Investigating hydrological parameters for Nature Based Solutions characterization

Dissertation

submitted to the

Escuela Tecnica Superior de Ingenieros de Caminos, Canales y Puertos

Universidad Politecnica de Madrid

and the

Department of Civil and Environmental Engineering

University of Florence

in candidacy for the degree of a

Dr.-Ing /dottore di Ricerca Civil and Environmental Engineering [1]

by

Matteo Pampaloni

born 12th December 1987

from Firenze, Italy

[1] Either the Spanish or the Italian form of the title may be used.

ABSTRACT

Alternative stormwater management approaches for urban watersheds, also called Sustainable urban Drainage Systems (SuDS) or Low Impact Developments (LIDs), are increasingly being adopted with the aims of providing flow management, flood control, water quality improvements and opportunities to harvest stormwater. SuDS structures are typically small, decentralized systems form managing stormwater runoff near the source. These systems interact with the urban hydrological cycle, modifying the evapotranspiration, runoff, and groundwater recharge fluxes. It is challenging to quantify these hydrological changes because of the cost and complexity of modelling multiple SuDS systems in larger scale urban watersheds. Nevertheless, hydrological design of SuDS is commonly achieved by setting rainfall volumetric percentiles from daily rainfall series, but due to the small scale of urban watersheds and quantities involved, design rainfall data at sub-hourly time step are necessary. For these reasons, operation of new modelling and designing tools need to be explored. The research work discussed here is aimed to analyze the ability of a synthetic rainfall generation process to improve SuDS design. Particularly, the temporal disaggregation of daily rainfall records using stochastic methodologies is applied to improve SuDS design parameters and to run a long-term hydrological model to evaluate watershed scale effects of several SuDS scenarios. The first part of this research is aimed to analyze: 1) the ability of the synthetic rainfall generation process to reproduce the main characteristics of the observed rainfall; 2) the hydrologic parameters often used for SuDS design based on the generally available daily rainfall data. Other specifics objectives concern with the evaluation of Minimum Inter-event Time (MIT) and storm volume threshold on rainfall volumetric percentiles, commonly used in SuDS design. The reliability of the stochastic spatial-temporal model RainSim V.3 to reproduce observed key characteristics of rainfall pattern and volumetric percentiles, is also investigated. Observed and simulated continuous rainfall series with sub-hourly time-step are used to calculate four key characteristics of rainfall and two types of rainfall volumetric percentiles. To separate independent rainstorm events, MIT values of 3, 6, 12, 24, 48 and 72 h and storm volume thresholds of 0.2, 0.5, 1 and 2 mm are considered. Results show that the proposed methodology improves the estimation of the key characteristics of the rainfall events as well as the hydrologic parameters for SuDS design, compared with values directly deduced from the observed rainfall series with daily time-step. Moreover, MITs rainfall volumetric percentiles of total number of rainfall events are very sensitive to MIT and threshold values, while percentiles of total volume of accumulated rainfall series are sensitive only to MIT values.

In the second part of the research work discussed here, an approach based on a stochastic temporal disaggregation of daily rainfall data is coupled with a hydrological model implemented at urban watershed scale. The long-term efficiency of several LID scenarios on reducing runoff is tested both with independent flow events approach and with the annual maxima peak flows associated with some return periods over the considered time-period. The evaluation is done using twenty LID scenario characterized by four percentages of impervious area retrofitted with LIDs (25, 50, 75 and 100%), and five LID combinations of Green Roofs, Rain gardens and Cisterns on peak flow reduction. Stochastic temporal disaggregation and generation of 500 years of rainfall data with sub-hourly time-step has been achieved using the rainfall generator RainSim V.3. and coupled with the LID module of the Soil and Water Assessment Tool (SWAT) hydrological model. Results show that combinations of different LID types generally offer higher peak flow reduction when more type of LIDs area is added. Hydrological performances of LID combinations are very sensitive to the intensity of rainfall events as well as percentages of area treated. Watershed scale performance of single LID types may not be proportional to what observed for the single infrastructure, due to synergy processes that occurs between multiple structures.

RESUMEN

Los enfoques alternativos de gestión de aguas pluviales para cuencas hidrográficas urbanas, también llamados Sistemas de drenaje urbano sostenible (SuDS) o Desarrollos de bajo impacto (LID), se están adoptando cada vez más con el objetivo de proporcionar gestión de flujo, control de inundaciones, mejoras en la calidad del agua y oportunidades para recolectar aguas pluviales. Las estructuras SuDS suelen ser sistemas pequeños y descentralizados que gestionan la escorrentía de aguas pluviales cerca de la fuente. Estos sistemas interactúan con el ciclo hidrológico urbano, modificando los flujos de evapotranspiración, escorrentía y recarga de aguas subterráneas. Es un desafío cuantificar estos cambios hidrológicos debido al costo y la complejidad de modelar múltiples sistemas SuDS en cuencas urbanas de mayor escala. Sin embargo, el diseño hidrológico de SuDS se logra comúnmente mediante el establecimiento de percentiles volumétricos de lluvia a partir de series de lluvia diarias, pero debido a la pequeña escala de las cuencas hidrográficas urbanas y las cantidades involucradas, se necesitan datos de lluvia de diseño en pasos de tiempo inferiores a una hora. Por estas razones, es necesario explorar el funcionamiento de nuevas herramientas de modelado y diseño. El trabajo de investigación discutido aquí tiene como objetivo analizar la capacidad de un proceso de generación de lluvia sintética para mejorar el diseño de SuDS. En particular, se aplica la desagregación temporal de los registros de precipitaciones diarias utilizando metodologías estocásticas para mejorar los parámetros de diseño de SuDS y ejecutar un modelo hidrológico a largo plazo para evaluar los efectos a escala de la cuenca hidrográfica de varios escenarios de SuDS. La primera parte de esta investigación tiene como objetivo analizar: 1) la capacidad del proceso de generación de lluvia sintética para reproducir las principales características de la lluvia observada; 2) los parámetros hidrológicos que se utilizan a menudo para el diseño de SuDS en función de los datos de precipitaciones diarias generalmente disponibles. Otros objetivos específicos se

relacionan con la evaluación del Tiempo Mínimo Inter-Evento (MIT) y el umbral de volumen de tormenta en los percentiles volumétricos de lluvia, comúnmente utilizados en el diseño de SuDS. También se investiga la confiabilidad del modelo espacio-temporal estocástico RainSim V.3 para reproducir las características clave observadas del patrón de lluvia y los percentiles volumétricos. Las series de precipitaciones continuas observadas y simuladas con intervalos de tiempo subhorarios se utilizan para calcular cuatro características clave de las precipitaciones y dos tipos de percentiles volumétricos de precipitaciones. Para separar los eventos de tormenta independientes, se consideran valores MIT de 3, 6, 12, 24, 48 y 72 h y umbrales de volumen de tormenta de 0,2, 0,5, 1 y 2 mm. Los resultados muestran que la metodología propuesta mejora la estimación de las características clave de los eventos de lluvia, así como los parámetros hidrológicos para el diseño de SuDS, en comparación con los valores deducidos directamente de las series de lluvia observadas con paso de tiempo diario. Además, los percentiles volumétricos de lluvia de MIT del número total de eventos de lluvia son muy sensibles al MIT y los valores de umbral, mientras que los percentiles del volumen total de las series de lluvia acumulada son sensibles solo a los valores de MIT.

En la segunda parte del trabajo de investigación discutido aquí, un enfoque basado en una desagregación temporal estocástica de datos de precipitación diaria se combina con un modelo hidrológico implementado a escala de cuenca urbana. La eficiencia a largo plazo de varios escenarios LID para reducir la escorrentía se prueba tanto con el enfoque de eventos de caudal independientes como con los caudales pico máximos anuales asociados con algunos períodos de retorno durante el período de tiempo considerado. La evaluación se realiza utilizando un escenario de veinte LID caracterizado por cuatro porcentajes de área impermeable readaptada con LID (25, 50, 75 y 100%), y cinco combinaciones de LID de techos verdes, jardines de lluvia y cisternas en reducción de flujo máximo. La desagregación temporal estocástica y la generación de 500 años de datos de lluvia con pasos de tiempo sub-horarios se lograron utilizando el generador de lluvia RainSim V.3. y junto con el módulo LID del modelo hidrológico de la Herramienta de Evaluación de Suelos y Aguas (SWAT). Los resultados muestran que las combinaciones de diferentes tipos de LID generalmente ofrecen una mayor reducción del flujo máximo cuando se agrega más tipo de área de LID. Los rendimientos hidrológicos de las combinaciones LID son muy sensibles a la intensidad de los eventos de lluvia, así como a los porcentajes de área tratada. El rendimiento a escala de la cuenca hidrográfica de los tipos de LID únicos puede no ser proporcional a lo observado para la infraestructura única, debido a los procesos de sinergia que se producen entre múltiples estructuras.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1 Thesis structure

The thesis is organized in four main chapters detailed below:

- Introduction (chapter 1).
- Materials and Methods (chapter 2).
- Results and Discussion (chapter 3).
- Conclusions and recommendations (chapter 4).

Chapter 1 presents the main and specific objectives of the thesis, also providing a review of the literature concerning SuDS design. First, an overview of existing design parameters, hydrology of SuDS, rainfall design and use of sub-daily rainfall series is provided. Second, a comprehensive summary of open questions regarding watershed application of SuDS using long-term climatic series and hydrological models is achieved.

Chapter 2 presents the two methodologies adopted in the thesis. First, the stochastic methodology used to generate a temporal disaggregation of daily rainfall records in a single rain gauge, is explained. The stochastic methodology is calibrated and validated, then simulated rainfall series are compared with the observed ones by means of the rainfall design parameters of SuDS. Second, the implementation of an urban-watershed model in SWAT, is reported. The effects of different SuDS scenarios on peak flow reduction are studied over a very-long term analysis. In addition, correlation of peak flow reduction and key rainfall characteristics, based on a flow event approach over the used long period, is analyzed.

Lastly, chapter 3 and 4 discuss and then summarizes the main findings of the work and proposes outlooks for future studies.

1.2 Objectives and methodology

The current research has two main general objectives:

1) to develop a quantitative and stochastic approach to estimate SuDS design parameters, based on a temporal disaggregation methodology of daily rainfall data commonly available and recorded by rain gauges all over the world. In this context the effectiveness of the methodology on reproducing hydrological parameters often used for SuDS design, is tested.
2) to quantify the runoff reduction potentiality and analyze the mutual hydrological interactions of different SuDS scenarios. With this aim, the analysis is carried out at urban watershed-scale and using a very long-term analysis based on the stochastic approach developed at point 1.

