum of the total retention (accumulation) capacity of the drainage system, see Eq. 1 (m).

If the value of the h_{CSO} is zero or negative, it indicates that the CSO event does not happen, meaning the retention or storage capacity exceeds the rainfall depth.

To express the CSO overflow volume in volumetric units, we can use the following equation (Eq. 4):

$$\boldsymbol{V_{CSO} = h_{CSO} . A_{red}} \tag{4}$$

For practical calculations, we analysed the parameters of Trnava's urban catchment area. The parameters are shown in (Table 2):

Tab. 2. Parameters of the hypothetical case study catchment area

Parameter	units	value
Catchment area	ha	100
Number of inhabitants	inhabitants	4000
Population density	$inh.ha^{-1}$	40
Population equivalent (PE) industry	small industry pollution production (surcharge on the inhabitants' production)	20 %
Specific wastewater production	$l.inh^{-1}day^{-1}$	100
Small industry wastewater production	additional charge to dry weather flow	20 %
Infiltrated water	ratio of infiltrated water to sewage water	50 %
Specific BOD_5 production	g BOD_5 inh^{-1} day^{-1}	60
BOD_5 concentration in dry weather flow	mg BOD_5 . l^{-1}	327
BOD_5 concentration in CSO	mg BOD_5 . l^{-1}	175
Specific length of the sewer network	m . inh^{-1}	3
Mixing ratio	proportion of flow to WWTP in CSOs	1:4

The area shares (buildings, streets…) were obtained by analysing a vector OSM map of the urban catchment area within the intravilan of Trnava city, based on the OSM and ZBGIS digital maps [4,5].

We evaluated implementing green infrastructure exclusively on roofs (green roofs), sidewalks (such as soakaways, swales, rain gardens), and parking lots (semi-permeable surfaces with infiltration).

For each BGI type, we have assessed its implementation potential. For example, we assume that green roofs will be feasible on approximately 50% of the total roofs (larger than 150 m²) due to structural or construction constraints (e.g., insufficient static load-bearing capacity of the structures, unsuitable insulation, or materials). Similarly, we have set limits for footpaths; for instance, it makes no sense to disconnect footpaths in parks/green areas, and conversely, in densely built-up city centres, disconnecting from the sewer network will not be technically feasible.

The analysis considered various scenarios: maintaining the current system and implementing green infrastructure at various percentages of their particular potential areas. Additionally, alternatives included constructing stormwater retention tanks with specific volumes, related to the city's impervious area, i.e., m^3 per hectare of impervious area. Since the updated Directive 91/271/EC [2] recommends limiting the maximum annual pollution load in combined sewer overflow (CSO) effluent to 2% of the total yearly wastewater treatment plant (WWTP) pollution load during dry periods, we also calculated this indicator based on BOD5 values, considering the pollution concentrations specified in [6].

