Urban Climate 51 (2023) 101596

Contents lists available at ScienceDirect

Urban Climate

journal homepage: www.elsevier.com/locate/uclim

SuDS as a climate change adaptation strategy: Scenario-based analysis for an urban catchment in northern Italy

R. D'Ambrosio [a,*], A. Longobardi [a], B. Schmalz [b]

[a] Department of Civil Engineering, University of Salerno, Via Giovanni Paolo II 132, 84084 Fisciano, Italy
[b] Chair of Engineering Hydrology and Water Management, Department of Civil and Environmental Engineering, Technical University of Darmstadt, Franziska-Braun-Straße 7, 64287 Darmstadt, Germany

A R T I C L E I N F O

Keywords:
Climate change
Rainfall extremes
Urban flooding
Sustainable drainage systems SuDS
Storm water management model
Climate change adaptation

A B S T R A C T

Urbanization and climate change effects on precipitation are the leading cause of flood risk increase in urban settlements. Sustainable Drainage Systems (SuDS) are effective strategies to improve city resilience toward flooding but usually they are designed to meet performance standards based on historical climate settings. The reported modeling scenario-analysis strives for investigating the potential of SuDS as adaptation strategy to a projected medium-term climate change affecting Sesto Ulteriano (Milan, Northern Italy). Two drainage models, a benchmark scenario reproducing the drainage network current configuration and a designed scenario involving SuDS retrofitting, were tested under historical (observed) and expected future precipitation extremes (projected) to assess and compare hydrological and hydraulic variables essential for the definition of a Precipitation Variability Adaptation Index (PVAI), which measures the adaptation strategy performance. Results indicate that even though SuDS were confirmed as effective flood control measures, their adaptability potential is affected by changes in rainfall severity indeed. In particular, the multi-variable PVAI, a global index able to take into account the effects of different determinants for an overall assessment of SuDS potential as adaptation strategies to climate changes, decreases when rainfall frequency decreases, among the same climate scenario, or when rainfall intensity increases due to climate changes.

1. Introduction

Soil sealing and climate change effects are the leading cause of an increase of flooding phenomena in urban context (Miller and Hutchins, 2017; Nanni et al., 2021). During the past century, this issue raised the interest of the scientific community concerned with climate changes on one side and focused on the identification of sustainable solutions for flood adaptation on the other side (Kabisch et al., 2017; Rosenberger et al., 2021). The management of this two-fold issue requires both starting to curb the climatic dynamics in progress, a process that is as necessary as tragically slow, and exploring the possibility to implement adaptation and mitigation strategies for flood risks reduction in urban context. Sustainable Drainage Systems (SuDS) consist of a range of technologies based on the philosophy of replicating as closely as possible the natural, pre-development drainage from a site (Fletcher et al., 2015; Woods Ballard et al., 2015). Researchers agree on their ability of reducing stormwater runoff volume and delaying its peak flow (Mobilia et al., 2020; D'Ambrosio et al., 2021a), features that make them valid adaptation strategies to climate changes.

* Corresponding author.
E-mail address: robdambrosio@unisa.it (R. D'Ambrosio).

https://doi.org/10.1016/j.uclim.2023.101596
Received 8 January 2023; Received in revised form 19 April 2023; Accepted 7 July 2023
Available online 13 July 2023

Urban stormwater management systems are usually designed to meet performance standards based on historical climate data. However, considering the possible impact of climate change on precipitation regime, researchers started assessing flood risk adaptation strategies under future climate conditions (Kirshen et al., 2015; Moura et al., 2016; D'Ambrosio et al., 2023). Several modeling studies showed that an optimal design of SuDS (type, location, and covered area) succeed in increasing stormwater runoff reduction or functional resilience of the drainage network (Mugume and Butler, 2016) even under climate change impacts indeed (Ghodsi et al., 2020; Abduljaleel and Demissie, 2021; Guptha et al., 2022). However, a hydrological performance decrease is certainly observed if current precipitation is supposed to increase in the future (Yang et al., 2022). Developing an adaptation option is undoubtedly challenging for long-term engineering decisions due to uncertain future climatic condition (Liu et al., 2018) and there is still little information on how SuDS should be sized for the future to ensure they continue to perform throughout their life-span (Semadeni-Davies, 2012; Cortinovis et al., 2022). Given the inherent uncertainty of this issue, successful adaptation strategies will likely involve actions to reduce vulnerabilities across a wide range of plausible future climatic conditions, further considering these "no-regrets strategies", beneficial in addressing current stormwater management needs, regardless of whether or how climate may change in the future (Means III et al., 2010).

However, an adequate knowledge of the climate context is actually extremely important for the definition of SuDS behaviour in the future management of urban stormwater. There are different approaches toward this broad and complex field of research that mainly involve Global and Regional Climate Models, appropriately tailored with downscaling procedures, and statistical methodologies of detection of non-stationarity signals from historical rainfall datasets. Even widely implemented in hydrological modeling analysis (Liu et al., 2018; Abduljaleel and Demissie, 2021; Le Floch et al., 2022; Guptha et al., 2022), their efficiency in reproducing the temporal clustering of heavy precipitation is also discussed (Yang et al., 2022). As an alternative, several methodologies of statistical investigation of historical rainfall datasets have been largely applied to identify the current signals of a changing climate (Treppiedi et al., 2021; Gao et al., 2022) but they may be affected by the quality of the historical datasets and by the presence of a natural variability of precipitation that can hide climate temporal trends (Morin, 2011; Longobardi and Boulariah, 2022). In this context, the main challenge for reducing the uncertainty in the detection of future rainfalls is the identification of a relationship between the coarse spatial and temporal resolution of the climate projections and the observed precipitation at the urban catchment scale (Kourtis and Tsihrintzis, 2021). To this end, different approaches employing a wide variety of spatial downscaling, bias correction and temporal disaggregation techniques and/or weather generators have been proposed in the past literature (Forestieri et al., 2018; Padulano et al., 2019). However, given their complexity, these are often stand-alone studies in that simplified procedures are often preferred for assessing SuDS effectiveness under climate change (Martel et al., 2021). In several studies, for example, future rainfall scenarios were obtained adjusting the historical pattern with a fixed percentage of variation (Le Floch et al., 2022; Guptha et al., 2022). Always having to admit an important degree of uncertainty in climate projections, as suggested by Kourtis and Tsihrintzis (Kourtis and Tsihrintzis, 2021), it would be better not to see climate projections as a possible future but as an "opportunity to incorporate uncertainty in new design practices".

Nevertheless, the knowledge in this field is still far from having achieved satisfactory results. In fact, uniqueness and variability of the findings due to the influence of structural, climatic and design factors specifically related to the specific case studies investigated, do not allow inferring universally valid remarks.

The Sesto Ulteriano urban catchment, in the suburbs of Milan (Northern Italy), is an emblematic example of the critical stormwater management issues experienced by most of the contemporary cities. A massive urbanization phenomenon actually led to significant problems related to the stormwater quality as well as frequent urban flooding phenomena that also occur under the effect of moderate rainfalls. In the perspective of climate change, these evidences are likely to become even more remarkable. The reported research, a typical scenario-based analysis, specifically strives for assessing the potential of a SuDS retrofitting strategy in adapting the urban drainage network to the effects of a projected medium-term climate change. Two models of the case study drainage network, representative of a benchmark scenario reproducing its current configuration and a designed scenario involving SuDS, were tested under historical (observed) and expected future (projected) precipitations extremes to detect: total volumes and maximum peak flows discharged from the Combined Sewer Overflows (CSOs); number of the sewer nodes overcoming an 70% filling degree threshold. The Precipitation Variability Adaptation Index (PVAI) was introduced as a simple tool for assessing the potential of SuDS in adapting urban context to the hydrological consequences of potential climate changes taking into account several hydrological and hydraulic variables. The additional strengths and novelties of this study certainly are the knowledge of the feasibility of the project of retrofitting and a repeatable methodology of a statistical nature that allows the assessments of the future climatic characteristics of short rains relying only on long-term historical observations. Provided the spatial rainfall properties and urban landscape geographical continuity, these two elements, applied to the Sesto Ulteriano urban area, allow establishing a regional methodology capable of assessing, in similar regional urban context, SuDS potential as adaptation strategies to climate change consequences.

2. Materials and methods

2.1. The study site

Sesto Ulteriano (45°23′45″N 9°15′13″E) is a hamlet for primarily industrial designation of about 1100 ha and 3500 inhabitants in the municipality of San Giuliano Milanese, belonging to the Metropolitan Borough of Milan, Lombardy Region (Northern Italy). Even if still surrounded by large agricultural parcels, the built up area experienced a remarkable development between 1954 and 2015 that led to an alteration of the hydrological cycle with a consequent increase of flooding phenomena that also occur under light rain events (Fig. 1). Moreover, Sesto Ulteriano drainage network, which is mainly combined, delivering both stormwater and wastewater, is

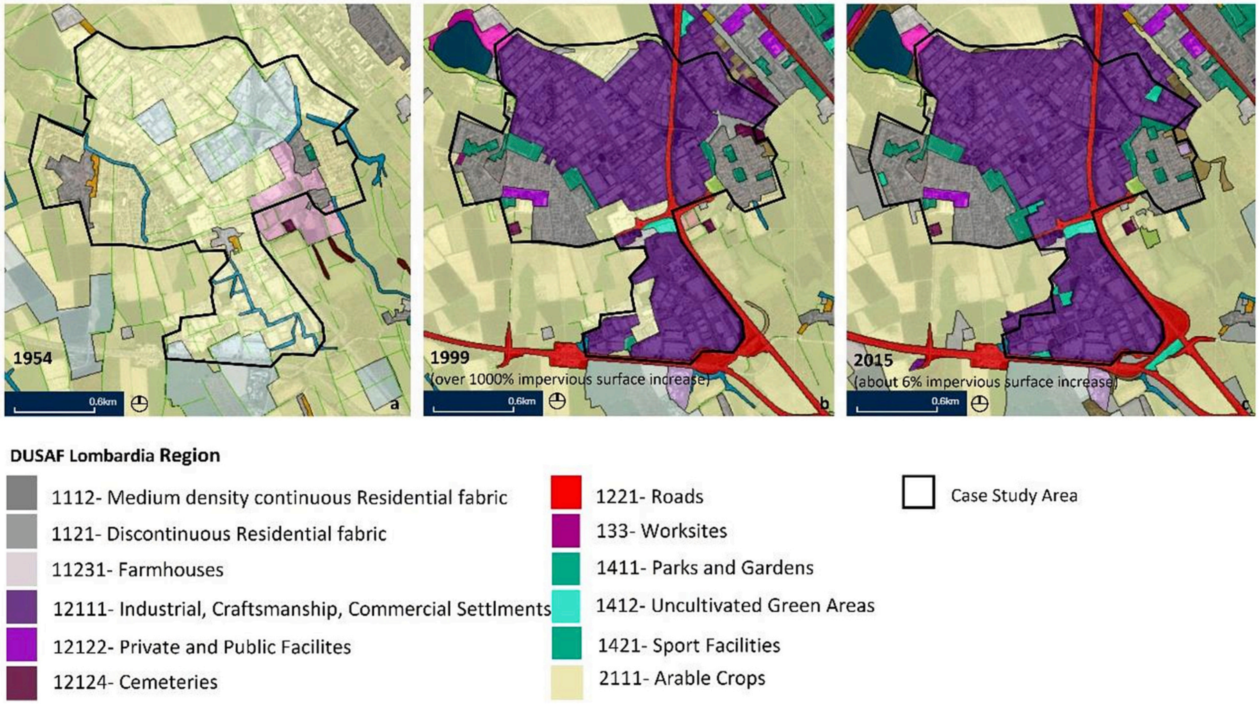

Fig. 1. Sesto Ulteriano urban development. Sesto Ulteriano Land Use evolution, "Destinazione d'Uso dei Suoli Agricoli e forestali" DUSAF 1954, 1999, 2015 (Geoportale Lombardy Region).

