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Resilience of the Urban Drainage System in Brescia (Northern Italy) to Climate Change: a preliminary analysis

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Abstract

Climate change is a global phenomenon that even more severely affects Italian cities causing extreme hydrometeorological events that overload the urban drainage infrastructure. In addition to climate change, the continuous consumption of land and the increasing soil-sealing contribute as well to the formation of surface runoff. These issues are particularly relevant for combined sewer systems, where critical situations may not only to generate localized flooding, but also impact the receiving water bodies downstream of the flood spillways. The enhancement of these issues expected in the near future will require higher performances of the hydraulic infrastructure. The conventional solutions, based on the re-sizing of the pipes sections, the improvement of the hydraulic characteristics of the canals and the construction of detention basin, no longer seem to adequately respond to the need of land hydraulic protection. In recent years, however, a new plural and integrated approach is being implemented, promoting the adoption of sustainable urban drainage systems that provide multiple benefits, such as surface runoff reduction, water quality improvement and rainwater collection and reuse. In this perspective, sustainable urban drainage represents a useful and necessary solution to reduce the impact of climate change effects especially in highly urbanized areas. In this study, a preliminary analysis was carried out for the Brescia case study, an Italian city that is facing the effects of the climate change. A multi criteria scenario analysis was used to attempt and estimate of the effectiveness of sustainable adaptation strategies under the deep uncertainties due to climate change. In addition, different solutions were investigated to find those which better fit the specific urban context of the town, where free space is seldom available as in many other Italian cities.

Keywords: Climate Change, Sustainable Urban Drainage, Integrated systems, Sustainable adaptation technologies.

1. INTRODUCTION

The changes in global climatic conditions of the last decades led to an increase in extreme rainfall events, with direct consequences on urban floods formation, contributing to the deterioration of the urban drainage systems level of service (Liu et al., 2021). According to the sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC, 2021) for the late 21st century a further increase in the frequency of heavy storms is expected, as a result of global warming. In addition to climate change, population growth, urbanization and other changing factors as well represent additional factors that act simultaneously, posing more difficult challenges for the future sewerage performances (Dada et al., 2021; Kleidorfer et al., 2009). These challenges are further complicated by the unpredictability of the future conditions that could questione the robustness and the effectiveness of the mitigation solutions adopted to prevent the potential future changes, given the deep uncertainty of their nature (Urich and Rauch, 2014).

In this context, the sewer network needs adaptive improvement interventions in order to become less vulnerable and more resilient to future conditions (Hattum et al. 2017). In fact, the urban drainage system is expected to be always reliable and functional, able to collect and deliver the water to the treatment plants and to the waterways, in any conditions and with any extreme event, acting resiliently. At the same time, these mitigation systems should also provide social and environment benefits and pursue sustainability in the long term. However, it is largely uncertain how to ensure that a drainage strategy will maintain its reliability, resilience and sustainability qualities over the time in face of changing conditions. Moreover, the different adaptation solutions (e.g., centralized or decentralized) do not ensure equal performances for all urban realities but must be evaluated individually in order to guarantee the most reliable outcomes, now and in the future (Scholten et al., 2017).

2. MATERIALS AND METHODS

2.1 Overview

The procedure developed in this study is illustrated by the flow chart shown in Fig. 1. In the first step, the data needed were collected and analyzed. These data were classified in different groups: topographic, hydrologic (runoff coefficient), hydraulic (sewerage network) and climatic data (rainfall). Second and third steps consisted in estimating heavy storms under different scenarios and evaluating the rainfall depth-duration-frequency curves. In the fourth step the state of the art system performance was evaluated and in the fifth different flood risk mitigation solutions were considered and tested under different scenarios. In the next steps the critical flow was estimated after the implementation of the different solutions, the sizing of the stormwater detention tank was calculated in the actual and in the RCP 2.6 scenarios and finally the obtained outcomes were compared to identify the most effective and robust solution.