Moreover, this research study has the following specific objectives:

1a) validation of the proposed stochastic methodology to reproduce observed key characteristics of rainstorms among the analyzed rainfall series.

1b) sensitivity analysis of SuDS design parameters regarding the variables used to identify independent rainstorm events at point 1a).

2a) effectiveness of peak flow reduction using every SuDS scenario, analyzing every independent flow event extracted among the stochastic long-term model of the urban-watershed case study.

2b) efficiency of the annual maximum peak flow reduction of every SuDS scenario based on a return period approach over the considered long-term analysis.

To achieve the first objective, a temporal disaggregation methodology based on the Neyman-Scott Rectangular Pulse Method, was carried out applying the stochastic rainfall generator RainSim V.3 to a single rain gauge station located in Florence (Italy). The stochastic model was calibrated based on sub-hourly observed rainfall data. Moving on the second objective, the calibrated stochastic model was used to generate a very long-term rainfall series at sub-hourly time-step, that was used as climate input of a hydrological model in an urban-watershed likewise located in Florence (Italy). Implementation of this long-term hydrological analysis was achieved by using the Soil & Water Assessment Tool-SWAT hydrological model. In particular, the SWAT-LID module was used to represent several SuDS scenarios.

Research questions, aims and the methodology are summarized in Table 1.1.

Table 1.1 Summary of the main research questions aims and methodology of the carried-out research.

Research question	Aim	Methodology
Which is the way to solve the lack of sub-daily rainfall records in SuDS engineering practice?	To provide a temporal disaggregation approach of daily rainfall records	Application of the stochastic rainfall generator RainSim V.3., based on the Neyman-Scott Rectangular Pulse Method, to a rain gauge case study
Which is the reliability of the defined stochastic approach in reproducing rainfall volumetric percentiles often used in SuDS design?	To demonstrate that the stochastic methodology provides better key features of rainfall patterns and volumetric percentiles than using daily observed rainfall data	Comparison of key characteristics of rainfall pattern and rainfall volumetric percentiles from observed and simulated sub-daily rainfall series
Which are the hydrological effects of several SuDS types and configurations at urban-watershed scale?	To test the effectiveness of several SuDS scenarios on reducing peak flows during single flow events and on annual basis	Implementation of an urban-watershed model using SWAT; implementation of the SWAT LID module for the definition of the SuDS scenarios
How can be solved the lack of continuous long-term climatic inputs with sub-daily time step, in urban-watershed modeling?	To analyze the peak flow reduction of SuDS scenarios at urban-watershed scale, during a very long-term modeling	Simulation of 500 years long rainfall series using RainSim V.3. and application of a hundred years as input of the analyzed SWAT model

1.3 Literature Review

1.3.1. The hydrological impact of urbanization

Currently, more than half of the world population lives in urban areas and a growth is expected [1]. Human activity on urban watersheds induces changes on the hydrological characteristics, such as increased runoff volume and rates, decreased runoff lag time, reduction of aquifer recharge [2].

Moreover, urbanization increases stormwater runoff peaks and reduces the time delay between peak rainfall and peak runoff when compared to natural areas [3]. In this context the risk of flooding increases and major implications for water quality are underlined. Urban drainage infrastructures and artificial wastewater treatments are thus required to manage the increased stormwater runoff from urban areas. The cost of sewer systems and treatment plants is generally high [4] and current urban drainage systems only have a limited capacity to deal with flooding. Moreover, climate change will increase the risk of flooding because of the shortage of the sewers systems in urban areas [5,6].

There are several other consequences associated with urbanization. It can impact the local climate [7] and often leads to an over exploitation of surface water and groundwater that, depending on specific area, it may cause problems of seawater intrusion, subsidence, and depleted streams and wetlands [8]. The construction of subsurface pipe networks such as water-mains and sewer networks modify the natural pathways of groundwater recharge and discharge. Foster et al., 1994 [9] and Lerner, 1987, 1990 [10,11] have reported an increase of urban recharge due to leaking mains, leaking sewers, and wastewater disposal. Carcia Fresca et al., 2004, 2005 [12,13] have described several case studies and have shown that urbanization often leads to an increased groundwater recharge.

1.3.2. The role of Nature Based Solutions in mitigating urbanization effects

Conventional stormwater management practices, like surface water networks and combined sewerage systems, may turn out to be unsustainable. They are costly and have a limited ability to treat outlet contaminants, to reduce runoff volume and peak flow and to adapt to changes, as the expansion of urbanized areas and the increase of storm frequency due to climate change [14]. In recent years, alternative stormwater management practices i.e. Nature Based Solutions, such as Low Impact Development (LID) or Sustainable urban Drainage Systems (SuDS), have been adopted to address these issues as they offer different characteristics that potentially make these facilities attractive to developers and local administrations [15,16].

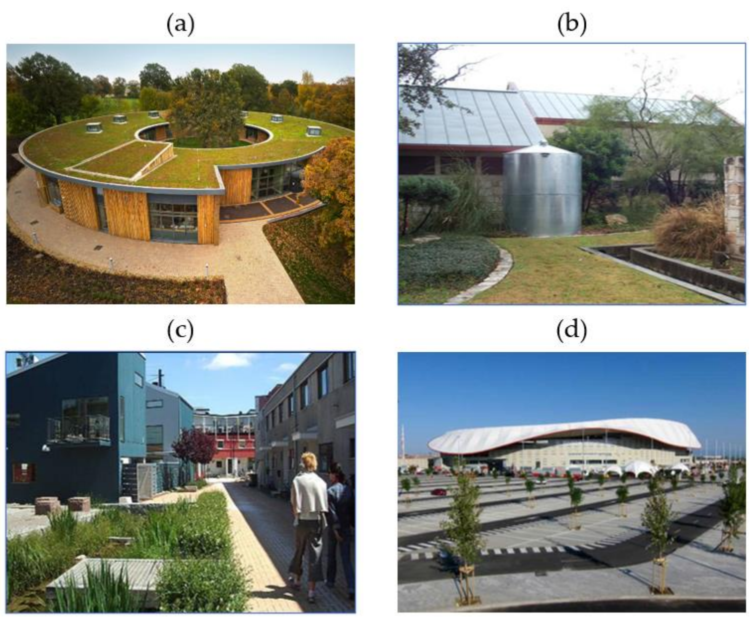

Figure 1.1 Examples of SuDS installed over the world. (a) Green roof at British Horse Society sedum blanket, Birmingham (UK). (b) Rainwater Cistern in St. Antonio, Texas (USA). (c) Rain garden in Malmö (Sweden). (d) Permeable pavement in Wanda Metropolitano Stadium, Madrid (Spain).

Nowadays, the Nature Based Solutions are among the systems used for sustainable storm water management and runoff reduction in urban watersheds [17,18].

The hydrological situation in urban areas before urbanization, can be mimicked by LID retrofitting of impervious land-use surfaces, as LIDs are able to mitigate the impacts on water quality and quantity caused by intensive urbanization [19,20,21]. LIDs can restore processes of infiltration and evapotranspiration in urban watersheds; they reduce peak flow rate and flow velocity as well as they extent the concentration time, restore water balance and improve water quality [22,23].

Among the Nature Based Solutions, SuDS are blue-green structures which work reinstating natural elements of urban catchment with the aim of retaining rainfall, retarding its movement through the surface network, restore infiltration and evapotranspiration through natural or seminatural processes, among others [24-26]. Water and pollutants in urban landscapes may be retained by a combination of conventional methods supported by SuDS structures, like pervious pavements, infiltration trenches, swales, filter strips, filter drains for the streetscape, soakaways, infiltration and detention basins, bioretention areas, ponds and wetlands, trees for open spaces, green roofs, and attenuation tanks for special uses, among others [24,27-29].

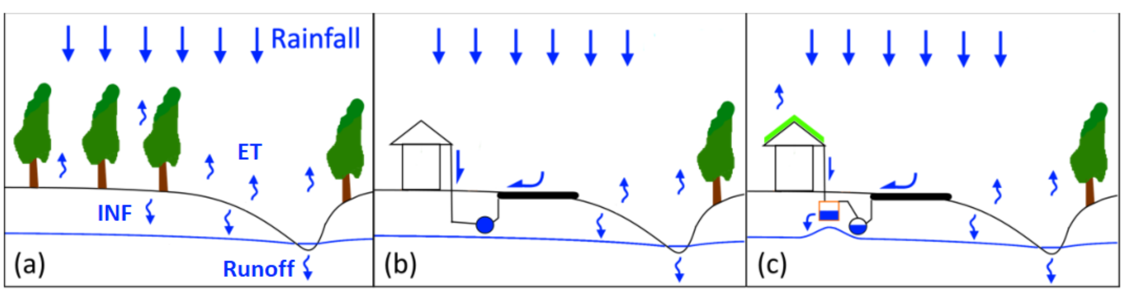

Figure 1.2 Representation of some of the main hydrological processes involved in the urbanization process. (a) Pre-development conditions. (b) Urbanization with a conventional stormwater management approach. (c) Example of retrofitting green roofs. ET: evapotranspiration; INF: infiltration.

From the standpoint of engineering modelling practice, hydrological and hydraulic design parameters for SuDS follow its geometrical discretization: i) vegetation and volume fraction, surface slope, surface roughness and storage depth for surface layer; ii) thickness, porosity, field capacity, hydraulic conductivity and suction head for soil layer ; iii) thickness, permeability and impervious fraction for pavement layer if present; ; iv) thickness and void ratio for storage layer if present; v) flow coefficient, control volume and flow capacity for drain layer if present [30].

1.3.3. Rainfall design parameters of SuDS and rainfall disaggregation approach

As highlighted by many authors, the analysis of rainfall spectrum and its consequences represents a key component of the design of urban drainage systems. Historical data collected by a rain gauge can be considered as a sequence of rainstorm events composed by very frequent, common, heavy, and extreme ones [31,32]. Although extreme events are responsible to pluvial floods of higher intensities, small and moderate rainstorm events are responsible for most of the runoff and mass pollutant discharges, representing in many cases the most important storms for SuDS characterization [33,34]. Some authors state that urban flood management should be addressed with a holistic and long-term vision to achieve a resilient and cost-effective solution [28,35]. Fratini et al., 2012 [35] propose the use of the 3 Point Approach (3PA), developed by Geldof and Kluck, 2008 [36], as a tool for decision making process in urban flood management. Smit Andersen et al., 2016 [31] followed the qualitative approach proposed by Fratini et al., 2012 [35] to select the representative storms for analyzing the design and functioning of a SuDS. They showed that SuDS may not be efficient on mitigating extreme events. SuDS perform better in the field of Small Storm Hydrology of urban environments [37].