currently unable to completely manage the stormwater runoff in a sustainable manner: the excess stormwater in fact is discharged into artificial irrigation ditches through combined sewer overflows (CSOs) placed along the network (Fig. 2). Therefore, this strong interconnection between the hydrographic and drainage network makes the water quality issue an additional concern. The study catchment covers about 290.33 ha of the entire territory of Sesto Ulteriano, an area characterized by a flat landscape with industrial and residential settlements (73% and 23% respectively) with a significant soil imperviousness.

2.2. Available data

The case study area has been object of a previous research aimed at assessing the impact of rainfall severity, SuDS areal extension and land use on the effectiveness of a sustainable re-development of the urban catchment (D'Ambrosio et al., 2022a). The mentioned study relied on a detailed and feasible preparatory study of SuDS feasible retrofit design, based on a punctual identification of the areas suitable for retrofitting and the most appropriate combination of SuDS technologies. Drainage models of the case study catchment were set up using the Storm Water Management Model 5 (SWMM5), an open-source software developed by the United States Environmental Protection Agency (Rossman and Huber, 2016). It involves a flexible set of hydraulic modeling capabilities and accounts for various hydrological processes, some of them specifically focused at investigating stormwater runoff in urban catchments where SuDS are installed. In particular, the study reported in the current paper involved two of the drainage models set up in D'Ambrosio et al. (D'Ambrosio et al., 2022a): the “traditional” drainage scenario (T-DS), that is the benchmark option, and the “SuDS-based” drainage scenario (S-DS), where the SuDS were accounted for, according to the mentioned feasible preparatory study. A brief description of both is given below but additional details can be found in D'Ambrosio et al. (D'Ambrosio et al., 2022a).

2.2.1. Drainage models: traditional (T-DS) and SuDS-based drainage scenario (S-DS)

The “traditional” drainage scenario is representative of the actual drainage network of Sesto Ulteriano and does not include SuDS facilities. It was modelled using the SWMM5, including 1148 nodes, 1141 conduits, 27 combined sewer overflows (CSOs) for a total of 36 km of sewer. To best capture the effect of spatial variability in topography, drainage pathways, land cover, and soil characteristics on runoff generation, a large number of sub-catchments were identified, almost one for each node of the network, each characterized, among others, by a fraction of pervious and impervious sub-areas (D'Ambrosio et al., 2021b; D'Ambrosio et al., 2022a). Infiltration patterns typical of residential and industrial catchments, the latter characterized by a higher impervious surface, were defined according to the soil's tabulated Curve Number (United States Department of Agriculture, 1986), thus selecting the NRCS (Natural Resources Conservation Service) Curve Number method for runoff estimation.

The “SuDS-based” drainage scenario was conceived as an upgrade of the discussed T-DS, since it provides for a retrofitting of some of the existing impervious surfaces implementing SuDS facilities. Specifically, this scenario involves the implementation of drainage trenches, rain gardens and permeable parking lots for an overall challenging retrofitting percentage area of 8.3% (24.2 ha over about 290 ha). Each SuDS type was designed and located according to the actual maximum transformation potential of the catchment, thus considering the important role of feasibility in urban land planning (D'Ambrosio et al., 2022a). Specifically, about 17.60 ha of impervious surface were converted into drainage trenches and rain gardens (6% of the total area) and 6.40 ha into permeable parking lots (2.3%). Even though this research does not focus on the definition of the individual role of each implemented SuDS type in the

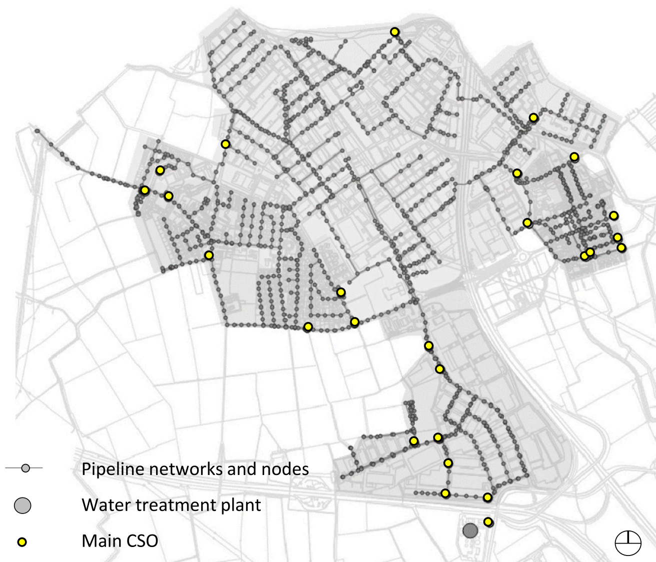

Fig. 2. Sesto Ulteriano drainage network scheme. Representation of Sesto Ulteriano drainage network with the identification of conduits, nodes and main Combined Sewer Overflows (CSO).

overall hydrological performance of the drainage system, it is deemed essential to clarify the most significant similarities and differences between them. All of the SuDS facilities implemented were selected for their specific attitude to enhance the retention processes within the catchment. However, drainage trenches and rain gardens, if compared to the permeable parking lots, are characterized by an higher storage capacity that increases their ability to reduce the surface runoff and to promote stormwater infiltration in the soil deeper layers. Moreover, the flexible configuration of drainage tranches makes them easier to place within already established urban areas. This means that the performances of the SuDS-based drainage scenario will be necessary mostly influenced by the drainage tranches due to the combined effect of a higher retention capability and a higher possibility of implementation. A high variability should be highlighted in SuDS distribution within the catchment. If compared to residential areas, industrial ones (73% of the case study area), the most concerned by flooding phenomena, are indeed characterized by a larger impervious surface and thus a larger retrofitting potential. Drainage trenches and rain gardens were both modelled in SWMM5 using the "Bio-retention Cell" module while for the permeable parking lots the specific "Permeable Pavements" module has been selected. Parameters related to surface, soil and drainage layers, and drains were adopted according to design choices, SWMM5 typical values, SWMM5 ranges and SuDS Manual suggestions (Woods Ballard et al., 2015; Rossman and Huber, 2016) to mimic the specific facilities. Parameterization is reported in D'Ambrosio et al. (D'Ambrosio et al., 2022a). SWMM5 enables to implement SuDS as a fraction of the pervious and impervious surfaces within each sub-catchment. In this study, as a hypothesis, SuDS were conceived as systems directly connected with the urban context, therefore able to treat the runoff generated by the surrounding impervious and pervious areas along with the rainfall directly falling on them before the excess runoff is re-routed to the pervious areas and then to the sewer system.

2.2.2. The climate database

According to the classification of climates of Köppen (Köppen, 1936; Beck et al., 2018), the case study area is part of the Cfa group, usually defined as "warm temperate climate" characterized by the absence of a dry season and by hot summer. The "Portale Idrologico Geografico" of the National Environmental Protection Agency (ARPA) of the Lombardia Region (https://www.geoportale.regione.lombardia.it/) provides users with measured and processed rainfall datasets, among other main hydrological and climatic variables. Specifically, an interactive map allows the identification of both active digital rain gauges and historical mechanical ones, previously managed by the Servizio Idrografico e Mareografico Nazionale (SIMN). Rainfall data can be easily acquired with a specific request procedure on the website. Among the several rain gauges around the case study area, it was considered appropriate to choose those located in the municipality of Lodi (45°19′N 9°30′E), about 25 km far from the study catchment. The appropriateness lies in the availability of measurements of both historical and active sensors (ID 7 and 8193 respectively), and thus in the largest temporal operating range, with about 60 years of sub-hour measurements. The latter were essential to assess the maximum cumulative rainfall at different durations for an appropriate design of the depth-duration-frequency curves for the case study catchment. Preliminarily, data quality was assessed and dataset inspection was performed to detect the existence of anomalies or marked changes in the time series. A deeper inspection made also possible to assess the percentage of recording failure within sub-hour datasets of each year. The inspection, essential for excluding from the following analyses those years with a percentage of missing recordings overcoming a 5% threshold, made it possible to verify that about 84% of the years could be considered "complete" and thus suitable for the climate scenario assessments. The statistical homogeneity between the datasets registered by historical and active rain gauges was moreover verified through the *t*-test (Hald, 1952; Panofsky and Brier, 1968) to assess whether the means of two groups were not statistically different from each other. The analysis pointed out that the two datasets can be defined "statistically homogeneous" and thus suitable for merging in a single longer dataset. General statistics on the mentioned dataset pointed out that the average annual rainfall is about 778 mm. The maximum value, 1336 mm, was registered in 2014 while the lowest, 495 mm, in 2011. The maximum daily value, 115 mm, was registered in 1979 (August 18th, 1979). The 90% of the precipitations characterized by intensities higher than 10 mm/h, occurred between 1960 and 2021 and had a duration less then or at most equal to 3 h, supporting the idea that extreme rainfall events are usually very short in the case study area (Fig. 3).