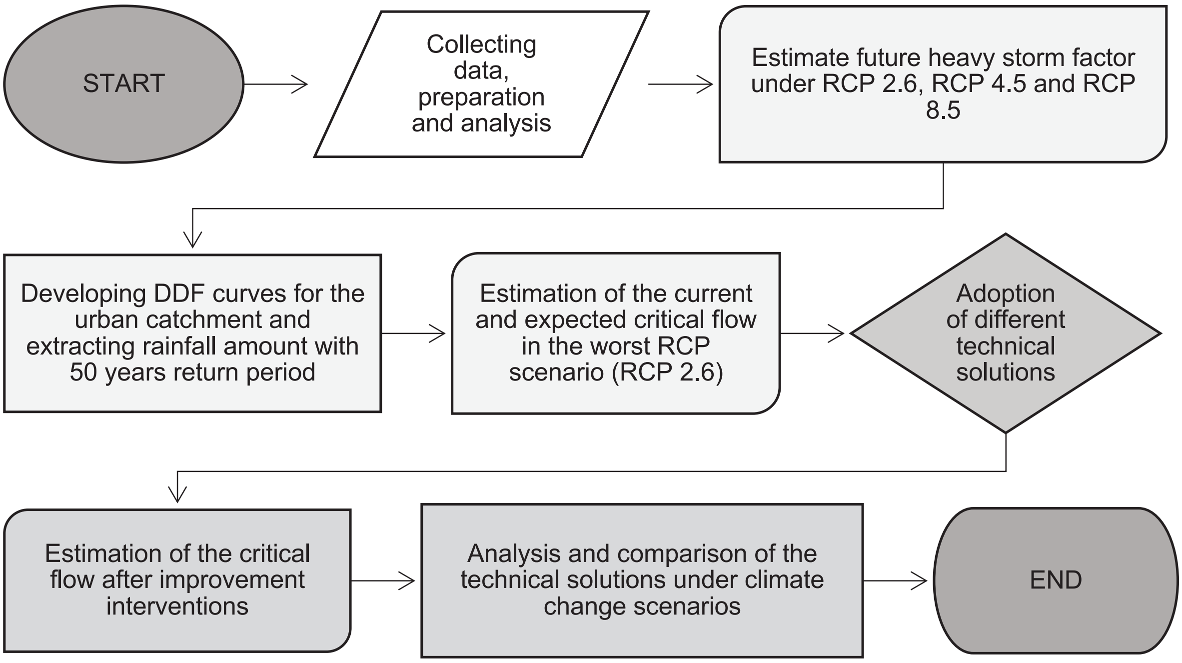

Figure 1. Flowchart representing the procedure used to quantify benefits of technical solutions in different climate scenarios

2.2 The case study

The urban catchment analyzed for this investigation is “Villaggio Prealpino”, a 1,414 km2 – wide district of Brescia (Northern Italy Fig.2). The area occupied by the neighborhood is substantially flat, with elevations ranging from 192 m.a.s.l. at the northernmost point to 175 m.a.s.l. at the southernmost point, with an average elevation gradient of 5,7 ‰ (https://www.geoportale.regione.lombardia.it/servizi). Until the second post-war period Villaggio Prealpino consisted of open country. Subsequently it underwent 14 years of urban development that led to the formation of the current urban agglomeration. The catchment system consists of a combined sewer network (main pipes having a diameter of 1,2 m) that collects and conveys both wastewater and stormwater to the sewage treatment plan of the city. Excess flows are discharged through a spillway directly into the local water body.

Figure 2. The study area “Villaggio Prealpino” (Google Maps)

2.3 Future scenarios

Changes in the rainfall regimes is one of the major uncertainties that affect the urban drainage system planning and management. To evaluate the effect of climate change on urban runoff CORDEX (www.cordex.org) climate projections for three different Representative Concentration Pathways (RCP 2.6, RCP 4.5 and RCP8.5) were used (Berteni and Grossi, 2020). For each RCP, yearly correction factors were derived and used to adjust the DDF Curves (rainfall depth-duration-frequency curves) provided by the Regional Environmental Protection Agency (ARPA - https://idro.arpalombardia.it). Average precipitation correction factors of 1.108, 0.949 and 1.097 were respectively derived for RCP 2.6, RCP 4.5 and RCP 8.5. For the peak flow estimation and for the stormwater detention tank sizing only the worst climate scenario was considered (RCP 2.6).