Hydrological design of SuDS is, therefore, usually based on rainfall percentiles to be managed. The formulation and selection of these rainfall percentiles can be made following different criteria, as the number of rainstorm events or the accumulated volume of the rainfall series to be managed [24,38–40]. In small urban watersheds there are two different ways of using rainfall-runoff hydrological models. By one side, the design storm approach relates the concept of return period and various severity grades of extreme rainfall forcing that can be applied to the facility under design. On the other hand, the approach consists of achieving continuous streamflow series from the numerical model using historical or synthetic rainfall records as input data [41,42].

The most accurate rainfall data can be obtained from rain gauges located in the urban watershed, with typical temporal aggregation between 5 min and 1 h, due to the small size of the urban catchments and short time of concentration occurred [43]. This high-resolution type of data is required for SuDS planning and designing. However, in general, only rainfall data with daily temporal aggregation is available [44,45]. Rainfall disaggregation produced by stochastic rainfall generators can be an attractive option to overcome this fine scale rainfall data requirement. Different types of stochastic models exist to generate n-years series of point (or areal) rainfall at sub-hourly resolutions. First type of methods is based on Markov Chain modelling [46], that use a miscellaneous of rainfall probability distribution functions (e.g., Exponential, Gamma, Weibull, Generalized Pareto—GPD, etc.) to describe the characteristics of rainfall ranging from low to high intensities. The second type is represented by the Rectangular Pulse model, as proposed in Neyman-Scott [47] and Barlett-Lewis [48], both schematizing storms as clusters of rain cells by means of rectangular pulses. Storm occurrences are described by means of Poisson processes: cell rainfall arrivals are random in time with exponential interarrival times, which are independent each other. A combined approach between a Semi–Markov Chain based model and the Neyman–Scott rectangular pulse stochastic generator was introduced by some authors to consider atmospheric indices, as in the Markov Chain models, as a condition to the combined model [49,50].

Nevertheless, applications of these different disaggregation stochastic methodologies to SuDS design are not fully developed [51]. Occurrence of rainstorm events can be characterized by some statistical parameters like number of rainfall events, storm durations, intensities, and cumulated depths as well as inter-event times [52]. To analyze key properties of rainstorm events, separation of time series of point rainfall records into individual and independent rainfall events is needed. Several methods are reported in the literature to identify independent rainstorm events, like autocorrelation method [53], rank correlation method [54] and exponential method [55]. Alternatively, some authors suggest that key statistical properties of rainstorms can vary significantly depending on: (a) the minimum temporal resolution timestep of rainfall series; (b) the minimum antecedent dry weather period to be used in separating independent rainstorm events; (c) the storm volume threshold, i.e. the minimum precipitation volume that must be exceeded to consider a storm occurrence as an event [56,57].

For SuDS design, both (b) and (c) depend on the specific facility to be designed. Despite the numerous studies related to storm characterization, the correct definition of (b) and (c) values for each type of urban drainage design are vague and arbitrary [42].

1.3.4. Hydrological modeling of LIDs

Recent studies have reported key findings about effectiveness of different LIDs on water quantity treatment (e.g. peak flow and runoff volume reduction) and quality at local scales [58,59,60]. Moreover, some of them have explored LID hydrological performances and responses at different spatial scales that support their uptake as a solution to control stormwater in urban watersheds [61]. However, the evidence of LID effectiveness at watershed scale is limited [62,63] and questions remain on how LID practices can individually or cumulatively affect urban watershed hydrology.

Another critical issue concerns the analysis of LID effects on the simulation time-length at watershed scale. Most of studies focus the attention on hydrological modeling under a single design rainstorm characterized by key features such as: mean or maximum intensity, total rainfall volume and short duration, depending on the goal of LIDs treatment design, i.e. management of small, moderate, and frequent rainstorms or extreme events [64,65,66]. Some authors have pointed out that LID practices need to be evaluated as a sustainable measure for long-term functioning [67], thus, analyzing hydrological responses under all rainstorm events that occur during multiple years of study, i.e. hundreds of years of simulations, possibly using data with sub-hourly temporal resolution. These authors base on that effectiveness of LIDs to treat water pollutant, to reduce runoff and to manage urban stormwater variation that depends on seasons as well as alternance of wet and dry periods [68,69]. Nevertheless, the cost-effectiveness of LIDs changes with time and needs to be evaluated in the long term, due to maintenance and operative costs [70]. In this regard, there is a lack in literature regarding very long-term LIDs performances analysis since observed climatic data, with sub-daily temporal aggregation, are usually provided only for a few years and they need to be corrected to characterize LIDs hydrology. In addition, another issue concerns the temporal aggregation of rainfall and other climatic data which is usually done daily, and it is too coarse for LIDs modeling purposes. Rainfall disaggregation from stochastic rainfall generators can be an option to overcome this fine-scale rainfall data requirement and long-term rainfall series generation in LIDs analysis [71,72]. Pampaloni et al. 2021 [71] have demonstrated the potential of a temporal disaggregation methodology, based on the stochastic rainfall generator RainSim V.3. [73,74], to reproduce key features of rainfall pattern and volumetric percentiles commonly used in LIDs design [75].

Nonetheless, studies on the coupling of stochastic climatic data, generated in short and long-term, and hydrological models to test LID effectiveness at the watershed scale are still lacking. A critical aspect for that process is the selection of suitable tools to explore LID effects on watershed processes, i.e. process-based hydrological models, which reproduce hydrological processes and outputs at watershed scale. Kaykhosravi et al., 2018 [76], point out a list of properties that LID models should have at watershed scale: i) representation of all natural processes occurring in a LID; ii) capability of simulating long-term continuous LIDs hydrology; iii) representation of synergies between LIDs and urban watershed hydrology; iv) simulation of LID connections with existing sewers network. Hydrological models able to represent LIDs of small size and short time of concentration in urban watershed, as well as to use sub-hourly temporal resolution, should be preferred. Among others, Hydrus 1D/2D and GIF-MOD models have been widely used in previous studies that focused on exploring the synergies between LIDs properties and their performances [77,78,79]. The performance of LID practices has also been evaluated under different urban land use densities with the Soil and Water Assessment Tool (SWAT) [80,81] and, has been demonstrated that the effectiveness of LID practices differs among the urban land use densities [82]. Likewise, Her et al., 2017 [83] have proposed an innovative LID computational module integrated into the sub-hourly simulation of SWAT components. The module simulates the hydrological processes of predefined facilities which include green roof, rain garden, cistern, and permeable pavement among the whole Hydrological Response Unit - HRU where LIDs are implemented. An interesting outcome of this work is the assessment of the effectiveness on twenty-six LID scenarios in treat runoff at urban-watershed scale and it represents a suitable option to assess the effects of several LID combinations into the whole watershed. Moreover SWAT-LID module together with sub-hourly simulation capability, enables SWAT model as a viable tool in assessing LIDs urban watershed processes in a distributed and process-based manner [84,85].

2. MATERIALS AND METHODS

This section is divided in two parts, as already mentioned in section 1.1. In the first part (sub-section 2.1), a quantitative and probabilistic method to estimate SuDS design parameters is developed. Specifically, a temporal disaggregation methodology based on the Neyman-Scott Rectangular Pulse Method is proposed and applied in a single site, by using the stochastic rainfall generator model Rain-Sim V.3 [49]. The model application is carried out with reference to the Florence University rain gauge located in Florence (Tuscany, Italy). A 20–year long series of observed precipitation volumes, recorded every 15 min, is available and was used to define the current scenario. The main objective of the first part is to analyze the ability of the proposed methodology to estimate hydrologic parameters often used for SuDS design and by using the generally available daily rainfall data. Another two specific objectives are achieved: to verify the ability of the stochastic generator to reproduce observed key properties of storm events and to analyze the dependence of SuDS design parameters with the minimum antecedent dry weather period and the storm volume threshold considered.

The following steps schematizes the methodology applied (Figure 2.1):

1. Aggregation of observed 15-min rainfall into a time-step of 24 h. Consequently, two observed rainfall series with different time aggregation were obtained. This process was done to manage the rainfall field information commonly available. Nevertheless, the use of sub-hourly series is crucial to verify the results of disaggregation stochastic methodology.
2. Calibration of the stochastic rainfall generator based on the 24 h observed rainfall series. Once the model was calibrated, 100 rainfall series, each of 20 years of continuous data with 15 min time-step, were generated.

3. Independent storm events were extracted from each, observed, and stochastically generated, rainfall series. We considered different values for the minimum antecedent dry weather period (MIT, Minimum Inter-event Time) and different thresholds of storm event total volume. Then, for every MIT and threshold value, key characteristics were calculated for all rainfall event patterns. The comparison of these characteristics was done for the observed and the median of simulated series to verify the ability of the stochastic rainfall generator to reproduce the observed rainfall properties.
4. Determination of hydrological design parameters of SuDS associated to the storms extracted, considering the different values of MIT and threshold, from each observed and simulated rainfall series. These parameters are usually based on percentiles of rainfall to be managed. These percentiles may be formulated in terms of the number of rainfall events to be managed, N_x or the accumulated volume of the rainfall series to be managed, V_x. Sub-index x refers to the percentage (number or volume) to be managed, commonly used in the practice.
5. Two distinct sensitivity analysis were applied to the values of N_x and V_x. Effects of (a) different MIT values and (b) different storm total volume thresholds, on the rainfall volumetric percentiles values were analyzed.