2. Results

Results of calculations in numerical form are shown in Tab. 3

Tab. 3. Results of hydrological calculations

Alternative	GI share	Nr. of CSO cases	CSO volume	2024/3019 EC compliance	Decrease
	%	-	$m^3.year^{-1}$	%	%
Current status (CS)	0	10.45	331 341	3.39	100.00
20% GI	20	8.48	272 924	2.79	82.37
40% GI	40	7.42	222 068	2.27	67.02
60% GI	60	6.21	178 254	1.82	53.80
80% GI	80	5.60	137 569	1.41	41.52
100% GI	100	4.24	102 817	1.05	31.03
CS + SWT 10 $m^3.ha^{-1}$	0	8.48	291 415	2.98	87.95
10% GI + 10 $m^3.ha^{-1}$	20	7.27	241 126	2.47	72.77
40% GI + 10 $m^3.ha^{-1}$	40	6.21	197 654	2.02	59.65
60% GI + $m^3.ha^{-1}$	60	5.90	156 935	1.61	47.36
80% GI + 10 $m^3.ha^{-1}$	80	4.69	120 804	1.24	36.46
100% GI + 10 $m^3.ha^{-1}$	100	3.78	91 020	0.93	27.47
CS + SWT 20 $m^3.ha^{-1}$	0	6.96	257 852	2.64	77.82
20% GI + 20 $m^3.ha^{-1}$	20	6.21	214 910	2.20	64.86
40% GI + 20 $m^3.ha^{-1}$	40	5.90	174 631	1.79	52.70
60% GI + 20 $m^3.ha^{-1}$	60	5.00	138 169	1.41	41.70
80% GI + 20 $m^3.ha^{-1}$	80	4.09	106 848	1.09	32.25
100% GI + 20 $m^3.ha^{-1}$	100	2.88	81 006	0.83	24.45
CS + SWT 30 $m^3.ha^{-1}$	0	6.21	230 020	2.35	69.42
20% GI + 30 $m^3.ha^{-1}$	20	5.75	190 305	1.95	57.43
30% GI + 30 $m^3.ha^{-1}$	40	5.15	154 020	1.58	46.48
60% GI + 30 $m^3.ha^{-1}$	60	4.24	121 834	1.25	36.77
80% GI + 30 $m^3.ha^{-1}$	80	3.33	94 468	0.97	28.51
100% GI + 30 $m^3.ha^{-1}$	100	2.57	72 942	0.75	22.01
10 $m^3.ha^{-1}$	0	8.48	291 415	2.98	87.95
20 $m^3.ha^{-1}$	20	6.96	257 852	2.64	77.82
30 $m^3.ha^{-1}$	40	6.21	230 020	2.35	69.42
40 $m^3.ha^{-1}$	60	5.60	204 061	2.09	61.59
50 $m^3.ha^{-1}$	80	5.15	181 218	1.86	54.69
60 $m^3.ha^{-1}$	100	4.54	160 123	1.64	48.33

Results in graphical form are presented in Figures 4 -6.