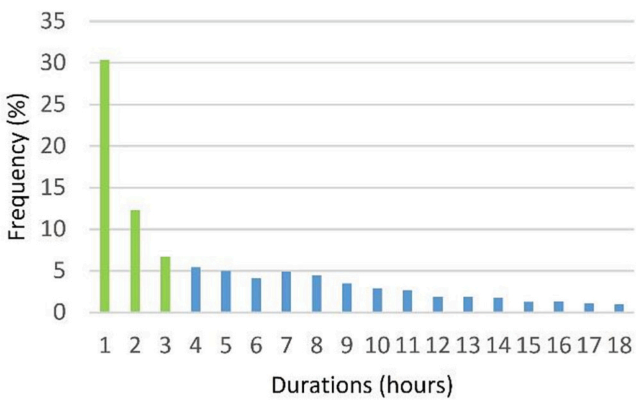

Fig. 3. Frequency of the Lodi rainfall events durations. Frequency, major than 1%, of durations of rainfall events occurred in Lodi from 1960 to 2021.

2.3. Climate scenarios methodological framework

The methodological approach is based on the awareness that the knowledge of the actual climate context and its temporal pattern is actually extremely important for assessing SuDS role in the future management of urban stormwater. In particular, the depth-duration-frequency ("ddf") curves represent the climate input typically used in hydrological modeling analysis. If the procedure to design historical observed "ddf" curves is rather codified, uncertainty lies in the design of future projected "ddf" curves.

The methodological approach here presented is based on the assumption that the stationarity of precipitation statistical parameters may not be a valid assumption in hydrologic-hydraulic design (Cheng and AghaKouchak, 2014; Ganguli and Coulibaly, 2017; Hosseinzadehtalaei et al., 2020). According to Hosseinzadehtalaei et al. (Hosseinzadehtalaei et al., 2020), both the location parameter (distribution mean) and the scale parameter (distribution dispersion) of the Generalized Pareto Distribution (GPD) are expected to increase all over Europe by an average change of 10% (location parameter) and 11% (scale parameter) for RCP4.5 (IPCC, 2014) and 17% (both) for RCP8.5 (IPCC, 2014) respectively. These variations will result into a substantial uplift and steepening of the depth-duration-frequency curves under future climate change with some differences according to the duration and the return period.

Starting from these considerations, historical extreme rainfall observations (maximum annual precipitation at varying durations) were fitted by statistical distributions in order to detect temporal evolution in relevant distribution parameters at varying durations, to be used to define future (projected) depth-duration-frequency curves. The details of the procedure for defining historical (observed) and future (projected) precipitation patterns are given below. The climate change effect on temperatures, and thus on the catchment evapotranspiration, was here not considered since not significant in event-scale investigations.

2.3.1. Hyetographs definition of projected precipitation: shape, durations, frequencies

For the purpose of the model-based scenario analysis, it was necessary to define the characteristics of the synthetic rainfall events as input setting to the SWMM5. A simple rectangular hyetograph has been selected to reproduce several rainfall events with different frequencies and durations. This hyetograph, surely the most implemented, is obtained from the ddf curves under the hypothesis that the rainfall intensity is constant during the event duration (Wartalska et al., 2020). Since it does not consider a peak intensity effect, the use of this schematization may slightly underestimate the effects of the precipitation on the runoff production. As typically accounted for in hydrological simulations involving SuDS, 2-years, 5-years and 10-years return periods (T) were chosen. As for the durations, 1-h, 2-h, 3-h and 9-h were selected. The shortest durations (1-h, 2-h and 3-h) were selected since they are representative of the most frequent durations of the rainfall events that occurred between 1960 and 2021 and registered by the Lodi historical rain gauge stations. In this study, they are also relevant due to a highly possible increase, in the next future, of extreme precipitations that for the case study area, as stated in the Subsection 2.2.2, are mainly characterized by short durations (Fig. 3). The 9-h duration, instead, was selected since it was representative of the "critical duration" of the catchment, defined as the duration that maximize the peak flows and volumes discharged from the CSOs (D'Ambrosio et al., 2022a).

2.3.2. Definition of observed historical (H-PS) and projected future (F-PS) precipitation scenarios

Therefore, with the aim of identifying historical (observed) and future (projected) rainfall depths, for given rainfall frequencies and durations, the following purely statistical "data-driven" methodology was implemented. Given the need to simulate events with different recurrence (T), the analysis was focused on the parameters (μ and α) of the probability distribution that best interprets the process of sub-daily heavy rainfall in the case study area.

I) Maximum rainfall depth at 1-h, 2-h, 3-h and 9-h time scale aggregation were considered for each year of the dataset. Outliers were identified through the interquartile range method and were excluded for the subsequent analyses. The Gumbel distribution (Generalized Extreme Value distribution Type-I) was selected to model the distributions of the mentioned maximum rainfall depths for a fixed duration (Gumbel, 1941). The Gumbel Cumulative Distribution Function (CDS) is:

$$F(x) = e\left(-e\left(-(x-\mu)/\alpha\right)\right) \tag{1}$$

where:

x = observed variable, μ = position parameter, α = shape parameter. As described also in Khemwong et al. (Khemwong et al., 2015), the parameters of the CDF were computed as follows:

$$\mu = \overline{x} - \alpha\gamma \tag{2}$$

$$\alpha = \frac{\sqrt{6}}{\pi} S \tag{3}$$

where:

$\overline{x}$ = sample mean, γ = Euler's constant ≈ 0.57722, S = sample standard deviation. The x, maximum rainfall depth for a selected duration and return period T, was computed as follows from the Eq. (1):

$$x = \mu - \alpha \ln(-ln(F(x))) \tag{4}$$

where F(x) can be explicated as a function of return period T (2-years, 5-years, 10-years) as follows:

$$F(x) = \frac{T}{T-1} \quad (5)$$

II) In order to define the event-scale historical (H-PS) scenarios, the maximum rainfall depths based on historical measurement were simply detected according to Eq. (4), computing, for each selected duration, the Gumbel parameters and varying the F(x) according to Eq. (5).

III) In order to define the event-scale future (F-PS) scenarios, a moving window of 10 years (i.e. 1960–1969, 1961–1970, 1962–1971…) was used to follow the temporal evolution and compute time varying μ and α values. For each investigated duration, μ values were plotted over time and linear regression was implemented to detect possible trend. Once verified the significance of the trend, the equations of the trend lines were used to assess a 30 years medium-term projection of μ (Treppiedi et al., 2021). As for the parameter α, its temporal variations were not statistically significant so, in the F-PS simulations, it was decided to use the parameter value corresponding to the historical dataset. In more detail, the parameter series μ and α were also subjected to Fisher tests for the identification of temporal regimes shifts and trend in variance, finding no significant variability. The significance level was found to be higher for smaller durations suggesting for those cases a more robust statistical interpretation of the trends. The projected μ value and the historical α value, for each duration, were used therefore in Eq. (4) to compute the maximum projected rainfall depth, varying again F(x) according to Eq. (5).

IV) Once obtained the maximum rainfall depths at the selected durations for the three different return periods ($T = 2, 5, 10$ years), 24 synthetic event-scale precipitation patterns (12 historical and 12 future) were designed using a rectangular hyetograph.

The event-scale historical (observed) precipitation scenarios will be referred to in the following with the acronym H-PS while the future (projected) ones with the acronym F-PS. A double subscript (H-PS$_{d,T}$ or F-PS$_{d,T}$), where necessary, will be added to directly recall the specific duration (d-hours = 1, 2, 3, 9) and the return period (T-years = 2, 5, 10).

2.4. Climate variability and adaptation indexes

2.4.1. Simulations and output assessment

Overall, 48 SWMM5 simulations were performed to assess and compare the 2 drainage scenarios (T-DS and S-DS) under the 24 event scale rainfall scenarios (Fig. 4). The outputs of each simulation were processed in order to obtain hydrological and hydraulic parameters: the maximum peak flow (MPF) and the total stormwater volumes (TV) discharged from the CSOs of the modelled drainage network of Sesto Ulteriano along with the number of the sewer nodes overcoming a 70% filling degree threshold referred to as “Flooded Nodes” (FN). These quantities were then used to compute, for each investigated scenario, single or multiple-variable adaptation indexes and to assess their variability under a changing climate as follows.

24 PRECIPITATION SCENARIOS			
Historical		Future	
Historical rainfall extremes H-PSd,T	H-PS$_{1,2}$	Future rainfall extremes F-PSd,T	F-PS$_{1,2}$
	H-PS$_{1,5}$		F-PS$_{1,5}$
	H-PS$_{1,10}$		F-PS$_{1,10}$
	H-PS$_{2,2}$		F-PS$_{2,2}$
	H-PS$_{2,5}$		F-PS$_{2,5}$
	H-PS$_{2,10}$		F-PS$_{2,10}$
	H-PS$_{3,2}$		F-PS$_{3,2}$
	H-PS$_{3,5}$		F-PS$_{3,5}$
	H-PS$_{3,10}$		F-PS$_{3,10}$
	H-PS$_{9,2}$		F-PS$_{9,2}$
	H-PS$_{9,5}$		F-PS$_{9,5}$
	H-PS$_{9,10}$		F-PS$_{9,10}$
2 DRAINAGE SCENARIOS			
Traditional drainage scenario			T-DS
SuDS-based drainage scenario			S-DS
48 SWMM5 SIMULATIONS			

Fig. 4. Simulated scenarios. Report and classification of scenarios and SWMM5 simulations.

2.4.2. Precipitation variability adaptation indexes (PVAI): objectives and definitions

The adaptation index here presented, defined by the authors for the purpose of this research investigation, is a valuable representation of SuDS performance as adaptation strategies in urban contexts under historical and reliable future extreme precipitation projections. Since the study area is currently characterized by urban floods also under light rains, in fact, it was considered interesting to compute adaptation indexes under both the historical rainfall patterns and future projections. Given the relevant role, it was deemed appropriate to refer to it as "Precipitation Variability Adaptation Index – PVAI".

The PVAI has the structure of the "Relative Root Mean Square Error" (RRMSE). RRMSE is a dimensionless form of Root Mean Square Error (RMSE) and is computed as the RMSE normalized by the root mean square value where each residual is scaled against the actual value. Since it expresses a percentage error, higher values are related to inaccurate predictions. Specifically, the formula was here used to measure differences between each selected parameter obtained from S-DS and T-DS under varying precipitation inputs. Parameters related to T-DS were set as "actual values", thus considering T-DS as benchmark scenario. Major differences between the hydrological and hydraulic parameters obtained from the simulation of S-DS and those obtained from T-DS, and thus higher PVAI values, would have represented larger differences between the drainage scenarios and thus better performances of SuDS.