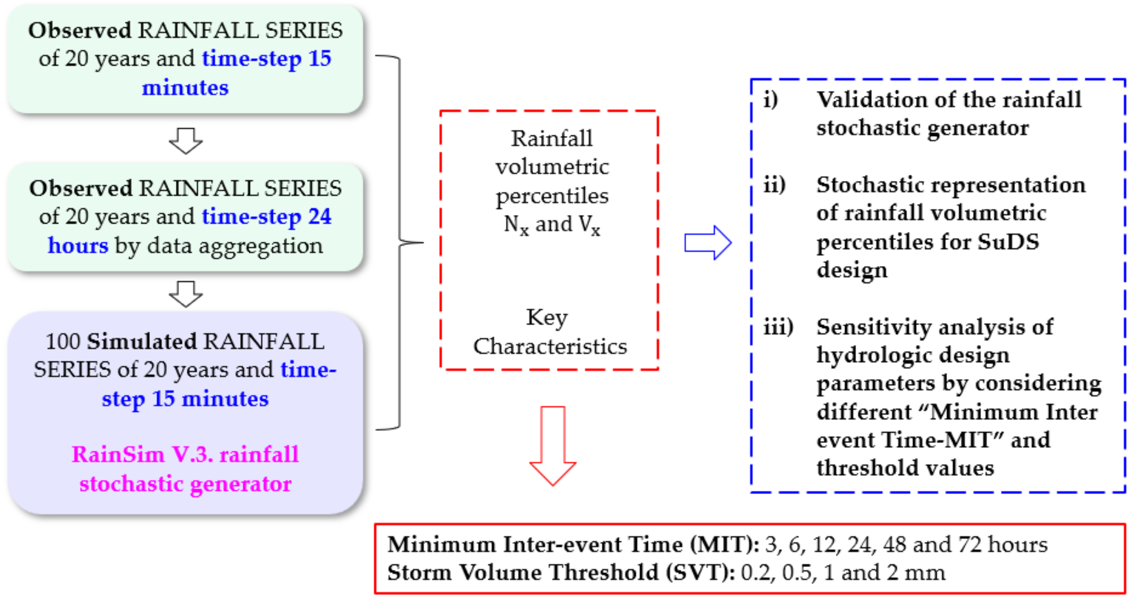

Figure 2.1 Flow chart of the stochastic temporal disaggregation approach and elaborations on independent storm events used to estimate SuDS design parameters.

The second part (sub-section 2.2) assesses how LID implementations affect watershed hydrologic responses in a highly urbanized area during a very long-term stochastic modeling, i.e. hundreds or thousands of years at sub-hourly time step. It proposes: i) a quantification of the potential peak flow reduction-PFR on twenty spatial LID configurations set at watershed scale, which are modeled using SWAT together with its LID module tool [83]; ii) a stochastic methodology to generate sub-hourly rainfall series with arbitrary high length (in this case 500 years at 15 minutes time-step), used as input for the SWAT urban hydrological model. Additional two specific objectives are achieved: (1) to analyze the capability of every LID scenario to reduce the peak flow corresponding to every rainstorm and flow event among the entire rainfall stochastic spectrum, from frequent to extreme events; (2) to explore the potentiality of every LID scenario to reduce the annual maximum peak flow over the entire long-term period, analyzing peak flow reduction of events with different return period.

The methodology's steps of the second part of the thesis are as follows (Figure 2.2):

1. A SWAT model was prepared to simulate the dynamic runoff hydrographs in the study watershed. Green-Ampt Mein-Larson (GAML) equation [86], and Penman-Monteith method were used to evaluate infiltration and potential evapotranspiration rates, respectively. A rainfall series of 500 years with 15 min time step was generated using the stochastic rainfall generator RainSim V.3, and then used as SWAT rainfall input data. LID scenarios were implemented by the SWAT-LID Module [83] within a sub-hourly SWAT model routine.
2. A total of 20 LID scenarios were composed by mixing five LID combinations (Green Roof - GR, Rain Garden - RG, Green Roof and Cisterns - GR+CS, Green Roof and Rain Garden - GR+RG, all the LID together GR+CS+RG) and four growing ratio of impervious areas where LIDs are installed (25%, 50%, 75% and 100%) within the respective Hydrological Response Unit (HRU). The scenario outputs were compared to the actual baseline scenario, i.e., the watershed configuration without LIDs.
3. Independent rainstorm events were extracted from the stochastically generated rainfall series and different values of minimum antecedent dry weather period (MIT, Minimum Inter-event Time) were considered. Then, for the baseline and LIDs scenarios, flow series were extracted by the reach scale outputs of LID module, which depends on starting and ending dates of every rainstorm event previously identified. The PFR percentages between the baseline scenario and the 20 LID scenarios were calculated for each flow event extracted among the 500 years.
4. The percentages of PFR for every flow event were extracted considering different values of MIT and calculated based on the corresponding rainstorm event intensities. First, a sensitivity analysis of results, based on MITs, was conducted.

Then, it was studying the effect of impervious different fractions treated at the same LID combination, and of different LID combinations with the same percentage of impervious treated area.

5. The PFR percentage of the annual maximum flow peak was calculated for each event within the 500-years and every LID scenario.
6. For every LID combination, the PFR of annual maximum flow peak was analyzed based on the corresponding empirical return period T_r. Likewise, the effects of different fractions of impervious areas treated on PFR were also analyzed.

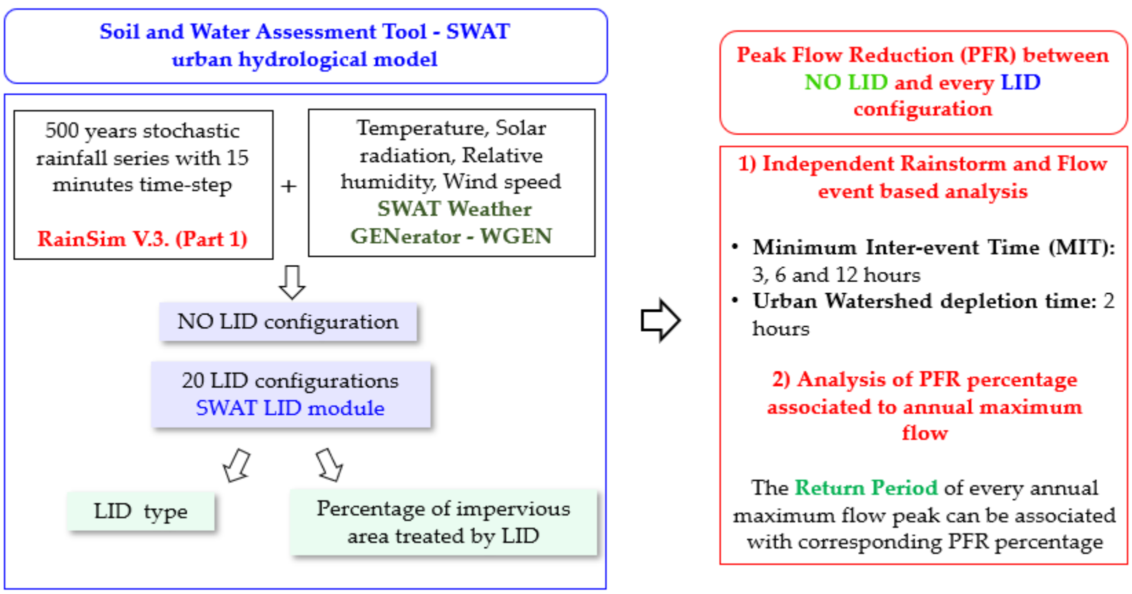

Figure 2.2 Flow chart of the long-term modeling phase using the Soil and Water Assessment Tool- LID module, coupled with a stochastic generation of rainfall series using RainSim V.3.

2.1 Stochastic procedure for temporal disaggregation of daily rainfall data in suds design

This sub-section is structured as follow. First, a description of the case study, consisting of 20 years rainfall data of the Florence University gauge station, is presented. Then, a full description of the methodology adopted is provided. The stochastic rainfall generator RainSim V.3 is described, after that, the procedure to identify independent rainstorm events using minimum antecedent dry weather period and storm volume threshold as variables of the process is described in addition with calculation of key characteristics of rainfall patterns. Lastly, SuDS design parameters calculation are explained, describing the double approach based on percentiles of total number of rainfall events and of the total volume of accumulated rainfall series.

2.1.1. Case study

The automatic rain-gauge "Florence University" (id. TOS01001096) was selected as case study (Figure 2.3). The rain gauge is located at School of Engineering—University of Florence (Tuscany, Italy), at an altitude of 84 m a.s.l. Its coordinates are E 1681124, N 4852004 (EPSG 3003 Monte Mario/Italy zone 1). Observed rainfall data of 20 years, from 1998 to 2018, with temporal aggregation 15 min, were collected and subsequently aggregated with time-step 24 h. The pluviography measurements have a minimum resolution of 0.2 mm. All rainfall data are recorded by the regional monitoring network and archived by the Hydrological Service of Tuscany Region—SIR. Florence experiences a humid subtropical climate characterized by hot sunny, moderately dry summers and mildly cool, rainy winters. The average annual precipitation is 864 mm.

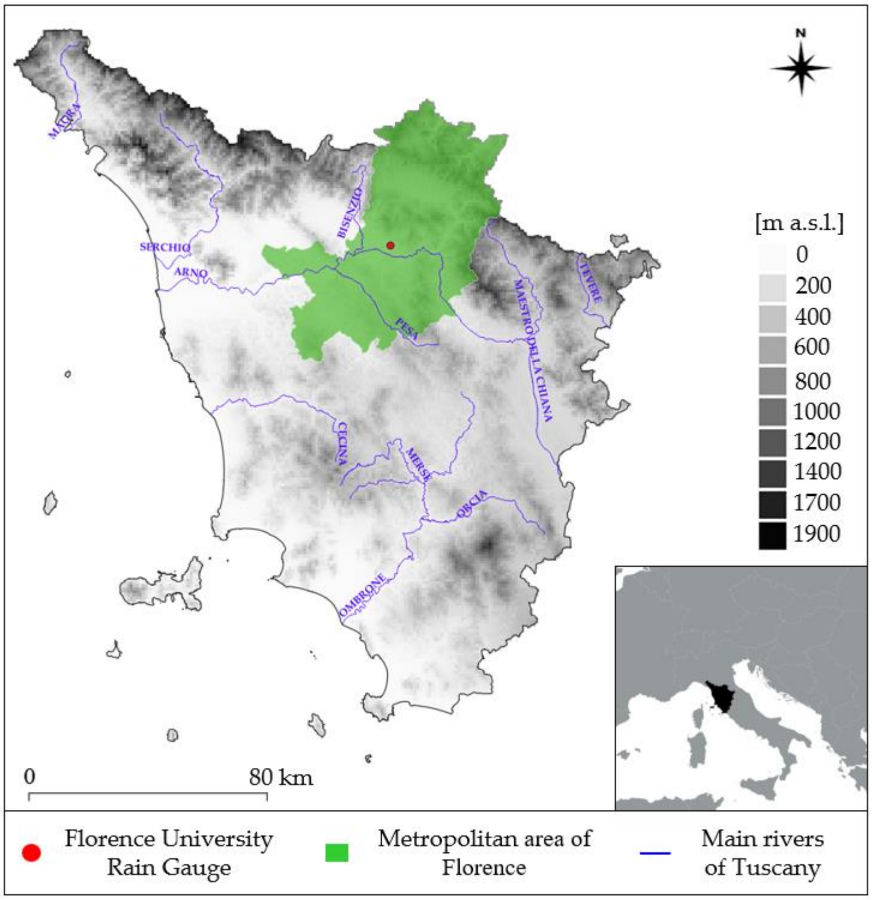

Figure 2.3 Location of the study case on a Digital Terrain Model (DTM) with a grid resolution of 10 m. The red dot indicates the rainfall gauge location within the Metropolitan Area of Florence.