2.4 Estimation of rainfall DDF Curves (Storm rainfall analysis)

To define the rainfall depth-duration-frequency curves, rainfall data available on the hydrological website of ARPA Lombardia and referring to the period 1985 – 2005 were used. Assuming a homogeneous distribution of rainfall over the Villaggio Prealpino district, the DDF curves were defined and the T-year rainfall depth hT was calculated using the following Eq. [1] and Eq. [2]:

$$h_T(D) = a_1\, w_T\, D^n \qquad [1]$$

$$w_T = \varepsilon + \frac{\alpha}{k}\left\{1 - \left[ln\left(\frac{T}{T-1}\right)\right]^k\right\} \qquad [2]$$

where hT(D) is the rainfall depth of duration D for a return time T, a1 is the hourly rainfall coefficient, wT is the probabilistic coefficient linked to the return time T, n is the exponent of the curve (parameter of scale, lower than 1), D is the duration of the rainfall event and α, ε, k are the parameters of the adopted GEV probabilistic law. The n value provided by ARPA relates to a rainfall event lasting > 1 h, for an event duration <1 h, n was considered equal to 0.5, as required by the regional law “Regolamento Regionale 23 novembre 2017, n. 7” (updated on 21/12/2019 - BURL, 2019)) reporting criteria and methodologies to comply with the hydraulic and hydrologic invariance in accordance with the article 58 bis of the regional law of 11th March 2005 n.12 (the so called "Law for the territorial administration"). Referring to a rainfall event with a return time of 50 years and with a duration more than one hour, a and n were found to be respectively equal to 55,2019 and 0,2818. Representing the rainfall DDF curve in the classic formulation, Eq. [3] was considered:

$$h = 55{,}2019\ t^{\,0{,}2818} h = 55{,}2019\ t^{\,0{,}2818} \qquad [3]$$

where h (mm) is the cumulative rainfall height in the time interval t.

The rainfall obtained (point storm rainfall) was then related to the whole study area by applying a correction factor (areal reduction factor) to the parameters in order to evaluate the areal storm rainfall. To evaluate the new parameters a' and n' reference was made to the formulas proposed by Marchetti (1964), eq. [4] and eq. [5], valid for areas between 100 and 500 ha:

$$a' = a \left[1 - 0.06 \left(\frac{A}{100}\right)^{0.4}\right] \qquad [4]$$

$$n' = n + 0.003 \left(\frac{A}{100}\right)^{0.6} \qquad [5]$$

where A is the area considered expressed in hectares. The value obtained are shown in the Tab. 1 while in Fig. 3 the DDF Curves of the historical series are plotted, together with the corresponding curves in the RCP 2.6 scenario.

Table 1. Values of the parameters of the rainfall depth-duration-frequency curves for Brescia

Scenarios	**Point storm rainfall**		**Areal storm rainfall**	
	a	**n**	**a'**	**n'**
Historical Series (1985 – 2005)	55.2	0.28	51.4	0.28
RCP 2.6	61.2	0.28	56.9	0.28
RCP 4.5	52.4	0.28	48.8	0.28
RCP 8.5	60.6	0.28	56.4	0.28