Overall, three single-variable PVAI and a multiple-variables PVAI were defined. In particular, the three single-variable PVAI were conceived to assess changes of each selected variables between the two drainage scenarios considered (S-DS and T-DS):

- $PVAI_{MPF}$, dependent on MPF
- $PVAI_{TV}$, dependent on TV
- and $PVAI_{FN}$, dependent on FN

Moreover, with the objective of defining an index able to take into account the combined effects of the selected hydrological and hydraulic parameters, a multiple-variable PVAI was proposed, referred to in the following as $PVAI_G$ where the subscript "G" stands for "Global". This index, here proposed in an early form, was conceived as a simple, repeatable and embeddable tool for the assessment of SuDS as adaptation strategies to climate change consequences. For the purpose of this investigation, the variables assessed are supposed to have the same weight.

For each precipitation scenario investigated, the indexes were computed as follows:

$$PVAI_{MPF} = \sqrt{\frac{(MPF_{S-DS} - MPF_{T-DS})^2}{(MPF_{T-DS})^2}} \tag{6}$$

$$PVAI_{TV} = \sqrt{\frac{(TV_{S-DS} - TV_{T-DS})^2}{(TV_{T-DS})^2}} \tag{7}$$

$$PVAI_{FN} = \sqrt{\frac{(TV_{S-DS} - TV_{T-DS})^2}{(TV_{T-DS})^2}} \tag{8}$$

$$PVAI_G = \sqrt{\frac{\frac{1}{n}\sum_{i=1}^{n}\left(y_{i,S-DS} - y_{i,T-DS}\right)^2}{\sum_{i=1}^{n}\left(y_{i,T-DS}\right)^2}} \tag{9}$$

where:

$MPF_{S-DS/T-DS}$ = Maximum Peak Flows obtained under each investigated precipitation input respectively in S-DS and T-DS drainage scenarios.

$TV_{S-DS/T-DS}$ = Total Volumes obtained under each investigated precipitation input respectively in S-DS and T-DS drainage scenarios.

$FN_{S-DS/T-DS}$ = Number of nodes exceeding 70% filling degree threshold obtained under each investigated precipitation input respectively in S-DS and T-DS drainage scenarios.

n = number of the considered variables. In the formula presented n is 3.

i = count for the examined variables.

$y_{i,\ S-DS/T-DS}$ = original result of the variable under each investigated precipitation input respectively in S-DS and T-DS drainage scenarios.

3. Results

3.1. Observed historical and projected future precipitation scenarios

Values of the position parameter μ of rainfall extremes at 1-h, 2-h, 3-h, and 9-h durations registered in Lodi within the years 1960–2021 and computed using a 10-years moving window (Subsection 2.3.2), were plotted in Fig. 5 with their linear regression lines. Significance levels of the regression analyses were reported in Table 1, along with the average historical values of μ for each investigated duration, the projected values of μ over a 30-years medium-term period and their overall percentage variation. Both looking at

Fig. 5 and Table 1, it is possible to detect a statistically significant increasing trend ($P \leq 0.05$) for the shortest durations, suggesting future increases of the position parameter of rainfall extremes of 1-h and 2-h durations. Instead, a significant decreasing trend can be observed for 9-h duration rainfall extremes. As for the 3-h duration rainfall extremes, an increasing trend can be still observed but this time not statistically significant, suggesting the presence of a trend reversal between the 3-h and 4-h duration (out of the scope of the research work but characterized by a slight decreasing trend).

Rainfall depths that characterize historical (observed) and future (projected) event-scale scenarios, obtained implementing Eq. (4) and the methodology proposed in Subsection 2.3.2, are collected in Table 2 and plotted in Fig. 6. Percentages of variations between historical and future event-scale rainfall depths (V% in Table 2), indicates that the highest difference occurs for the lower return periods (Tr = 2 years) and for the shortest duration (1-h). Consequently, the 1-h precipitation with a 2-years return period, registered the highest increase (30%) while the 3-h precipitation with a 10-years return period the lowest (4%). Looking at Fig. 6 it is possible to visually notice changes in depth-duration-frequency tendency curves, designed according to the four studied durations. In addition to what has already been detected from the table, the plot emphasizes changes in the shape of the curves characterized by a future flattening, with higher maximum rainfall depths at the shortest durations, almost up to the 4–5 h durations, and lower maximum rainfall depths at the largest durations.

3.2. SWMM5 simulations results

The results of the 48 SWMM5 simulations, as combination of drainage and climate scenarios, were processed to assess and further analyze the hydrological and hydraulic parameters selected (MPF, TV and FN). These preliminary findings go beyond the evaluation of SuDS potential as adaptation strategies to climate change consequences, to which the next section will be entirely devoted, but represent an essential framework for understanding and contextualizing the typical behaviour of the SuDS. Output parameters are collected in Tables 3(a, b, c) and 4(a, b, c), respectively representing historical and future precipitation scenarios with varying frequencies and durations. Undoubtedly, precipitation increases result into an increase in MPF, TV and FN, thus potentially triggering increasing flooding phenomena in the urban area. However, even under the most severe precipitation conditions, SuDS proved to be essential strategies for hydrological and hydraulic risk mitigation, confirming the results proposed by the existing literature. However, while there is no doubt about this aspect, there is still concern about the adaptability of drainage networks involving SuDS to precipitation changes that will be specifically discussed in the following.

3.3. Precipitation variability adaptation indexes

The single-variable Adaptation Indexes $PVAI_{MPF}$, $PVAI_{TV}$ and $PVAI_{FN}$ are collected respectively in Tables 5(a, b), 6(a, b) and 7(a, b) while the multiple-variable Adaptation Index is collected in Table 8(a, b). Tables identified with the letter "a" include the results for the historical precipitation scenarios while the others (letter "b") include the results for the future precipitation scenarios. Adaptability indexes can assume values between 0 and 1. Higher values would indicate major differences between T-DS and S-DS, thus a higher effectiveness of SuDS in adapting the drainage network to climate changes. Microsoft Excel conditional formatting was implemented to better highlight data patterns in each couple of tables. In particular, the use of a three-color scale visual guide (green, yellow, red)

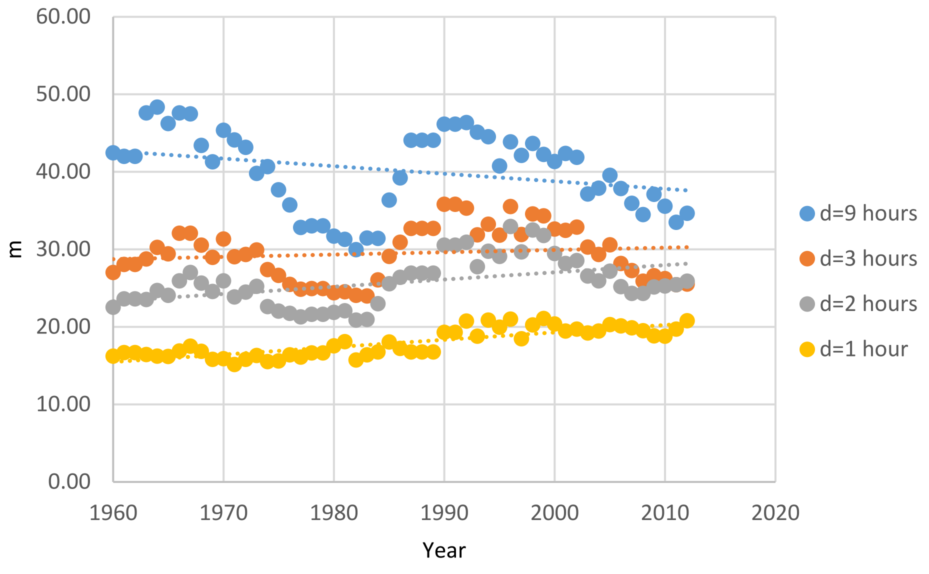

Fig. 5. Moving average of the position parameter of rainfall extremes registered in Lodi. Moving average of the position parameter of rainfall extremes at 1-h, 2-h, 3-h, 9-h durations registered in Lodi within the years 1960–2021. The moving average was computed using a 10-years moving window (i.e. the value at 1960 represent the average value of the position parameter in the 1960–1969 timeframe).

Table 1
Average values of m of rainfall extremes registered in Lodi at 1-h, 2-h, 3-h, 9-h durations in the period 1960–2021; significance level of the regression analyses of the historical values of m; projected values of m in 2050 and overall variation between the projected and the average historical values of m.

	m historical average value	Significance level (*p*-value)	m projected value at 2050	m variation (projected-average)
	mm		mm	%
d = 1 h	17.96	9.51E−14	24.05	33
d = 2 h	25.74	5.31E-04	31.68	23
d = 3 h	29.51	3.39E-01	31.41	6
d = 9 h	40.15	3.25E-02	33.90	-16

m = position parameter; d = duration (hours).

Table 2
Historical (observed) and Future (projected) cumulative rainfall depth at varying durations (d) and return periods (T) along with their percentage variation (V).

	d = 1			d = 2			d = 3			d = 9		
	$x_{H\text{-}PS}$	$x_{F\text{-}PS}$	V	$x_{H\text{-}PS}$	$x_{F\text{-}PS}$	V	$x_{H\text{-}PS}$	$x_{F\text{-}PS}$	V	$x_{H\text{-}PS}$	$x_{F\text{-}PS}$	V
	(mm)	(mm)	(%)	(mm)	(mm)	(%)	(mm)	(mm)	(%)	(mm)	(mm)	(%)
T = 2	20.03	26.13	30	28.75	34.70	21	32.49	34.39	6	44.37	38.12	-14
T = 5	26.46	32.55	23	38.07	44.02	16	41.70	43.60	5	57.43	51.18	−11
T = 10	30.71	36.81	20	44.24	50.19	13	47.79	49.70	4	66.07	59.83	−9

$X_{H\text{-}PS}$ and $X_{F\text{-}PS}$ = historical observed and future projected rainfall depth (millimetres); T = return period; d = duration (hours); V = percentage variation between historical and projected x (positive values indicates increases and negative values indicate decreases).