2.1.2. Generation of Stochastic Rainfall Series

The RainSim V.3 model is a robust and well tested stochastic rainfall generator. This model has already been applied in South-European basins [87]. This model facilitates the generation of continuous stochastic rainfall series using a Spatial Temporal Neyman-Scott Rectangular Pulses process (NSRP). A detailed description of RainSim V.3 can be found in Burton et al., 2008, 2010 [49,88]. Rainstorm events occurs as a temporal stationary Poisson process, while the distribution of the intensities is Exponential. The generator can be used in single or multi-site versions, depending on the number of rain gauges involved. NSRP processes can capture the main observed rainfall time-series statistical characteristics: (i) mean waiting time between adjacent storm origins [hours]; (ii) mean waiting time for rain cell origins after storm origin [hours]; (iii) mean duration of rain cell [hours]; (iv)mean intensity of a single rain cell [mm/h]. RainSim operates in three modes: analysis, fitting, and simulation. The procedure applied is composed by four steps:

1. Analysis to derive statistics from observed rainfall series with 24 h temporal aggregation.
2. Fitting/Model calibration. The single-site version of the model is calibrated by applying the log-parameter Shuffled Complex Evolution (InSCE) [89] algorithm with a convergence criterion. This numerical optimization allows to identify the model parameters such that the simulation best corresponds to a selected set of rainfall statistics for each month: mean (24 h), variance (24 and 48 h), lag-autocorrelation (24 h), dry period probability (24 h with a threshold of 1 mm) and skewness (24 and 48 h). For a single site application of RainSim V.3., five parameters usually adopted in NSRP simulators, were calibrated for every calendar month: λ (1/mean waiting time between adjacent storm origins [1/h]); β (1/mean waiting time for rain cell origins after storm origin [1/h]); η (1/mean duration of rain cell [1/h]); ν (mean number of rain cells per storm [-]); xi (1/mean intensity of a rainfall cell [h/mm]);
3. Simulation, that is, generation of 100 rainfall series of continuous data. Each series is composed by 20 years, with a length equal to that of the observed period (1998–2018), of rainfall data with 15 min time-step.
4. Analysis to check whether the simulated time series are consistent with the observed one.

2.1.3. Identification of Independent Rainstorm Events and Key Characteristics of Rainfall Patterns

Different approaches to extract storm events from a continuous rainfall series can be found in technical literature [55,90]. In this part, we applied an approach based on dry inter event time and a threshold value to define non-zero rainfall. The minimum resolution value of the considered rain gauge (Florence University) is 0.2 mm. Thus, this value was used to set the rainfall threshold. First, by applying this approach, homogeneity among observed and simulated series was achieved. Second, independent rainfall events were extracted from observed and simulated series using the minimum antecedent dry weather period approach (MIT, Minimum Inter-event Time). Antecedent dry weather period can be defined as the time of no-rainfall record in the continuous series, that is, the dry period observed between two consecutive non-zero rainfall records [56,57]. As showed in Figure 2.4, not-zero rainfall pulses belong to the same storm event only if the durations of the antecedent dry weather periods within it are less of an appropriate value, that is the MIT. Otherwise, the antecedent dry weather period represents the variable to separate the end of previous storm event 1 from the start of the successive 2. Different MIT values have been reported in literature, depending on the field of application [90-92]. Here, six values of MIT were selected: 3, 6, 12, 24, 48 and 72 h. These sub-daily MIT values were used only for the rainfall series with 15 min temporal aggregation. For observed series with time-step 24 h, only 24 h multiples were applied. As the daily rainfall is the most commonly available rainfall data, consequently, it is relevant to analyze MIT values equal to 24 h and multiples [44,45,54]. Starting from values of rainfall punctual records within every independent rainstorm event, four key characteristics of the rainstorm event pattern were calculated [39]: (a) total volume, that is, total rainfall depth [mm]; (b) duration of the event [hours]; (c) mean intensity [mm/h]; (d) maximum intensity [mm/h]. Afterwards, storm total volume thresholds were applied systematically to the independent rainstorm events previously individuated. This variable corresponds to the minimum precipitation volume that should be exceeded to have a storm relevant for analysis purposes [93].

A selection of four thresholds for the minimum cumulated rainfall volume of every event were used: 0.2, 0.5, 1 and 2 mm [39,94]. A threshold value equal to 0.2 mm leads to consider the entire rainfall information collected within every rainstorm event. Finally, the extraction of independent rainstorm events from observed and simulated series was conducted. These storm series were characterized by the four mentioned key variables of rainfall and their associated exceedance probability values. This process was done for the different volume thresholds.

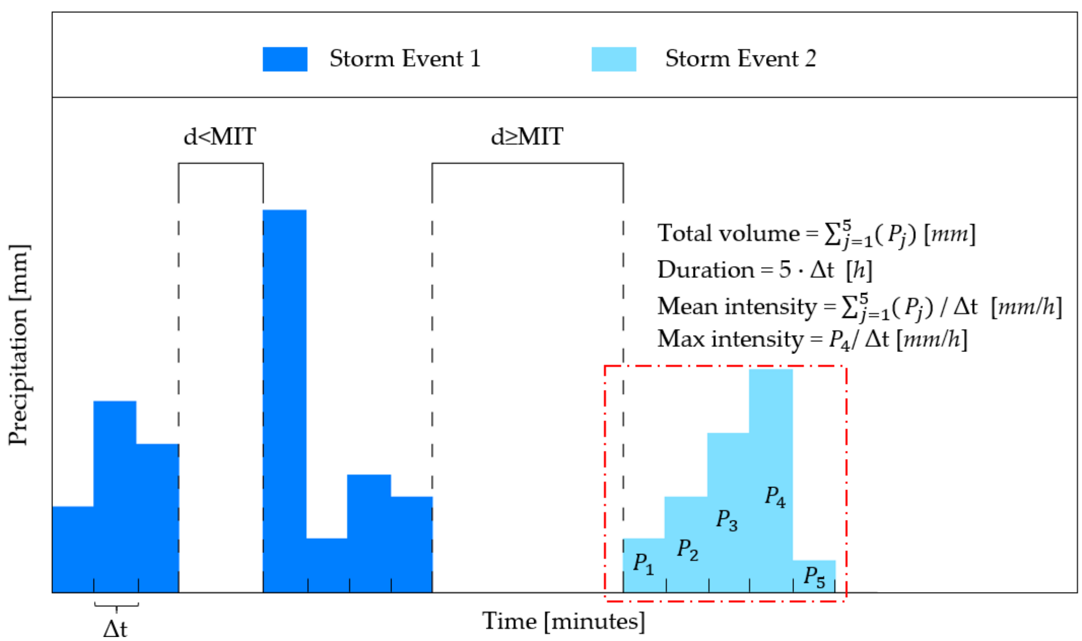

Figure 2.4. Identification of independent rainstorm events in a continuous rainfall series. As an example, the calculation of key characteristics of rainfall is showed for storm event 2, composed by five values of single rainfall impulse *j*.

2.1.4. Calculation of Rainfall Volumetric Percentiles for SuDS Design

Design of SuDS can be achieved based on rainstorm volumetric percentiles extracted from the analyzed series, observed, and simulated. There are various approaches to calculate these percentiles [24,38,40]. Here, hydrological design of SuDS was conducted based on two parameters: (a) those that manage a percentage of the total number of rainfall events, N_x; (b) those that manage a percentage of the total volume of accumulated rainfall series, V_x. Common rainfall percentiles to be managed, to which sub-index x refers, are 80%, 85%, 90%, 95% [24,40]. Rainstorm total volumes were firstly sorted by descending order for both procedures. After that, both procedures differ. In one hand, to find N_x values, the exceedance probabilities of every sorted storm event were determined and referred to the respective storm rainfall volume. In this case, N_x represents the total volume of a storm event such that it exceeds the (100−x) % of the total number of rainfall events (Figure 2.5a) [40]. On the other hand, to find V_x values, different total volumes of storm events were progressively selected from the highest to the lowest and compared to a threshold y.

The selected SuDS facility would be able to manage a maximum volume y in every rainstorm (Figure 3.3b, sum of red ordinates). Storm total volumes more than the value y would not be treated by the facility (Figure 2.5b, sum of blue ordinates). V_x is the threshold value such that the cumulative value of depths processed by the facility is the x% of total rainfall depth. By using these two different approaches, N_{80}, N_{85}, N_{90} and N_{95} values (same for N_x) were calculated for observed and simulated rainfall series, regarding the six MIT and four storm volume thresholds values.