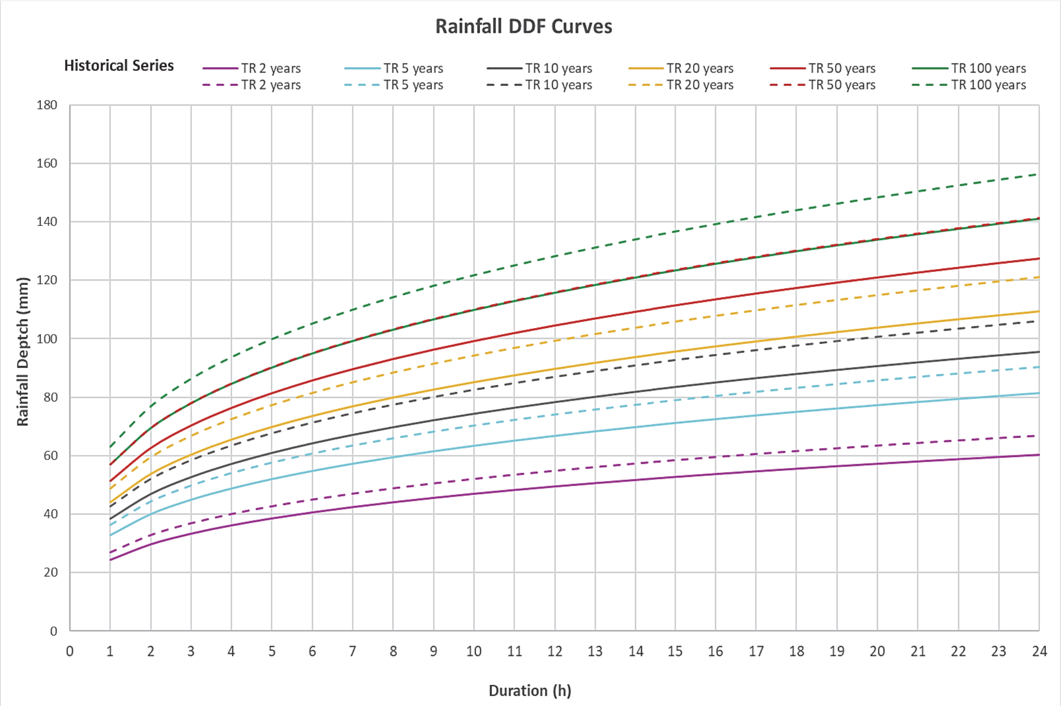

Figure 3. Rainfall Depth-Duration-Frequency curves of the historical series (continuous lines) and RCP 2.6 climate scenario (discontinuous lines) for Brescia

2.5 Estimation of rainfall DDF Curves (Storm rainfall analysis)

For the evaluation of the critical flow (or peak flow generated by a rainfall event with constant intensity and critical duration) under the different scenarios, the concentration method was used, assuming the critical rainfall duration equal to the time of concentration. This method is based on the following hypotheses:

i. The runoff coefficient is not varying during the rainfall event;
ii. The fixed percentage method is assumed;
iii. The catchment behaves as a linear and stationary system;
iv. The drained area vs time of concentration relationship is linear;
v. The rainfall intensity is constant (rectangular hyetograph).

With this model the peak flow increases until the duration of the event equals the time of concentration of the catchment and decreases when the duration of the event exceeds this time.

The time of concentration is defined as the time it takes for a generic drop of water to flow from the 'hydraulically' farthest point to the outlet of the basin (Becciu and Paoletti, 2020). The time of concentration of a urban catchment with a sewerage system can be estimated as the sum of the flow time on the basin surface before reaching the drainage system, defined as T_e (entry time), and the time of propagation along the pipes of the sewerage, T_r (network time).

Given the lack of direct data, T_e was set equal to 7 min, as suggested by Becciu and Paoletti (2020), in reference to the urban catchment characteristics as shown in Tab. 2.

Table 2. Entry time in relation to the type of catchment

Type of catchment	Te (min)
Intensive urban centers with roofs directly connected to the drainage system and with frequent street inlets	5 - 7
Semi-intensive urban areas with moderate slopes and infrequent street inlets	7 - 10
Extensive urban areas with small slopes and occasional street inlets	10 - 15

The network time *Tr* was calculated by adding the water flow time of each individual pipe upstream the outlet along the hydraulically longest path using the following Eq. [6]:

$$T_r = \sum_i \frac{L_i}{1.5\,V_i} \qquad [6]$$

where L_i and V_i are respectively the length and the velocity of the i-th pipe. The value of T_r obtained was 15.91 min while the To value was 22.914 min. The critical peak was then calculated using Eq. [7]:

$$Q_c = 2.78\,S\cdot\,\varphi\cdot\,a(T)\cdot\,{T_0}^{n-1} \qquad [7]$$

where Q_c is the critical flow in l/s, S is the urban catchment area extension in ha, f is the runoff coefficient, $a(T)$ is the rainfall DDF curve coefficient in mm/h, T_o is the time of concentration in h and n is exponent of the rainfall DDF curve.

2.6 Kinematic model for sizing the Stormwater Detention Tank

The determination of the minimum detention volume (critical volume) was carried out using the kinematic model developed by Alfonsi ed Orsi (1987), based on the following hypotheses:

i. Rainfall intensity is constant during the event (rectangular hyetograph);
ii. Linear drained area-concentration time curve;
iii. Emptying process at a constant flow equal to Q_{max}

Thus, the expression of the volume to be stored in the stormwater detention basin can be computed using Eq.8:

$$W = 10\cdot\varphi\cdot A\cdot a\cdot\theta^n + 1.295\cdot T_0\cdot {Q_u}^2\cdot\frac{\theta^{n-1}}{\varphi\cdot A\cdot a} - 3.6\cdot Q_u\cdot\theta - 3.6\cdot Q_u\cdot T_0 \qquad [8]$$

where W is the volume in m^3, f is the runoff coefficient, A is the catchment area in ha, a is the rainfall DDF curve coefficient in mm/h, Θ is the rainfall event duration in h, n is the exponent of the rainfall DDF curve, T_o is the time of concentration of the catchment in h and Q_u is the maximum outflow in l/s.