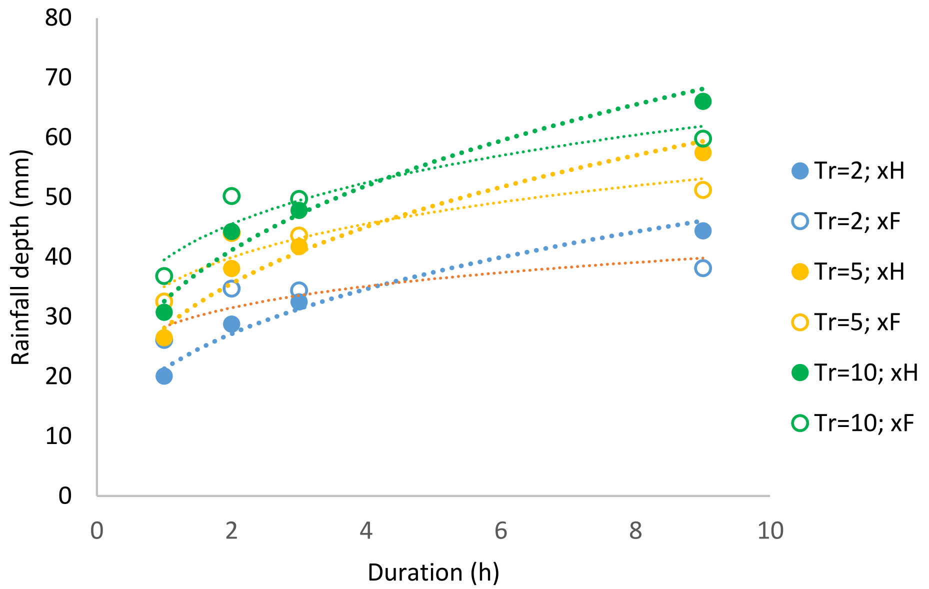

Fig. 6. Depth-duration-frequency curves Lodi. Historical (observed) and future (projected) Depth-Duration-Frequency curves at 2-years, 5-years and 10-years return periods.

proved to be relevant in the comparison of a range of cells by using a gradation of the selected colours. For the purpose of this investigation, the green color was selected for representing highest values, those suggesting a higher effectiveness of SuDS in adapting the drainage network to climate changes, while the red was selected for the lowest ones. Among them, a variety of shades helps to understand data distribution and variations.

3.3.1. Single-variable PVAI

Looking at Table 5a, representative of $PVAI_{MPF}$ in the historical precipitation scenarios, values range from a minimum of 0.40 (red-coloured), obtained under the lower frequency rainfall event ($T = 10$ years) with 9-h duration, to a maximum of 0.90 (green-coloured), obtained under the higher frequency rainfall event ($T = 2$ years) with 1-h duration. Higher $PVAI_{MPF}$, characterized by shades tending to

Table 3
(a, b, c). Hydrological and hydraulic parameters obtained under the historical (observed) rainfall scenarios with 2-years (a), 5-years (b) and 10-years return period (c).

a.

H-PS; T = 2	d = 1 h		d = 2 h		d = 3 h		d = 9 h	
	S-DS	T-DS	S-DS	T-DS	S-DS	T-DS	S-DS	T-DS
MPF [m^3/s]	0.07	0.62	0.33	1.01	0.48	1.20	0.53	1.29
TV [m^3]	1751.65	7101.86	5690.32	18,638.44	7930.73	24,281.57	16,260.59	44,303.82
FN (nr)	2	4	2	2	2	3	2	3

b.

H-PS; T = 5	d = 1 h		d = 2 h		d = 3 h		d = 9 h	
	S-DS	T-DS	S-DS	T-DS	S-DS	T-DS	S-DS	T-DS
MPF [m^3/s]	0.29	1.27	0.77	1.59	0.87	1.69	0.90	1.68
TV [m^3]	4846.29	15,918.90	13,608.08	35,297.38	15,668.42	41,486.67	29,651.17	71,838.05
FN (nr)	2	55	2	52	2	22	2	3

c.

H-PS; T = 10	d = 1 h		d = 2 h		d = 3 h		d = 9 h	
	S-DS	T-DS	S-DS	T-DS	S-DS	T-DS	S-DS	T-DS
MPF [m^3/s]	0.50	1.53	1.12	1.88	1.16	1.97	1.17	1.94
TV [m^3]	8476.78	21,921.48	21,005.56	46,429.97	23,023.69	53,690.81	40,481.59	91,234.82
FN (nr)	9	69	10	63	2	47	3	3

Table 4
(a, b, c). Hydrological and hydraulic parameters obtained under the future (projected) rainfall scenarios with 2-years (a), 5-years (b) and 10-years return period (c).

a.

F-PS; T = 2	d = 1 h		d = 2 h		d = 3 h		d = 9 h	
	S-DS	T-DS	S-DS	T-DS	S-DS	T-DS	S-DS	T-DS
MPF [m^3/s]	0.29	1.24	0.65	1.38	0.56	1.31	0.39	1.08
TV [m^3]	4738.05	14,764.07	10,680.75	28,715.72	9583.68	27,730.20	10,760.50	32,234.62
FN (nr)	2	54	2	36	2	3	2	3

b.

F-PS; T = 5	d = 1 h		d = 2 h		d = 3 h		d = 9 h	
	S-DS	T-DS	S-DS	T-DS	S-DS	T-DS	S-DS	T-DS
MPF [m^3/s]	0.60	1.65	1.06	1.87	0.96	1.78	0.71	1.50
TV [m^3]	9997.58	24,890.34	19,707.51	46,018.81	17,605.78	45,383.06	22,889.15	58,366.55
FN (nr)	8	90	7	63	2	29	2	3

c.

F-PS; T = 10	d = 1 h		d = 2 h		d = 3 h		d = 9 h	
	S-DS	T-DS	S-DS	T-DS	S-DS	T-DS	S-DS	T-DS
MPF [m^3/s]	0.88	1.91	1.34	2.14	1.21	2.06	0.97	1.76
TV [m^3]	14,463.67	32,255.98	27,362.56	58,050.42	24,235.13	57,878.94	32,453.25	77,164.72
FN (nr)	11	144	8	104	2	53	2	3

green, occurred under 1-h duration rainfall event, roughly dependent on their frequency. However, under higher frequency rainfall events, significant values of $PVAI_{MPF}$, even though progressively decreasing, were obtained also under larger durations. More specifically, under the same duration, the higher the frequency the higher is the adaptability while nearly always, under the same frequency, the larger the duration the lower is the adaptability. Observing Table 5b, which collects $PVAI_{MPF}$ in the projected precipitation scenarios, values range from a minimum of 0.37 (red-coloured), obtained under the lower frequency rainfall event ($T = 10$ years) with 2-h duration, to a maximum of 0.76 (green-coloured), obtained again under the higher frequency rainfall event ($T = 2$ years) with 1-h

Table 5
(a, b). Precipitation variability adaptation index according to the variable maximum peak flow for the historical (observed) (a) and future (projected) (b) precipitation scenarios.
a.

$PVAI_{MPF}$-H-PS	d= 1 hour	d= 2 hours	d= 3 hours	d= 9 hours
T=2	0.89	0.67	0.60	0.59
T=5	0.77	0.52	0.48	0.47
T=10	0.67	0.40	0.41	0.40
MEAN	0.78	0.53	0.50	0.48

b.

$PVAI_{MPF}$-F-PS	d= 1 hour	d= 2 hours	d= 3 hours	d= 9 hours
T=2	0.76	0.53	0.57	0.64
T=5	0.64	0.43	0.46	0.52
T=10	0.54	0.37	0.41	0.45
MEAN	0.65	0.45	0.48	0.54

Table 6
(a, b). Precipitation variability adaptation index according to the variable total volume for the historical (observed) (a) and future (projected) (b) precipitation scenarios.
a.

$PVAI_{TV}$-H-PS	d= 1 hour	d= 2 hours	d= 3 hours	d= 9 hours
T=2	0.75	0.69	0.67	0.63
T=5	0.70	0.61	0.62	0.59
T=10	0.61	0.55	0.57	0.56
MEAN	0.69	0.62	0.62	0.59

b.

$PVAI_{TV}$-F-PS	d= 1 hour	d= 2 hours	d= 3 hours	d= 9 hours
T=2	0.68	0.63	0.65	0.67
T=5	0.60	0.57	0.61	0.61
T=10	0.55	0.53	0.58	0.58
MEAN	0.61	0.58	0.62	0.62

duration. Again, green-shaded $PVAI_{MPF}$, representative of higher values, occurred under 1-h duration or high frequency rainfall events however, if compared with the results in Table 5a, it is clearly visible here a reduction of the $PVAI_{MPF}$ for all the rainfall events with a projected increase with green cells gradually fading and red ones getting darker. As for the 9-h rainfall events, characterized by a future decrease, a slight intensification of green-coloured cells and a fading of red ones can be observed, thus suggesting an increase of $PVAI_{MPF}$.

Table 6a collects $PVAI_{TV}$ related to the historical precipitation scenarios. Values range from a minimum of 0.55 (red-coloured), obtained under the lower frequency rainfall event (T = 10 years) with 2-h duration, to a maximum of 0.75 (green-coloured), obtained under the higher frequency rainfall event (T = 2 years) with 1-h duration. As already observed for $PVAI_{MPF}$, under the same duration, the higher the frequency the higher is the adaptability (green-shaded cells) while, under the same frequency, the 1-h duration event and the 9-h duration events always show respectively the highest and lowest value of $PVAI_{TV}$. Under the future (projected) precipitation scenario, $PVAI_{TV}$ (Table 6b) ranges from a minimum of 0.53 (red-coloured), obtained under the 10-years rainfall with 2-h duration, to a maximum of 0.68 (green-coloured), obtained under 2-years rainfall with 1-h duration, thus confirming the previously stated relation between rainfall event frequency and adaptability. Moreover, as for the $PVAI_{MPF}$, it is possible to observe green cells gradually fading and red ones getting darker, suggesting again a reduction of the $PVAI_{TV}$ in the future for all the rainfall events featured by a projected increase. Overall, $PVAI_{MPF}$ and $PVAI_{TV}$ show a very similar behaviour. However, under both projected and historical rainfalls with 1-h duration, $PVAI_{TV}$ is lower than $PVAI_{MPF}$ while it is higher in all the other cases. If compared to the $PVAI_{MPF}$, the $PVAI_{TV}$ exhibits a narrower range, especially under future (projected) precipitations, suggesting that in that conditions $PVAI_{TV}$ is just slightly dependent of precipitation characteristics (frequency, duration). Nevertheless, the presence of so many green-shaded cells

Table 7
(a, b). Precipitation variability adaptation index according to the variable flooded nodes for the historical (observed) (a) and future (projected) (b) precipitation scenarios.

a.