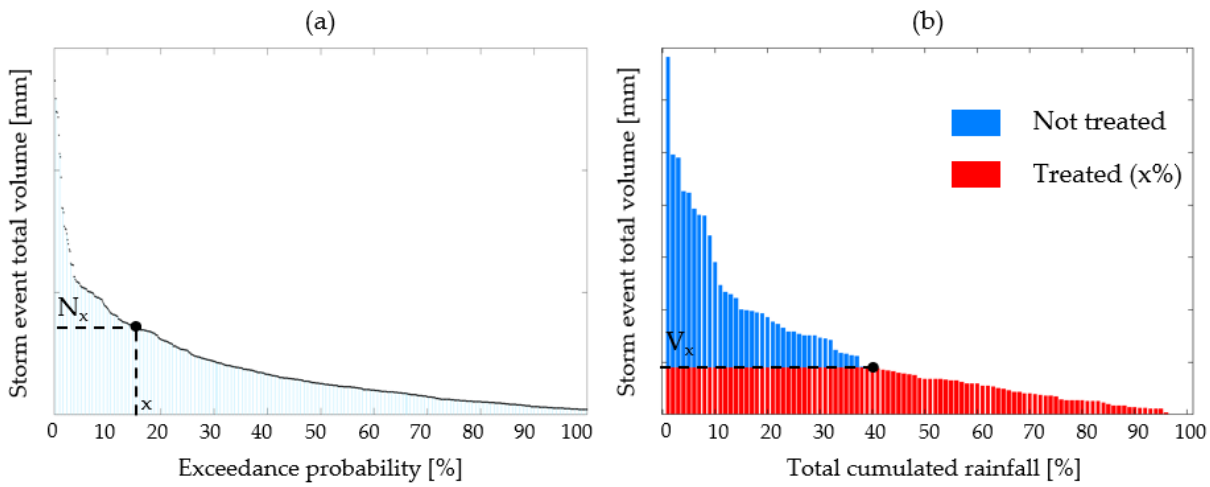

Figure 2.5. Rainfall percentiles calculated using: (**a**) the number of rainfall events to be managed, N_x. Black point represents the rainstorm event volume that ensures a treatment of the x% of the number of storm events. (**b**) the accumulated volume of the rainfall series to be managed, V_x. Sum of red vertical values represents the x% of the total cumulated precipitation of the series, which the Sustainable urban Drainage Systems (SuDS) facility will be able to fully manage. Sum of blue line vertical values represents the total cumulated precipitation unmanaged by the facility.

2.1.5. Evaluation of the Stochastic Model Performance

To evaluate the effectiveness of the proposed temporal disaggregation methodology, the simulated key characteristics of rainfall were compared with the observed counterparts with 15 min time-step. A comparison between observed key characteristics of rainfall with 24 h and 15 min time-step, was also conducted. The evaluations of errors were done through the calculation of three statistical indices: mean absolute error (MAE), root mean square error-observations standard deviation ratio (RSR) [95] and Percent Bias (PBIAS) [96].

$$\text{MAE} = \frac{\sum_{i=1}^{n} |x_i^{sim} - x_i^{obs}|}{n}, \qquad 2.1$$

$$\text{SR} = \frac{\text{RMSE}}{\text{STDEV}_{obs}} = \frac{\sqrt{\sum_{i=1}^{n}(x_i^{obs} - x_i^{sim})^2}}{\sqrt{\sum_{i=1}^{n}(x_i^{obs} - x^{obs,mean})^2}}, \qquad 2.2$$

$$\text{PBIAS} = \frac{\sum_{i=1}^{n}\left(x_i^{obs} - x_i^{sim}\right) * 100}{\sum_{i=1}^{n}(x_i^{obs})}, \qquad 2.3$$

where n is the number of coupled points used for the evaluations, x_i^{sim} and x_i^{obs} are the simulated and observed punctual key characteristics of rainfall, RMSE is the root mean square error and STDEV_{obs} is the standard deviation of the observed data. $x^{obs,mean}$ is the mean of the observed values.

2.1.6. Limitations of the Methodology

The main limitations of this part lie in the use: (i) of a single rain gauge and dataset; (ii) of a dataset with relatively short length and only valid for very frequent and common rainstorm events, not for heavy and extreme ones; (iii) of a unique stochastic rainfall generator model to simulate sub-daily rainfall records starting from observed data; (iv) of rainfall volumetric percentiles (N_x and V_x) that are suitable for hydrological design of some type of SuDS facilities but not for others. Nevertheless, the effects of temporal disaggregation models as well as different MIT and storm volume threshold values on SuDS types that need different hydrological design parameters, are not considered in the analysis. These points may limit generalizations of the results and conclusions. Moreover, the methodology did not consider climate change effects or possible long-term variations of the rainfall, that is, the rainfall series generated with the stochastic model do not account for non-stationarity [97]. Despite these limitations, the proposed methodology may provide a useful tool for hydrological design of SuDS. Additionally, SuDS are usually designed for frequent storms, as in the case studied here but not for extreme events.

2.2 Long-Term effects of Low Impact Development of watershed hydrology in an urban system

In this part, the PFR potential was analyzed on three LID types (green roofs, rain gardens and cisterns) at urban watershed scale for 500 years (stochastic long-term analysis). Temporal disaggregation of rainfall series was achieved based on the Neyman-Scott Rectangular Pulse Method by the stochastic rainfall generator RainSim V.3. An urban watershed located in Florence (Italy) was selected as case study. Likewise, a 20-year series of observed precipitations, recorded by the Florence University rain gauge (Florence, Italy), was used to calibrate the stochastic rainfall generator. Three LID types were jointed to generate different LID combinations and for each of them, growing retrofitting areas among the watershed were considered. The planimetric scheme and the hydrology of every LID scenario was modeled using the SWAT-LID module.

2.2.1. Case study

The case study area is within the Metropolitan city of Florence, in Tuscany (Italy). It covers about 3 km^2 inside a highly urbanized area, i.e. a portion of the city in which the mapped impervious area exceeds 50% [98] (Figure 2.6). The topography is flat on average 50 m a.s.l. The time of concentration of the urban watershed is 19 min. Soil properties were obtained from the FAO/Unesco world soil digital map. The soil of the study area is composed by two layers of loam and sandy loam texture, respectively. The maximum rooting depth is one m.

According to the Corine Land Cover 2018 database, the land uses are composed by 29% roads/transportation, 41% high density buildings, 27% high density residential areas and 3% green urban areas. Topographic information was obtained from 1 m LIDAR DEM created by Tuscany Regional Administration, which was used to delineate the watershed boundaries and to identify the drainage network. According to the LIDAR DEM, the average slope of the study watershed is 2.1%, and the length of the longest flow path is 4.3 km (blue line in Figure 2.6).

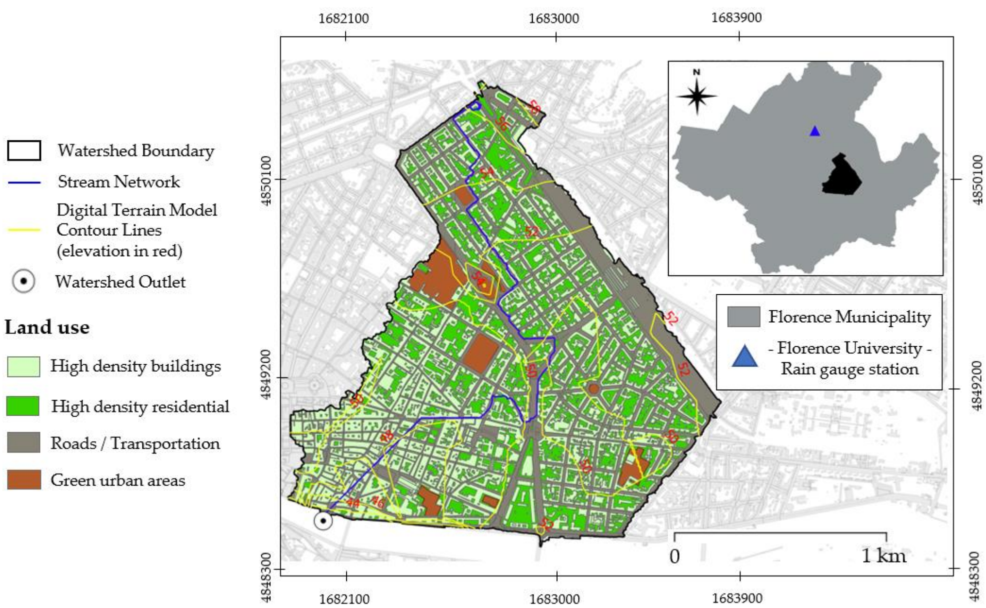

Figure 2.6. Location and land use of the study urban watershed. The blue triangle indicates the rainfall gauge location within the Municipality area of Florence.

2.2.2. SWAT model set-up

A SWAT model was implemented on the study urban watershed. It was chosen as hydrological model for LID analysis, as it is capable to: i) represent hydrological processes from small HRU scale to large-scale watersheds; ii) simulate continuous long-term watershed hydrology by accounting soil water taking into consideration:

infiltration, evapotranspiration and percolation between storm events [83], use sub-daily and sub-hourly time step climate input to provide sub-hourly outputs [86,99]; iv) model the LID wet and dry continuous cycles over long-term modeling. In SWAT, a river basin or an urban watershed can be divided in a chosen number of sub-basins based on the stream network, and each of them is divided based on Hydrological Response Units-HRUs. An HRU is a unique combination between one slope, one land use and soil type which have the same hydrological behavior regarding water runoff.

SWAT-LID module

The SWAT-LID module offers four types of pre-set LIDs: green roofs, rain gardens, cisterns, and permeable pavements. Each of them can be assigned with different percentage of impervious treated area in the HRU where the LIDs are installed (Figure 2.7). This percentage of impervious HRU area is then treated depending on the LID characteristics and contributes proportionally to the whole HRU's output. Except for green roofs and cisterns, that are suggested to be coupled [83], only one LID type can be assigned for every land use, i.e., for every HRU. In this part, green roofs, rain gardens and cisterns were selected as design facilities. Every LID type can be conceptualized as a storage connected to other elements by hydrological process and corresponds to a temporary storage before evaporating or percolating to other storage (Figure 2.8).

A Green roof is a designated area in HRU with a soil layer and vegetated. The soil layer retains rainwater and release it through seepage. Soil properties such as: depth, field capacity, wilting point, saturated hydraulic conductivity, and porosity can be modified in LID Module (Table 2.3). After soil saturation, rainfall moves toward the bypass seepage and runoff generation starts. The evapotranspiration and seepage rates are functions of soil moisture content and varied from field capacity to wilting point of the soil.

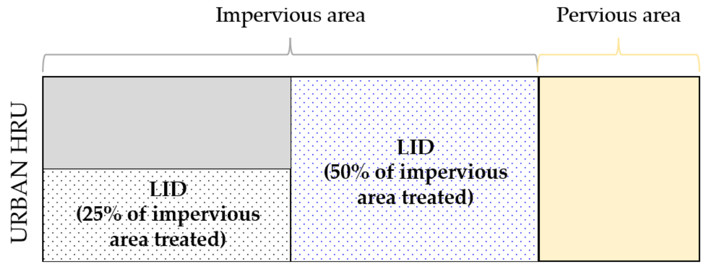

Figure 2.7. Example of LID implementation in an urban HRU. Impervious area of the urban HRU can be retrofitted with LID depending on various percentages of area treated by the infrastructure.