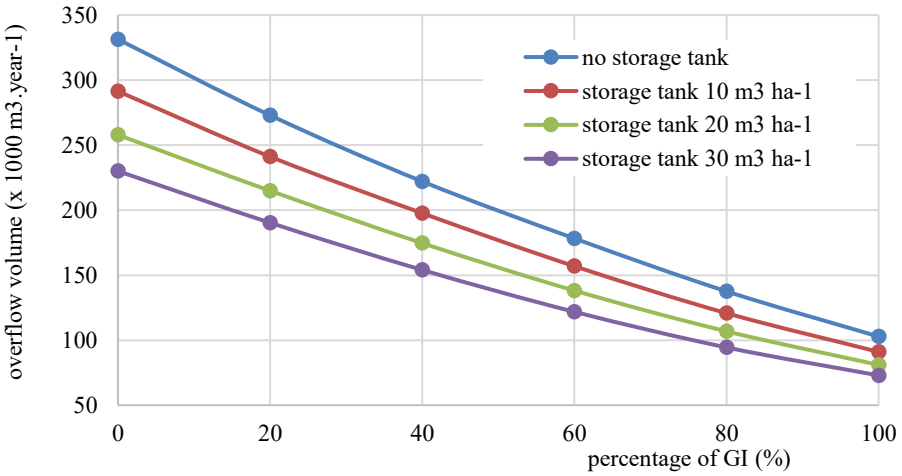

Fig. 4. Discharged CSO volume

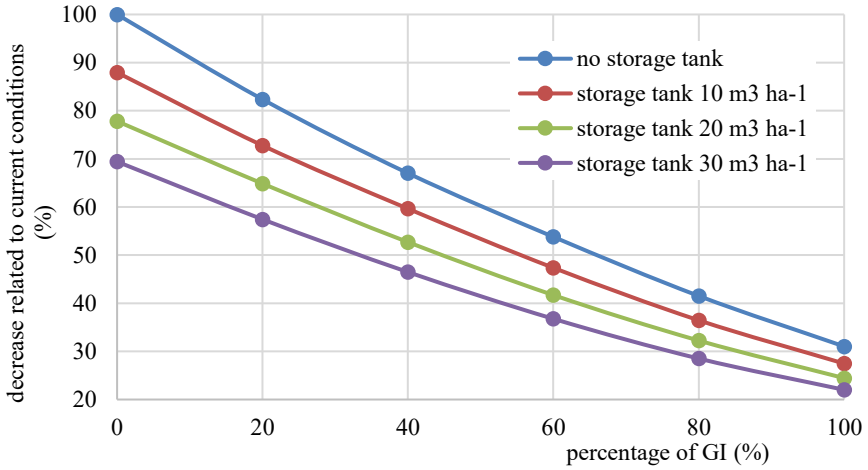

Fig. 5. Effect of retention measures (as in % of decrease)

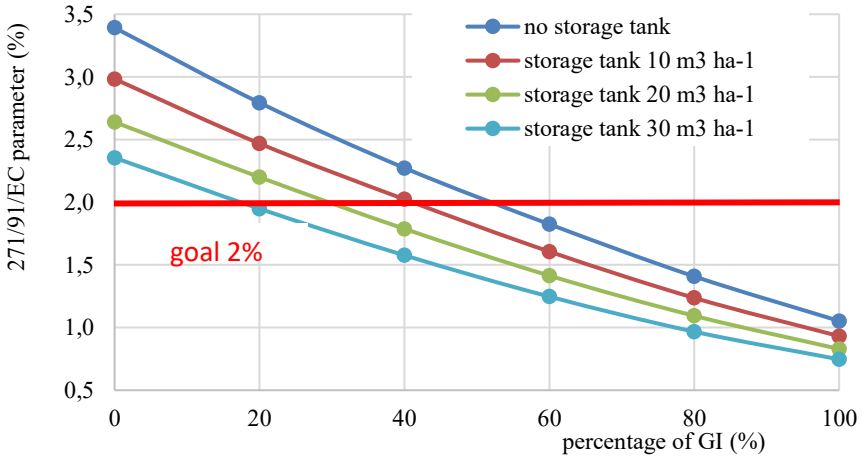

Fig. 6. Compliance of particular stormwater retention alternatives with the 2024/3019/EC directive [2]

3. Discussion

Model results show that increasing GI implementation decreases both the number of CSO events and CSO volume, as indicated by the downward trends in Figures 4 and 5. Adding a stormwater detention tank also lowers these parameters, as evidenced by the curves' lower positions in the same figures. However, both trends exhibit some non-linearity; for instance, when comparing curves with rainwater stormwater tanks, the reduction corresponding to larger tank volumes is not proportional to the increase in reservoir size. This suggests that both green and grey infrastructure may have physical or technical limits to reducing runoff, which cannot be surpassed with current technologies or only at significantly high costs.

This section should also address the model's uncertainties and simplifications, as these can significantly influence the study's results. The first key simplification is ignoring rainfall spatial distribution, an important factor in runoff from large urban catchments. Niemczynowicz [7] suggested using one rain gauge per square kilometre for large catchments. Schilling [8] found that, when based

on statistically processed data, the spatial rainfall distribution introduces only minor errors. However, in studies focused on individual rain events, spatial rainfall variability is crucial.

Uneven spatial rainfall distribution could introduce significant errors in our study, as the selected catchment area (1364 ha) may not experience uniform rainfall. It's important to note that the spatial rainfall variability problem is independent of the model type used. Modern radar rainfall measurement techniques, combined with ground-based rain gauge data, can mitigate this issue. However, the challenge lies in the availability of such data. This limits access and use of the data for research, engineering, and design purposes.

Another aspect is the oversight of rainfall-runoff process dynamics. Our approach assumes a constant runoff coefficient and rainfall intensity throughout the event (essentially a block rain model). It also presumes steady storage volumes, which is acceptable for a stormwater tank. Still, it overlooks the flow dynamics within the sewer network, including its non-uniform, non-stationary, and time-varying wastewater filling. Such neglect of flow dynamics is common in engineering, often leading to the assumption of flow stationarity. Incorporating these rainfall-runoff dynamics into the model would necessitate a fundamental redesign and require time-dependent input data, such as rainfall time series.