$PVAI_{FN}$ -H-PS	d= 1 hour	d= 2 hours	d= 3 hours	d= 9 hours
T=2	0.50	0.00	0.33	0.33
T=5	0.96	0.96	0.91	0.33
T=10	0.87	0.84	0.96	0.00
MEAN	0.78	0.60	0.73	0.22

b.

$PVAI_{FN}$ -F-PS	d= 1 hour	d= 2 hours	d= 3 hours	d= 9 hours
T=2	0.96	0.94	0.33	0.33
T=5	0.91	0.89	0.93	0.33
T=10	0.92	0.92	0.96	0.33
MEAN	0.93	0.92	0.74	0.33

Table 8
(a, b). Global precipitation variability adaptation index for the historical (observed) (a) and future (projected) (b) precipitation scenarios.

a.

$PVAI_G$-H-PS	d= 1 hour	d= 2 hours	d= 3 hours	d= 9 hours
T=2	0.43	0.40	0.39	0.37
T=5	0.40	0.35	0.36	0.34
T=10	0.35	0.32	0.33	0.32
MEAN	0.40	0.36	0.36	0.34

b.

$PVAI_G$-F-PS	d= 1 hour	d= 2 hours	d= 3 hours	d= 9 hours
T=2	0.39	0.36	0.38	0.38
T=5	0.35	0.33	0.35	0.35
T=10	0.32	0.31	0.34	0.33
MEAN	0.35	0.33	0.36	0.36

representative of high values of the indexes, regardless of the effects of precipitation increases, makes it clear the impressive effectiveness of SuDS as adaptation strategies in the mitigation of peak flows and total volumes discharged from the CSOs.

The behaviour of the $PVAI_{FN}$ seems rather different from the previously analysed indexes. Looking at Table 7a, values range from a minimum of zero (red-coloured), obtained under the 2-years and 10-years rainfall event respectively with 2-h and 9-h durations, to a maximum of 0.96 (green-coloured), obtained under the 5-years rainfall with 1-h duration. More generally, green-shaded cells representing the highest $PVAI_{FN}$ can be observed under the lower frequency rainfall events with small durations while lowest under 2-years rainfalls and 9-h duration events. Under the future (projected) precipitation scenario (Table 7b), values range from a minimum of 0.33 (red-coloured), obtained under the 9-h duration rainfall events, regardless of their frequency, and under a 3-h rainfall event with 2-years return period to a maximum of 0.96 (green-coloured), obtained under the 2-years rainfall with 1-h duration. However, if compared to the historical scenarios, a larger number of green-shaded cells and thus high $PVAI_{FN}$ were obtained under 1-h, 2-h and 3-h rainfall events, with a single exception and independently from the frequency. The $PVAI_{FN}$, in fact, as opposed to the other indexes, increases with the increase of rainfall severity.

3.3.2. Multiple-variables $PVAI_G$

The multiple-variables $PVAI_G$ is a global index able to take into account the effects of the different hydrological and hydraulic variables. In this regard, it is deemed appropriate to recall that this index was computed attributing equal weights to the examined variables, thus considering each of them equally important in reference to the criticality of the case study sewer system. Looking at Table 8a, collecting $PVAI_G$ in the historical precipitation scenarios, values range from a minimum of 0.32 (green-coloured), obtained under the lower frequency rainfall event ($T = 10$ years) with 2-h duration, to a maximum of 0.43 (red-coloured), obtained under the higher frequency rainfall event (T = 2 years) with 1-h duration. Observing the results of future projected precipitation scenarios (Table 8b), $PVAI_G$ minimum and maximum values become respectively 0.30 and 0.39. If compared to those of the single-variable indexes, these ranges, in the historical scenarios and even more in the future (projected) ones, appear narrower suggesting a reduction of the adaptation index variability as a function of precipitation characteristics (frequency, duration). Overall, it is possible to highlight that: i) both under historical and future precipitation scenarios, $PVAI_G$ decreases as the frequency of the rainfall event decrease; ii) under the historical precipitation scenarios with the highest frequency, $PVAI_G$ decreases as the duration of the rainfall event increase; iii) under the future precipitation scenarios, $PVAI_G$ decreases as the effect of the increase of precipitation extremes at 1-h, 2-h and 3-h.

Looking at Fig. 7 it is possible to visually observe the differences between $PVAI_G$ obtained in the historical precipitation scenarios and future ones for each duration and frequency investigated. In addition to the already mentioned points, precipitations characterized by 1-h and 2-h durations, regardless of their frequency, appear those most affected by a $PVAI_G$ decrease, certainly attributable to their highest future projected increase.

4. Discussion

The identification of the most realistic characterization of a potential change in the climate signal of the case study area was an essential preliminary stage of this study, mainly focused at assessing SuDS potential as adaptation strategies to climate change. Considering the uncertainties of climate models in predicting future short-rainfall extremes at the sub-regional scale and given the high complexity of these studies, the proposed methodology has proved to be a simple, repeatable and effective strategy to define reliable future precipitation datasets for feasibility studies and scenario-based modeling assessments at the catchment-scale resolution. The proposed approach aimed at defining a "single" value of future projection and the short-rainfall climate variability was not considered since it was found to be not statistically significant for the selected precipitation dataset. On the other hand, however, the use of "ensemble" projections, typically characterized by an index of variability, would not have ensured that the average signal of the ensemble was actually indicative of the phenomenon (Padulano et al., 2021). However, as an initial assumption, the medium term short rainfall intrinsic variability significance as well as their recurrence were assumed stationary.

Overall findings of the proposed methodology suggested a possible increase of maximum rainfall at 1-h, 2-h and 3-h durations and a significant decrease at 9-h duration in the case study area. According to a recently released IPCC reports (Bednar-Friedl et al., 2022), under a global warming level larger than 2 °C, a widespread increase of precipitation extremes is projected for all European sub-regions, except for Mediterranean areas. According to the review proposed by Martel et al. (Martel et al., 2021) a strong consensus emerges on the increase of extreme rainfall events in a warmer climate but the challenge is now detecting changing rates and their governing factors. Climate model simulations at a finer spatial and temporal resolution (i.e. convection-permitting models – CPMs) indicate that rainfall scaling may also increase as a function of duration, such that shorter-duration, longer return period events will likely see the largest rainfall increases in a warmer climate (Martel et al., 2021). However, this widespread perception of an increase in the severity of extreme rainfalls has not found yet clear confirmation at the regional scale in the scientific literature, often reporting varying and conflicting results. With reference to the national scale context, while considering the significant spatial variability of

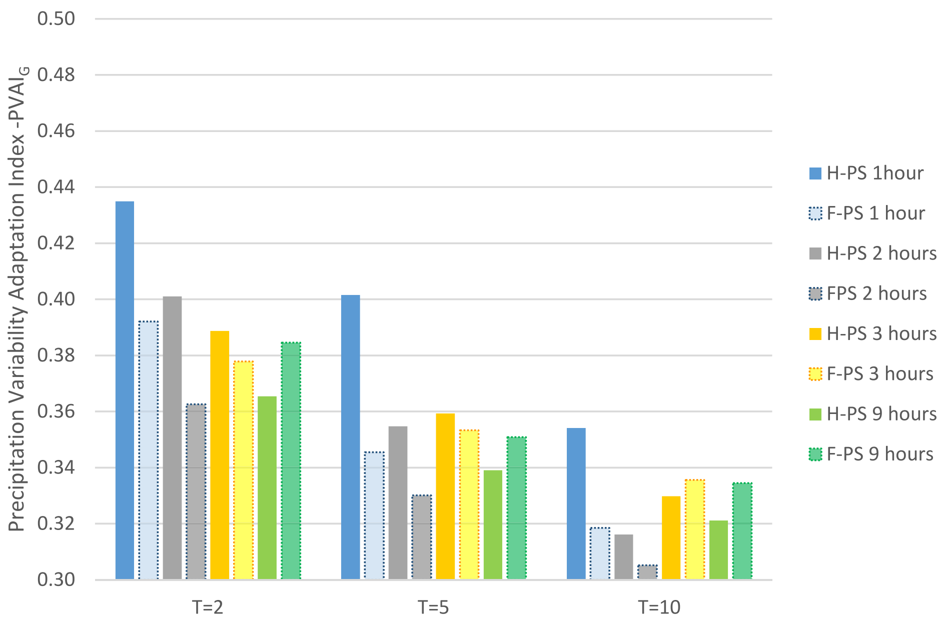

Fig. 7. Global precipitation variability adaptation index. Comparison of the Global Precipitation Variability Adaptation Index values under varying historical (observed) and future (projected) precipitation durations and frequencies.

precipitation trends, some authors (Crisci et al., 2002; Saidi et al., 2015) noticed a short rainfall increasing spot trend in north-west Italy and in Tuscany, thus supporting the results obtained.

The implementation of the Precipitation Variability Adaptation Index was also definitely a key focus of this research work. The importance of this index actually is related to the possibility to provide a simple, repeatable and embeddable tool taking into account several hydrological and hydraulic variables for an overall assessment of SuDS potential as adaptation strategies to climate change consequence in urban areas. Although here proposed in an early form it is well understood how, if properly managed (i.e. with introduction of additional variables, each with its own weight), can potentially support multi-criteria analyses aimed at identifying the best SuDS design alternative. The analyses of $PVAI_{MPF}$ and PV_{TV} pointed out the impressive hydrological effectiveness of SuDS as adaptation strategies in Sesto Ulteriano (MI), thus threated by future increases in rainfall severity. The overall performance of SuDS surely was affected by the specific case study features: significant SuDS retrofitting surface (8.3% of the total area) defined through a feasible exploitation of the maximum retrofitting potential of the catchment; choice and localization of different SuDS types each with a specific attitude to the enhancement of retention processes as explained in Subsection 2.2.1. These findings are nevertheless consistent with other modeling studies focused at assessing SuDS performance at the catchment scale (Jarden et al., 2016; D'Ambrosio et al., 2022a). However, as opposed to the other indexes, the $PVAI_{FN}$ increases with the increase of rainfall severity. The reason behind this behaviour could be ascribed to the fact that during less severe precipitation events, a very small percentage of sewer nodes, just the most critical ones, overcome their filling degree threshold in the T-DS (2 or 3 nodes) and SuDS implemented in the S-DS have no effect on them. On the contrary, during the most severe and impactful rainfalls, a higher number of sewer nodes overcome their filling degree threshold in the T-DS (up to 69 nodes in the H-PS and up to 144 nodes in the F-PS) giving at S-DS a greater margin of effectiveness. In addition to confirming SuDS ability as adaptation strategy, the $PVAI_G$ helped highlighting the sensitivity of these infrastructures to precipitation frequency and occasionally to rainfall duration, thanks to an overall consideration of different hydrological and hydraulic variables. The reason for this could be certainly ascribed to the strong relation between SuDS stormwater retention and detention capacity and the characteristics of the precipitation. This behaviour, widely discussed in literature and supported by several field and modeling studies, results into an overall decreasing performance of SuDS with the increase of rainfall severity (Samouei and Ozger, 2020; Hua et al., 2020; Mobilia et al., 2021; Demirezen and Cevza, 2022). The adaptability index for the drainage network involving SuDS proposed by Binesh et al. (Binesh et al., 2019), even though differently conceived, indicated as well a significant risk of its being affected by adverse climate changes, thus supporting the results obtained in this study.