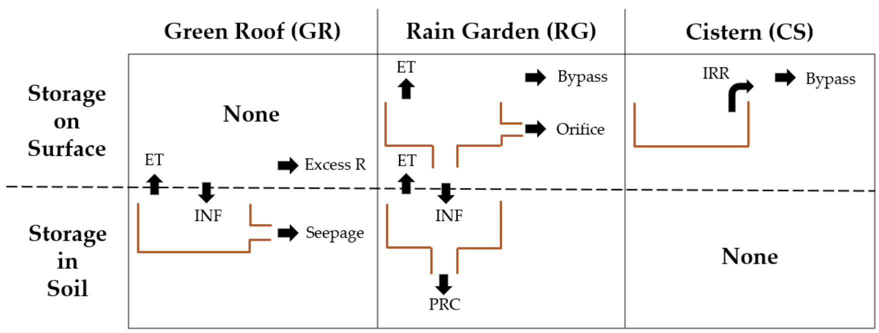

Figure 2.8. Storage of the three LIDs analyzed in SWAT simulation. (ET: evapotranspiration, INF: infiltration, Excess R: excess rainfall, Seepage: seepage of soil water, Bypass: bypass of stormwater, Orifice: discharge of stormwater through an orifice, PRC: percolation of soil water, IRR: irrigation [83].

Rain gardens (RG) are artificial depressions where stormwater can be retained and infiltrated. In LID Module, a Rain Garden is set to receive surface flow from the HRU impervious area, as well as raindrop that fall directly above it. A typical rain garden consists of two storage components (tanks): storage on the garden surface (upper tank) and an amended soil layer (lower tank). Water stored in the surface storage infiltrates into the soil layer and then percolates into the native soil. The water ponding at the upper tank can be discharged through an orifice pipe. Water stored in the upper and the lower tanks can evaporate to the air and can also percolate to native soil in the last. The depth, field capacity, wilting point, saturated hydraulic conductivity, and porosity of the amended soil choose in Green Roofs and Rain Garden can be set in LID Module (Table 2.3).

A cistern (CS) can be set to receive a certain volume of water from the coupled Green Roof located in the same HRU. Once rainwater fills up the cistern, the water excess will bypass and will drain. The harvested water will neither infiltrate nor evaporate, but it can be used for irrigation and can maintain the HRU's soil moisture content.

Land use data

The impervious area percentage associated with a land use type represents one of the most important features in an HRU. In this part, the default Total Impervious Amount - TIA of every urban land use inside the SWAT database was updated by the 2018 Copernicus imperviousness high resolution raster file [99]. According to Sutherland, R. C. 1995 [98], the Effective Impervious Amount – EIA of every urban land use was calculated from TIA that is directly connected to the drainage system, and then replaced instead of TIA in the SWAT database for land use, therefore for every HRU. After this data-processing, about 94% of the study area is composed by impervious surfaces (Table 2.1).

Since the scope of the sub-section aimed at evaluating overall LID performance in the entire study area, the watershed was not further divided into subbasins. In SWAT, there are various criteria to select or limiting the number of HRUs considered in every sub-basin. Here, the total amount of HRUs in the watershed was considered based on the number of land use type in the basin.

Table 2.1. Urban Land use features of the study watershed. Effective Impervious Amount – EIA, of every urban land use is presented.

SWAT code	Land use	Area [ha]	Watershed Area [%]	EIA [%]
URHD_roofs	Residential High density (roofs)	123	41	0.95
URHD	Residential High density	81	27	0.89
UTRN	Transportation/roads	87	29	0.98

Climate data

To run the sub-hourly SWAT-LID module routine, rainfall series with at least sub-hourly temporal aggregation is needed. Followed the methodology applied by Pampaloni et al., 2021 [71], the stochastic rainfall generator RainSim V.3 was calibrated with the 20 years observed rainfall series which were aggregated at 24 h time step. Once the stochastic model was calibrated, a continuous series of 500 years rainfall data, with 15 min time-step, was generated and used as input of the SWAT sub-hourly routine. The other four climatic variables (air temperature, solar radiation, wind speed and relative humidity) were simulated with daily time step using WGEN, the internal SWAT stochastic weather generator. This option overcome the lack of long-term observed climatic data to run hundred years simulations in SWAT. WGEN can be calibrated using observed statistics of the five climatic variables. The climatic data (observed rainfall, air temperature, solar radiation, and relative humidity) from a series of 20 years (1998 to 2018) were logged by the automatic gauge-station "Florence University" (id. TOS01001096). The gauge station is located at School of Engineering—University of Florence (Figure 2.6), at an altitude of 84 m a.s.l. and its coordinates are E 1681124, N 4852004 (EPSG 3003 Monte Mario/Italy zone 1). Observed wind speed series, from 2004 to 2018, were obtained from the anemometric gauge "Amerigo Vespucci airport", located 7 km away from the study urban watershed. All climatic data are recorded by the regional monitoring network and stored at 15-min temporal resolution by the Hydrological Service of Tuscany Region—SIR. The pluviography measurements have a minimum resolution of 0.2 mm.

LID scenarios

The combination of the three LID types resulted in five LID combinations: GR, RG, GR+CS, GR+RG and GR+CS+RG. For each of them, four fractions of impervious areas, where LID are installed, were analyzed: 25%, 50%, 75% and 100%. Finally, twenty LID scenarios were modeled (Table 2.2) to assess the watershed-scale effectiveness of stormwater management using the LID scenarios. The scenarios corresponded to the mixing LID combinations and retrofitting percentages.

Each LID type was designed in the whole urban HRU among the study watershed, but green urban areas were not implemented by any LID. The corresponding percentages of watershed retrofitted area by every LID scenario are also shown in Table 2.2.

Table 2.3 shows the design hydrological parameters of amended GR and RG soil layers. The values of the design parameters were calculated as in the Woods and Ballard (2015) [100] guide. For rain gardens, the orifice configuration was set as in Her et al., (2017) [83]. The height of the orifice from the bottom of the storage and the orifice pipe's diameter were set as 0.05 m. For cisterns, 100% of impervious areas draining water to the cisterns was set in every scenario (Table 2.3). It means that a cistern receives all runoff from the corresponding green roof.

Table 2.2. LID scenarios implemented in the study watershed.

	LID type			**Watershed Area Percentage**
	Green Roof	**Cistern**	**Rain Garden**	
Land use SWAT CODE	UHD_roofs	UHD_roofs	URHD - URTN	
LID SCENARIO	**Fraction of impervious area treated**			
baseline	0%	0%	0%	0%
GR - 25	25%	0%	0%	9.7%
GR – 50	50%	0%	0%	19.4%
GR – 75	75%	0%	0%	25.9%
GR – 100	100%	0%	0%	38%
RG - 25	25%	0%	0%	13.1%
RG – 50	50%	0%	0%	26.2%
RG – 75	75%	0%	0%	34.8%
RG – 100	100%	0%	0%	52.4%
GR+CS - 25	25%	100%	0%	9.7%
GR+CS – 50	50%	100%	0%	19.4%
GR+CS – 75	75%	100%	0%	25.9%
GR+CS – 100	100%	100%	0%	38%
GR +RG – 25	25%	0%	25%	22.8%
GR+RG – 50	50%	0%	50%	45.7%
GR+RG – 75	75%	0%	75%	60.9%
GR+RG – 100	100%	0%	100%	91.4%
GR+CS+RG – 25	25%	100%	25%	22.8%
GR+CS+RG – 50	50%	100%	50%	45.7%
GR+CS+RG – 75	75%	100%	75%	60.9%
GR+CS+RG – 100	100%	100%	100%	91.4%

Table 2.3. Hydrological parameters of amended soil layers of Green Roofs and Rain Gardens used in all the LID scenarios implemented.

	LID type		
Hydrological parameter	**Green Roofs**	**Rain Gardens**	**Parameter Range**
Depth [m]	0.8	0.5	0÷1
Field capacity [mm/mm]	0.4	0.4	0 ÷1
Wilting point [mm/mm]	0.15	0.15	0÷1
Saturated hydraulic conductivity [mm/h]	350	350	0÷500
Porosity [mm/mm]	0.5	0.5	0÷1

2.2.3. Identification of Independent Rainstorm and Flow Events

Chronological rainstorm events from the long-term stochastic precipitation series were extracted following an approach based on Minimum Inter event Time, MIT, and a threshold value to define not-zero rainfall [71]. The value of 0.2 mm was chosen as threshold, and it is the minimum resolution of the pluviometer at the Florence University gauge station. Two non-zero rainfall records can be considered as part of the same rainstorm event only if the time between them is less or equal to the MIT. Indeed, MIT can be defined as the no-rainfall time between two consecutive not-zero rainfall records among the analyzed series [101].

The selection of accurate MIT values is crucial to define independent rainstorm event in urban watersheds analysis. First, if MIT is too short, some consecutive rainfall pulses can be erroneously considered as independent events. If it is too long, a single independent event can be erroneously composed by too rainfall pulses that needs to be separated in multiple independent events. Second, since it is aimed at identifying runoff events, MIT should be longer than the response time of the study urban watershed. This time is defined as the sum of the time of concentration of the catchment and the detention time that urban runoff receives from stormwater management sewers. The response time of the study watershed at a rainfall impulse is equal to 30 min. Lastly, alternance of LIDs wet and dry periods needs to be considered. The goal of this part is to test the capacity of every LID combination to reduce runoff when every facility is fully recovered, therefore MIT must also consider the time that every LID process (infiltration, ponding, evapotranspiration, and drainage) needs to be completed. Based on the analysis of the flow hydrograph output of the SWAT model in the baseline scenario, the depletion time of the watershed without LIDs is about 2 h and it was set as the lower MIT value. Then, MIT values of 3, 6 and 12 h were selected for discretizing the long-term precipitation [101]. The extraction of flow events from runoff series of the baseline in the 20 LID scenarios was done by transposing the start date time of each rainstorm event by the response time of the watershed (Figure 2.9). The same flow events can be then extracted from all the scenarios (baseline and LIDs) by applying this approach. Therefore, the comparison of runoff between a given LID scenario and the others (baseline and LIDs) can be done referring to the same chronological flow event. Likewise, the key characteristics of every rainfall event (rainstorm total volume, duration, and mean intensity), that generate a flow event, can be calculated, and associated to the same flow event (Figure 2.10). For every rainfall event, the key characteristics of rainfall pattern were calculated and then associated to the percentage of PFR among every of the twenty LID scenarios and the baseline scenario without LIDs. Here, an approach based on classes of rainstorm event intensities is proposed. Rainstorm event intensities were sorted in ascending order and a PFR percentage was associated to corresponding sorted rainstorm event for every of the twenty LID scenarios. Rainstorm event intensities will be then grouped into different classes. For each class of rainstorm intensity, the following quantities were calculated: (i) mean percentage of PFR from every flow event; (b) mean rainstorm total volume; (c) the PFR percentage normalized for unit of impervious treated area, calculated by fraction of mean PFR percentage and the HRUs area where every LID type is designed.