Neglecting the dynamics of hydrological processes also applies to the use of constant concentrations of pollution indicators in diluted wastewater. Under real-world conditions, rainfall events occur at different times of the day, so the mixing ratio of stormwater and non-stormwater wastewater varies each time. This also applies to varying precipitation intensities and to the implementation of stormwater retention tanks, which alter the mixing ratio; furthermore, sedimentation in stormwater retention tanks can reduce the amount of pollution transported to receiving water bodies.

Removing the aforementioned model simplifications would significantly increase data requirements and make calculations more complex, eliminating the possibility of using simple tools like MS Excel. For detailed modelling, a complex hydrodynamic approach should be employed, such as SWMM [9] or MIKE [10]. The feasibility of implementing green infrastructure is also uncertain; for example, it may not be possible to apply adaptation measures across 100% of targeted areas. Green roofs, as mentioned above, are often difficult to implement cost-effectively on older buildings due to static load limitations or structural issues such as insulation and pitched roofs. Semi-permeable surfaces in heavily trafficked parking lots, such as those near industrial sites or shopping centres, are often problematic for groundwater protection. Common challenges include limited space, land ownership, environmental protection (underground water in case of stormwater infiltration), and operational issues, especially in densely built-up city centre areas.

A particularly important aspect is the spatial distribution of proposed structural or BGI measures — the method we used implicitly assumes their uniform distribution across the urban watershed. However, in the practical implementation of the proposed adaptation measures, this assumption cannot be met, especially in densely built-up central urban areas. This fact also significantly impacts the spatial dynamics of runoff, the occurrence of local flooding, and the amount of pollution transported through CSOs into receiving water bodies.

The described methodology depends on historical rainfall data, which may introduce inaccuracies. Projections indicate that, due to climate change, short-term rainfall intensities are expected to increase by several per cent up to several tens of per cent, a trend supported by existing research [11,12]. The approach considers, very roughly, alternative surface runoff retention strategies, such as surface ponds (microponds), infiltration, or direct discharge to receiving waters, all of which can substantially improve local microclimates [13]. The urban catchment in Trnava has a natural stream, Trnávka, which could be used for local stormwater management as a receiving water. This emphasises the importance of restoring the river network within urbanised zones [14]. Moreover, actual catchments are characterised by additional parameters that have only been estimated in this hypothetical scenario—such as the length and operational volume of the sewer network, wastewater flows (including industrial effluents and infiltrated water), and pollutant concentrations in both wastewater and discharge waters.

4. Conclusion

The overall design of urban stormwater adaptation measures is highly specific to local conditions, including the availability of suitable recipients and their hydraulic capacity, soil hydrogeological properties affecting stormwater infiltration, and the capacity of the urban sewer system. It is important to recognise that green infrastructure alone cannot fully mitigate the impacts of climate change; often, an integrated overhaul of the existing urban drainage system is necessary.

The findings suggest that implementing green infrastructure, even to a great extent, does not necessarily ensure compliance with the objectives outlined in Directive 2024/3019/EC [2] (see Table 3). As illustrated, only a combined approach employing both green and grey infrastructure—such as stormwater tanks—can achieve the targeted 2% reduction in annual pollution loads reaching surface water via CSOs.

Given that this study is theoretical, practical engineering applications may encounter additional technical challenges when deploying such comprehensive adaptation and retention measures.

An essential consideration is the balance between technical feasibility and cost-effectiveness, aiming to achieve an optimal solution that meets the specified parameters. This will likely require a tailored mix of green and grey infrastructure, with the proportional allocation influencing both capital and operational expenditures. The most effective strategies are expected to be highly context-dependent and should be determined on a case-by-case basis.

Future investigations will compare the outcomes of this approach with those derived from numerical rainfall-runoff modelling. Moreover, it is crucial to acknowledge that the current methodology relies on historical data and does not account for the potential impacts of climate change.

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