5. Conclusions

This research focused at assessing the potential of SuDS as adaptation strategies to the effects of a projected medium-term climate change, affecting the Sesto Ulteriano case study catchment (Northern Italy), a typical example of a contemporary city experiencing urban flooding phenomena due to rapid and massive urbanization dynamics occurred in the second half of the twentieth century. A massive urbanization phenomenon actually led to significant problems related to the stormwater quality as well as frequent urban flooding phenomena that also occur under the effect of moderate rainfalls. In the perspective of climate change, these evidences are likely to become even more remarkable. Thus aware that the specific results are inextricably linked to the characteristic of the investigated catchment, findings obtained so far are easy to extend to the other industrial/residential settlements included in the Metropolitan Borough of Milan, sharing with Sesto Ulteriano structural and climatic similarities. Even more broadly, this study was able to provide a regional methodology capable of assessing on a large scale SuDS potential as adaptation strategies to climate change consequences with the ambitious objective of reducing the uncertainty typical of these investigations.

Specifically, the study highlighted the importance of feasibility in SuDS projects, proposed a simple methodology easily applicable in other contexts for establishing sufficiently reliable future scenarios of maximum precipitation at different times, and provided an indicator able to quantify SuDS effectiveness in adapting drainage networks to climate changes consequences taking into account different hydrological and hydraulic variables.

The results, even specifically linked to the case study investigated, allowed drawing generally valid conclusions:

- The simple and repeatable statistical methodology of detection of climatic variations allowed understanding that the maximum rainfall in Lodi realistically could be characterized by an increase at low durations (up to 3 h) and a decrease at higher durations (i.e. 9 h) in the next decades.
- SuDS, if largely implemented in urban catchments, were confirmed as valuable flood control measures able to mitigate stormwater peak flows and volumes discharged from the CSOs as well as reducing the number of network nodes overcoming a 0.7 filling degree threshold.
- SuDS potential as adaptation strategies to climate changes consequences is affected by rainfall severity, whether as a result of a possible occurrence of low frequency events or an increase in rainfall cumulative due to future precipitation conditions. Specifically, it was observed that the $PVAI_G$ decreases as the frequency of the rainfall event decreases and only under the historical precipitation scenarios with the 2-years T decreases as the duration of the rainfall event increases. On the same basis, under a projected increase of precipitation extremes $PVAI_G$ decreases (the higher the precipitation increase and the more visible the index decrease).

Further studies are expected to take into account supplementary aspects for a detailed medium-term period analysis: non-stationarity of the return period in the future climate assessments, long-period SuDS performance assessment and SuDS aging with its negative medium-term consequences on the hydrological effectiveness of SuDS (Bouzouidja et al., 2018; D'Ambrosio et al., 2022b).

Additionally, the assessment and comparison of multiple alternatives of SuDS retrofitting (i.e. choice, localization, design, combination), as well as the definition of compensation measure (i.e. SuDS retrofitting surface increase) to counteract the effect of future precipitation increases, could be for sure the most effective methodology to select the best adaptation strategy to climate change consequences according to the needs of the urban context.

Author statement

Dr. Roberta D'Ambrosio: Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization.

Dr. Antonia Longobardi: Conceptualization, Methodology, Formal analysis, Investigation, Writing – review & editing, Supervision.

Dr. Britta Schmalz: Conceptualization, Methodology, Writing - review & editing, Supervision.

Term	Definition
Conceptualization	Ideas; formulation or evolution of overarching research goals and aims
Methodology	Development or design of methodology; creation of models
Software	Programming, software development; designing computer programs; implementation of the computer code and supporting algorithms; testing of existing code components
Validation	Verification, whether as a part of the activity or separate, of the overall replication/ reproducibility of results/experiments and other research outputs
Formal analysis	Application of statistical, mathematical, computational, or other formal techniques to analyze or synthesize study data
Investigation	Conducting a research and investigation process, specifically performing the experiments, or data/evidence collection
Resources	Provision of study materials, reagents, materials, patients, laboratory samples, animals, instrumentation, computing resources, or other analysis tools
Data Curation	Management activities to annotate (produce metadata), scrub data and maintain research data (including software code, where it is necessary for interpreting the data itself) for initial use and later reuse
Writing - Original Draft	Preparation, creation and/or presentation of the published work, specifically writing the initial draft (including substantive translation)
Writing - Review & Editing	Preparation, creation and/or presentation of the published work by those from the original research group, specifically critical review, commentary or revision – including pre-or postpublication stages
Visualization	Preparation, creation and/or presentation of the published work, specifically visualization/ data presentation
Supervision	Oversight and leadership responsibility for the research activity planning and execution, including mentorship external to the core team
Project administration	Management and coordination responsibility for the research activity planning and execution
Funding acquisition	Acquisition of the financial support for the project leading to this publication

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

Abduljaleel, Y., Demissie, Y., 2021. Evaluation and optimization of low impact development designs for sustainable stormwater management in a changing climate. Water 13, 2889. https://doi.org/10.3390/w13202889.

Beck, H., Zimmermann, N., McVicar, T., Vergopolan, N., Berg, A., Wood, E.F., 2018. Present and future Köppen-Geiger climate classification maps at 1-km resolution. Sci Data 5, 180214. https://doi.org/10.1038/sdata.2018.214.

Bednar-Friedl, B., Biesbroek, R., Schmidt, D.N., Alexander, P., Børsheim, K.Y., Carnicer, J., Georgopoulou, E., Haasnoot, M., Le Cozannet, G., Lionello, P., Lipka, O., Möllmann, C., Muccione, V., Mustonen, T., Piepenburg, D., Whitmarsh, L., 2022. Europe. In: Pörtner, H.-O., Roberts, D.C., Tignor, M., Poloczanska, E.S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A., Rama, B. (Eds.), Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 1817–1927. https://doi.org/10.1017/9781009325844.015.

Binesh, N., Niksokhan, M.H., Sarang, A., Rauch, W., 2019. Improving sustainability of urban drainage systems for climate change adaptation using best management practices: a case study of Tehran, Iran. Hydrol. Sci. J. 64 (4), 381–404. https://doi.org/10.1080/02626667.2019.1585857.

Bouzouidja, R., Séré, G., Claverie, R., Ouvrard, S., Nuttens, L., Lacroix, D., 2018. Green roof aging: quantifying the impact of substrate evolution on hydraulic performances at the lab-scale. J. Hydrol. 564, 416–423. https://doi.org/10.1016/j.jhydrol.2018.07.032.

Cheng, L., AghaKouchak, A., 2014. Nonstationary precipitation intensity-duration-frequency curves for infrastructure design in a changing climate. Sci. Rep. 4, 7093. https://doi.org/10.1038/srep07093.

Cortinovis, C., Olsson, P., Boke-Olén, N., Hedlund, K., 2022. Scaling up nature-based solutions for climate-change adaptation: potential and benefits in three European cities. Urban For. Urban Green. 67, 127450 https://doi.org/10.1016/j.ufug.2021.127450.

Crisci, A., Gozzini, B., Meneguzzo, F., Pagliara, S., Maracchi, G., 2002. Extreme rainfall in a changing climate: regional analysis and hydrological implications in Tuscany. Hydrol. Process. 16, 1261–1274. https://doi.org/10.1002/hyp.1061.

D'Ambrosio, R., Mobilia, M., Khamidullin, F.I., Longobardi, A., Elizaryev, A.N., 2021a. How substrate and drainage layer materials affect the hydrological performance of green roofs: CHEMFLO-2000 numerical investigation. In: Computational Science and Its Applications – ICCSA 2021. Lecture Notes in Computer Science, 12956, pp. 254–263. https://doi.org/10.1007/978-3-030-87010-2_17.

D'Ambrosio, R., Longobardi, A., Balbo, A., Rizzo, A., 2021b. Hybrid approach for excess stormwater management: combining decentralized and centralized strategies for the enhancement of urban flooding resilience. Water 13, 3635. https://doi.org/10.3390/w13243635.

D'Ambrosio, R., Balbo, A., Longobardi, A., Rizzo, A., 2022a. Re-think urban drainage following a SuDS retrofitting approach against urban flooding: a modelling investigation for an Italian case study. Urban For. Urban Green. 70, 127518 https://doi.org/10.1016/j.ufug.2022.127518.

D'Ambrosio, R., Longobardi, A., Mobilia, M., 2022b. Temporal changes of green roofs retention capacity. In: Computational Science and Its Applications – ICCSA 2022. Lect. Notes Comput. Sci, 13376, pp. 285–291. https://doi.org/10.1007/978-3-031-10450-3_24.

D'Ambrosio, R., Longobardi, A., Schmalz, B., 2023. Sustainable Drainage Systems Hydrological Sensitivity to Precipitation Changes. Advances in Science, Technology and Innovation. On press.

Demirezen, K., Cevza, K.A., 2022. Evaluation of the hydrological performance of infiltration trench with rainfall-watershed-infiltration trench experimental setup. J. Hydrol. Eng. 27 (3) https://doi.org/10.1061/(ASCE)HE.1943-5584.0002161.

Fletcher, T.D., Shuster, W., Hunt, W.F., Ashley, R., Butler, D., Arthur, S., Trowsdale, S., Barraud, S., Semadeni-Davies, A., Bertrand-Krajewski, J.L., Steen Mikkelsen, P., Rivard, G., Uhl, M., Dagenais, D., Viklander, M., 2015. SUDS, LID, BMPs, WSUD and more – the evolution and application of terminology surrounding urban drainage. Urban Water J. 525–542. https://doi.org/10.1080/1573062X.2014.916314.

Forestieri, A., Arnone, E., Blenkinsop, S., Candela, A., Fowler, H., Noto, L.V., 2018. The impact of climate change on extreme precipitation in Sicily, Italy. Hydrol. Process. 32, 332–348. https://doi.org/10.1002/hyp.11421.