By imposing the maximum condition for the volume equation that is deriving the equation with respect to the duration and setting the obtained expression to zero, Eq. [9], the critical duration value, ϴw was found.

$$2.78 \cdot n \cdot \varphi \cdot A \cdot a \cdot {\theta_w}^{n-1} + 0.36 \cdot (1-n) \cdot T_0 \cdot {Q_u}^2 \cdot \frac{{\theta_w}^{-n}}{\varphi \cdot A \cdot a} - Q_u = 0 \qquad [9]$$

This was then used to calculate the critical volume, W_o, for sizing the stormwater detention tank

3. RESULTS AND DISCUSSION

Table 3 and Figure 5 show the outcomes of the technical solution implementation to the case study: the adoption of the green infrastructures (green roofs and porous pavements) brought a runoff coefficient reduction and peak flow decrease of about 15%; whereas implementing grey solutions (downpipe diversion and stormwater detention tank) showed greater efficiency in reducing the peak flow. In particular, the adoption of the stormwater detention tank is bound to the regional regulation which imposes a maximum discharge of 10 l/s per hectare of impervious surfaces. In this study, this value corresponds to 1071 l/s.
The results of the RCP 2.6 scenario highlighted a 9.81% increase of the critical discharge due to climate change variation. This translates into an increase in the required detention volume to cope with this effect.

Table 3. Results related to the variation of the critical flow under the different scenarios

Mitigation strategy adopted	**f**	**Historical Series**	**Qc reduction**	**RCP 2.6**	**Qc increase**
		Qc [m^3/s]		**Qc [m^3/s]**	
State of the art	0.57	17.41	-	19.30	9.81 %
Green Roofs	0.52	15.63	- 13.10 %	17.33	
Porous Pavement	0.48	14.48	- 16.80 %	16.06	
Downpipe diversion	0.46	13.92	- 20.02 %	15.44	
Stormwater detention tank	0.577	1.07	- 93.85 %	1.07	-

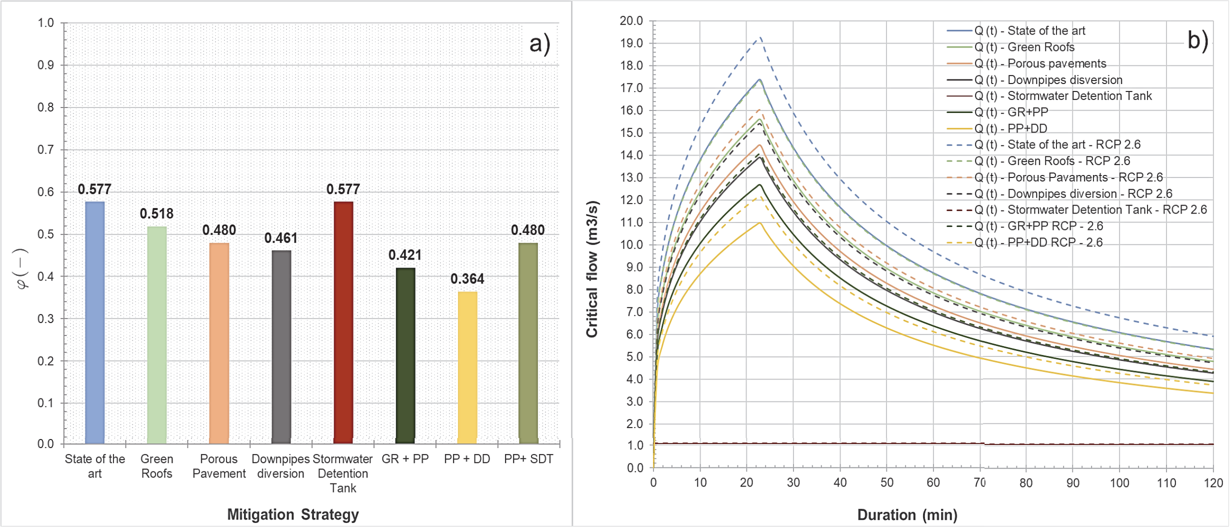

Figure 4. a) Runoff coefficient under various scenarios b) Critical flow curve as a function of the rainfall event duration under different scenarios

Table 4 shows the data about the stormwater detention tank calculation: in the actual scenario the minimum required volume, according to the regional regulation, should be of 83975 m3, and this means about 9 stormwater detention tanks for each hectare. The minimum value of the storage volume would though increase in RCP 2.6 scenario. In fact, the needed storage volume would have to be increased of about 11000 m3, that is by 13.24%, making 11 tanks for hectare necessary.