Ganguli, P., Coulibaly, P., 2017. Does nonstationarity in rainfall require nonstationary intensity–duration–frequency curves? Hydrol. Earth Syst. Sci. 21, 6461–6483. https://doi.org/10.5194/hess-21-6461-2017.

Gao, Z., Zhang, Q.H., Xie, Y.D., Wang, Q., Dzakpasu, M., Xiong, J.Q., Wang, X.C., 2022. A novel multi-objective optimization framework for urban green-gray infrastructure implementation under impacts of climate change. Sci. Total Environ. 825, 153954 https://doi.org/10.1016/j.scitotenv.2022.153954.

Ghodsi, S.H., Zahmatkesh, Z., Goharian, E., Kerachian, R., Zhu, Z., 2020. Optimal design of low impact development practices in response to climate change. J. Hydrol. 580, 124266 https://doi.org/10.1016/j.jhydrol.2019.124266. Ghofrani et al., 2019.

Gumbel, E.J., 1941. The return period of flood flows. Ann. Math. Stat. 12 (2), 163–190. https://doi.org/10.1214/aoms/1177731747.

Guptha, G.C., Swain, S., Al-Ansari, N., Taloor, A.K., Dayal, D., 2022. Assessing the role of SuDS in resilience enhancement of urban drainage system: a case study of Gurugram City, India. Urban Clim. 41, 101075 https://doi.org/10.1016/j.uclim.2021.101075.

Hald, A., 1952. Statistical Theory with Engineering Applications. Wiley, New York, pp. 72–77.

Hosseinzadehtalaei, P., Tabari, H., Willems, P., 2020. Climate change impact on short-duration extreme precipitation and intensity–duration–frequency curves over Europe. J. Hydrol. 590, 125249 https://doi.org/10.1016/j.jhydrol.2020.125249.

Hua, P., Yang, W., Qi, X., Jiang, S., Xie, J., Gu, X., Li, H., Zhang, J., Krebs, P., 2020. Evaluating the effect of urban flooding reduction strategies in response to design rainfall and low impact development. J. Clean. Prod. 242, 118515 https://doi.org/10.1016/j.jclepro.2019.11851.

IPCC, 2014. Climate change 2014: synthesis report. In: Core Writing Team, Pachauri, R.K., Meyer, L.A. (Eds.), Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland, p. 151.

Jarden, K.M., Jefferson, A.J., Grieser, J.M., 2016. Assessing the effects of catchment-scale urban green infrastructure retrofits on hydrograph characteristics. Hydrol. Process. 30 (10), 1536–1550. https://doi.org/10.1002/hyp.10736.

Kabisch, N., Korn, H., Stadler, J., Bonn, A., 2017. Nature-based solutions to climate change adaptation in urban areas—Linkages between science, policy and practice. In: Kabisch, N., Korn, H., Stadler, J., Bonn, A. (Eds.), Nature-Based Solutions to Climate Change Adaptation in Urban Areas. Theory and Practice of Urban Sustainability Transitions. Springer, Cham. https://doi.org/10.1007/978-3-319-56091-5_1.

Khemwong, J., Boonyawiwat, T., Kriengkomol, T., Songsiri, J., Hoisungwan, P., 2015. 2102531 Term Project Report.

Kirshen, P., Caputo, L., Vogel, R.M., Mathisen, P., Rosner, A., Renaud, T., 2015. Adapting urban infrastructure to climate change: a drainage case study. J. Water Resour. Plan. Manag. 141 (4) https://doi.org/10.1061/(ASCE)WR.1943-5452.0000443.

Köppen, W., 1936. Das Geographische System der Klimate, Handbuch der Klimatologie - the Geographical System of the Climate, Handbook of Climatology. Borntraeger, Berlin. Bd. 1, Teil. C.

Kourtis, I.M., Tsihrintzis, V.A., 2021. Adaptation of urban drainage networks to climate change: a review. Sci. Total Environ. 771, 145431 https://doi.org/10.1016/j.scitotenv.2021.145431.

Le Floch, N., Pons, V., Abdalla, E.M.H., Alfredsen, K., 2022. Catchment scale effects of low impact development implementation scenarios at different urbanization densities. J. Hydrol. 612 (Part B), 128178. https://doi.org/10.1016/j.jhydrol.2022.128178.

Liu, H., Wang, Y., Zhang, C., Chen, A.S., Fu, G., 2018. Assessing real options in urban surface water flood risk management under climate change. Nat. Hazards 94, 1–18. https://doi.org/10.1007/s11069-018-3349-1.

Longobardi, A., Boulariah, O., 2022. Long-term regional changes in inter-annual precipitation variability in the Campania region, southern Italy. Theor. Appl. Climatol. 148, 869–879. https://doi.org/10.1007/s00704-022-03972-2.

Martel, J.L., Brissette, F.P., Lucas-Picher, P., Troin, M., Arsenault, R., 2021. Climate change and rainfall intensity–duration–frequency curves: overview of science and guidelines for adaptation. J. Hydrol. Eng. 26 (10) https://doi.org/10.1061/(ASCE)HE.1943-5584.0002122.

Means III, E., Laugier, M., Daw, J., Kaatz, L., Waage, M., 2010. Decision support planning methods: incorporating climate change uncertainties into water planning. In: Water Utility Climate Alliance White Paper. Water Utility Alliance, San Francisco, CA.

Miller, J.D., Hutchins, M., 2017. The impacts of urbanisation and climate change on urban flooding and urban water quality: a review of the evidence concerning the United Kingdom. J. Hydrol. Reg. Stud. 12, 345–362. https://doi.org/10.1016/j.ejrh.2017.06.006.

Mobilia, M., D'Ambrosio, R., Longobardi, A., 2020. Climate, soil moisture and drainage layer properties impact on green roofs in a Mediterranean environment. In: Naddeo, V., Balakrishnan, M., Choo, K.H. (Eds.), Frontiers in Water-Energy-Nexus—Nature-Based Solutions, Advanced Technologies and Best Practices for Environmental Sustainability. Advances in Science, Technology & Innovation. Springer, Cham. https://doi.org/10.1007/978-3-030-13068-8_41.

Mobilia, M., D'Ambrosio, R., Longobardi, A., Claverie, R., 2021. Substrate soil moisture impact on green roof performance for an experimental site in Tomblaine, France. In: Computational Science and Its Applications – ICCSA 2021. Lecture Notes in Computer Science, 12950, pp. 564–570. https://doi.org/10.1007/978-3-030-86960-1_39.

Morin, E., 2011. To know what we cannot know: global mapping of minimal detectable absolute trends in annual precipitation. Water Resour. Res. 47, W07505. https://doi.org/10.1029/2010WR009798.

Moura, N., Pellegrino, P., Martins, J., 2016. Best management practices in a changing climate. J. Flood Risk Manag. 9, 243–254. https://doi.org/10.1111/jfr3.12194.

Mugume, S.N., Butler, D., 2016. Evaluation of functional resilience in urban drainage and flood management systems using a global analysis approach. Urban Water J. 14 (7), 727–736. https://doi.org/10.1080/1573062X.2016.1253754.

Nanni, P., Peres, D.J., Musumeci, R.E., Cancelliere, A., 2021. Worry about climate change and urban flooding risk preparedness in southern Italy: a survey in the Simeto River valley (Sicily, Italy). Resources 10, 25. https://doi.org/10.3390/resources10030025.

Padulano, R., Reder, A., Rianna, G., 2019. An ensemble approach for the analysis of extreme rainfall under climate change in Naples (Italy). Hydrol. Process. 33 (14), 1937–2043. https://doi.org/10.1002/hyp.13449.

Padulano, R., Rianna, G., Costabile, P., Costanzo, C., Del Giudice, G., Mercogliano, P., 2021. Propagation of variability in climate projections within urban flood modelling: a multi-purpose impact analysis. J. Hydrol. 602, 126756 https://doi.org/10.1016/j.jhydrol.2021.126756.

Panofsky, H.A., Brier, G.W., 1968. Some Applications of Statistics to Meteorology. Earth and Mineral Sciences Continuing Education, College of Earth and Mineral Sciences.

Rosenberger, L., Leandro, J., Pauleit, S., Erlwein, S., 2021. Sustainable stormwater management under the impact of climate change and urban densification. J. Hydrol. 596, 126137 https://doi.org/10.1016/j.jhydrol.2021.126137.

Rossman, L., Huber, W., 2016. Storm Water Management Model Reference Manual Volume III – Water Quality. U.S. EPA Office of Research and Development, Washington, DC. EPA/600/R−16/093.
Saidi, H., Ciampittiello, M., Dresti, C., Ghiglieri, G., 2015. Assessment of trends in extreme precipitation events: a case study in Piedmont (North-West Italy). Water Resour. Manag. 29 (1), 63–80. https://doi.org/10.1007/s11269-014-0826-5.
Samouei, S., Ozger, M., 2020. Evaluating the performance of low impact development practices in urban runoff mitigation through distributed and combined implementation. J. Hydroinf. 22 (6), 1506–1520. https://doi.org/10.2166/hydro.2020.054.
Semadeni-Davies, A., 2012. Implications of climate and urban development on the design of sustainable urban drainage systems (SUDS). J. Water Clim. Change 3 (4), 239–256. https://doi.org/10.2166/wcc.2012.043.
Treppiedi, D., Cipolla, G., Francipane, A., Noto, L.V., 2021. Detecting precipitation trend using a multiscale approach based on quantile regression over a Mediterranean area. Int. J. Climatol. 41 (13), 5938–5955. https://doi.org/10.1002/joc.7161.
United States Department of Agriculture, Natural Resources Conservation Service, Conservation Engineering Division, 1986. Urban Hydrology for Small Watersheds, Technical Release 55.
Wartalska, K., Kaźmierczak, B., Nowakowska, M., Kotowski, A., 2020. Analysis of hyetographs for drainage system modeling. Water 12, 149. https://doi.org/10.3390/w12010149.
Woods Ballard, B., Wilson, S., Udale-Clarke, H., Illman, S., Scott, T., Ashley, R., Kellagher, R., 2015. The SuDS Manual, Construction Industry Research & Information Association (CIRIA).
Yang, Z., Villarini, G., Scoccimarro, E., 2022. Evaluation of the capability of regional climate models in reproducing the temporal clustering in heavy precipitation over Europe. Atmos. Res. 269, 106027 https://doi.org/10.1016/j.atmosres.2022.106027.