Table 4. Results related to stormwater detention tank sizing

Stormwater detention tank values	Historical Series		RCP 2.6		Value increase
Storage volume	83975	[m^3]	95090	[m3]	13.24 %
Specific storage volume	784	[m^3/ha]	887	[m3/ha]	
Volume of a precast tank	63.75	[m^3]	63.75	[m3]	
Number of tanks needed	1317	[-]	1492	[-]	
Number of tanks per hectare	9		11		

The positive effects of the adaptation strategies were also assessed by combining the different interventions, specifically the effect of green roofs combined with porous pavements, porous pavements combined with downpipes diversion and porous pavement combined with detention tank implementation were evaluated. By the results in Tab. 5, it can be noticed how combining different strategies turn out to be more effective on the peak flow reduction.

Table 5. Results related to the variation of the critical flow by combining different strategies

Mitigation strategy adopted	f	Historical Series	Qc reduction	RCP 2.6	Qc increase
		Qc [m^3/s]		Qc [m^3/s]	
GR* + PP*	0.40	12.17	-30.06%	13.50	9.81 %
PP* + DD*	0.36	11.00	-36.82%	12.19	
PP* + SDT*	0.48	1.07	- 93.85 %	1.07	

* GR = Green Roof, PP = Porous Pavement, DD = Downpipe diversion, SDT = Stormwater Detention Tank

With regard to cost estimation, the cheapest intervention is the downpipes diversion (Tab. 6). The green roofs and the stormwater detention tank are equivalent in the expense, however, while the detention tank most contributes in reducing the discharge reduction it turns out to be more difficult to implement due to the massive volume needed. On the other hand, to the cost of green roofs does not correspond a sufficient efficiency. The best combination is represented by the couple porous pavement and downpipes diversion with a discharge reduction of 36 % at an affordable cost.

Table 6. Cost estimation related to the adoption of the various adaptation strategies (Prezzario regionale delle opere pubbliche di Regione Lombardia, 2022)

Mitigation strategy adopted	Price		Total Price
Green Roofs	per m^2	100 €	23,760,077 €
Porous Pavement	per m^2	15 €	2,937,918 €
Downpipes diversion	per unit	250 €	675,000 €
Stormwater detention tank	per m^3	750 €	62,981,488 €
GR* + PP*	-	-	26,697,996 €
PP* + DD*	-	-	3,612,918 €
PP* + SDT*	-	-	42,647,699 €

* GR = Green Roof, PP = Porous Pavement, DD = Downpipe diversion, SDT = Stormwater Detention Tank

4. CONCLUSIONS

The aim of this paper was to attempt an estimate and compare the robustness of urban drainage system mitigation strategies in terms of resilience and sustainability under the deep uncertainties of the future changes due to climate change. This analysis was carried out using a multi-criteria approach that assessed the performances of different solutions (grey and green infrastructures strategies) in the surface runoff and peak flow reduction under different future scenarios. This approach, based on the critical flow estimation, allows to evaluate and test the effectiveness of mitigation strategies adoption in future time and investigate the impact of different solutions (grey and green) on improving urban drainage resilience. However, as stated by Casal-Campos et al. (2018), the implementation of the only green infrastructure does not guarantee absolute benefits in terms of hydraulic robustness and efficiency, for this reason implementing hybrid solutions that combine green and grey strategies (soft engineering and hard engineering) represents the best strategy to counter the effects of climate change on critical flow reduction in urban areas. Indeed, the results indicate that strategies less effective in terms of runoff reduction are, however, the best in environmental and social terms.

The implementation of green interventions, which correspond to a reduction in impervious surfaces and therefore a reduction of the runoff coefficient, would lead to a lower critical flow with benefits not only in hydraulic terms but also from an environmental point of view. In fact, the increase in green surfaces helps to reduce the environmental impact of urbanization and of the soils sealing by effectively intervening in countering the phenomenon of rising temperatures in urban areas, thus reducing the effects of heat islands. On the other side, the grey intervention alone could be led to the best hydraulics situation, but its implementation would require a high land consumption to which would correspond an equally huge cost. To conclude, there is no single intervention totally effective against the climate change, but it is necessary to find the best combination of adaptation solutions that best integrate in the urban territory.

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