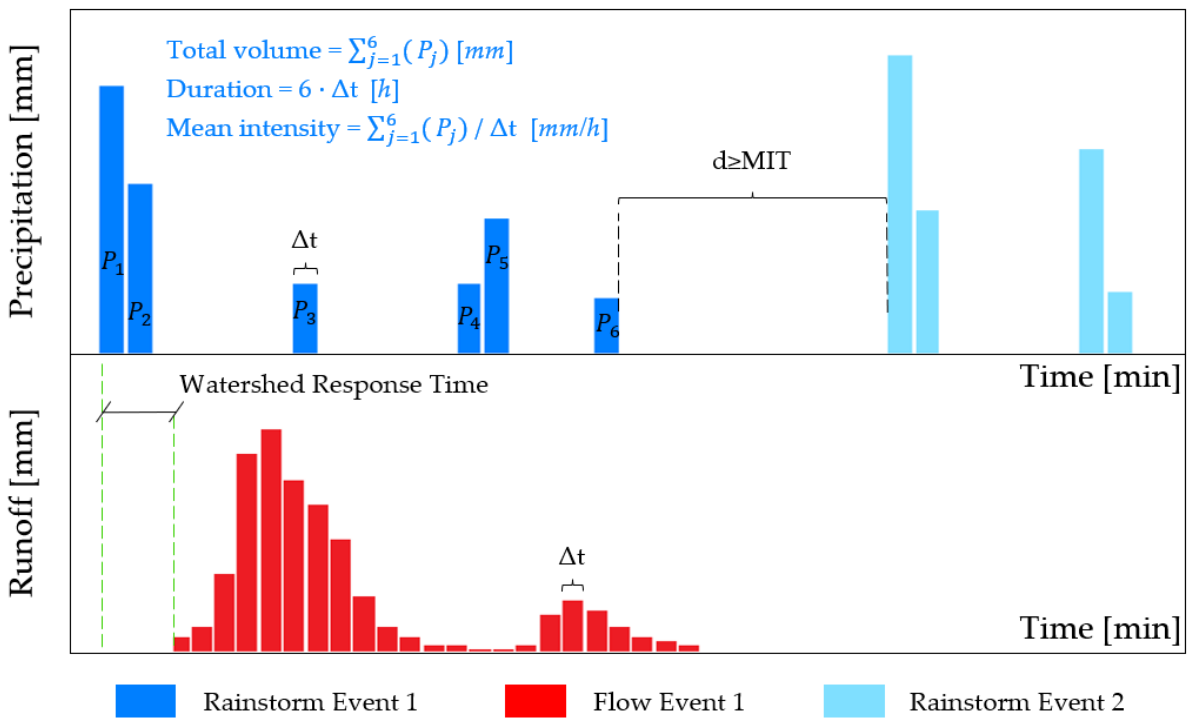

Figure 2.9. Identification of independent rainstorm and flow events in a continuous rainfall and runoff series respectively. The calculation of key characteristics of rainfall, based on single rain impulse *j*, associated with flow event 1 is showed in blue text/fonts.

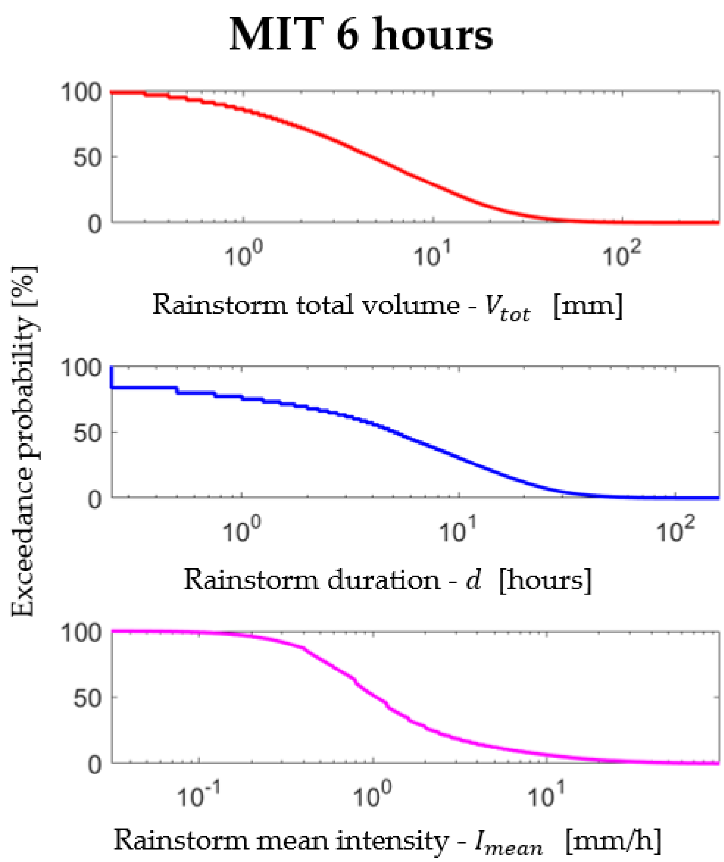

Figure 2.10. Key characteristics of stochastically generated rainfall pattern calculated using a MIT of 6 hours: (a) rainstorm total volume [mm]; (b) duration of the rainstorm event [hours]; (c) rainstorm mean intensity [mm/h].

2.2.4. Annual analysis of Peak Flow Reduction

The percentage of PFR associated to the annual maximum flow, can be calculated for every LID scenario and every of the 500 years of rainfall stochastically generated with RainSim V.3. Then, for every LID scenario among the entire period analyzed, the return period of every annual maximum flow peak can be associated with corresponding PFR percentage. This approach represents another interesting potentiality provided by the proposed stochastic disaggregation methodology, that allow designers to perform long-term hydrological simulations at fine resolution and then to associate sampling return periods to the annual maximum peak flow. This permits also to overcome the use of traditional approaches based on few decades of observed data and statistical inference, i.e., fitting of probability distribution functions like Gumbel or GEV.

3. RESULTS AND DISCUSSION

3.1 Stochastic procedure for temporal disaggregation of daily rainfall data in suds design

Here, the results of RainSim V.3 validation by calculating and comparing key characteristics of rainfall patterns (Sub-Section 3.1.1) are presented. Second, the ability of the stochastic rainfall generator to reproduce rainfall volumetric percentiles commonly used in SuDS design (Sub-Section 3.1.2) is tested. Third, the sensitivity analysis of SuDS rainfall volumetric percentiles is achieved both for observed and simulated series, using different minimum antecedent dry weather periods and storm volume thresholds as variables of the process (Sub-Section 3.1.3).

3.1.1. Key Characteristics of Rainfall Series

The ability of the stochastic model to reproduce observed rainfall series with n-minutes temporal aggregation was analyzed by comparing key characteristics of the precipitation. The results are shown in Figure 3.1, which compares the key characteristics derived from three rainfall sources: (i) observed series with 15 min time-step (red lines); (ii) observed series constructed by aggregating observed 15 min time-step to 24 h aggregation time (magenta lines); (iii) 100 stochastic simulated rainfall series and its median value (light blue and dashed blue lines correspondingly). These series were generated at 15 min time step from the model calibrated with observed series aggregated to 24-h time step. The rainfall characteristics analyzed in Figure 3.1 are: (a) storm total volume [mm], Figure 3.1a; (b) storm event duration [hours], Figure 3.1b; (c) storm mean intensity [mm/h], Figure 3.1c; and (d) storm maximum intensity [mm/h], Figure 3.1d. Since one objective of this section is to demonstrate the ability of RainSim V.3 to produce better key characteristics of sub-daily rainfall than observed rainfall series with daily time-step, a 24 h MIT value was chosen. Indeed, daily data are the most common data available all over the world. It should be noted that MIT and storm volume threshold values used during calculation of independent rainstorm events, also depend on the type of SuDS, according on their geometry, vegetation percentage and treatment purposes [56]. In addition, Table 3.1 presents the total amount of rainfall volume, along the entire series (20 years), that is neglected by selecting different MIT and thresholds. It could be seen that influence of the threshold and MIT selected on the total volume considered for the analysis is negligible.

Table 3.1. Percentage of not considered total cumulated rainfall of observed series with 15 min temporal aggregation, depending on Minimum Inter-event Time (MIT) and storm volume thresholds used during the identification of independent rainstorm events.

Storm Volume Threshold 0.5 mm		**Storm Volume Threshold 1 mm**		**Storm Volume Threshold 2 mm**	
MIT [hours]	**Observed Data 15 min Time-Step**	**MIT [hours]**	**Observed Data 15 min Time-Step**	**MIT [hours]**	**Observed Data 15 min Time-Step**
3	1.52%	3	2.65%	3	6.02%
6	0.93%	6	1.63%	6	3.96%
12	0.58%	12	1.01%	12	2.52%
24	0.33%	24	0.57%	24	1.63%
48	0.17%	48	0.29%	48	0.85%
72	0.11%	72	0.2%	72	0.59%

In this analysis, we assumed 0.5 mm as storm volume threshold value. Furthermore, by applying Restrepo-Posada and Eagleson, 1982 [55] methodology and using a storm volume threshold of 0.5 mm, an MIT equal to 22 h was obtained. This result strengthens the selection of 24 h for the MIT. Table 3.2 shows results of MAE, RSR and PBIAS statistical indices, calculated applying equations 2.1, 2.2 and 2.3, using errors between key characteristics of median simulated data and observed data with 15 min time-step, as well as errors between key characteristics of observed daily data and observed 15 min data. Using a MIT equal to 24 h and a storm volume threshold of 0.5 mm, it can be noticed that the median of simulated data improves the values of every statistical index and every key characteristic of rainfall, compared with observed data with 24 h time-step. Except for storm total volume, where a small decrease of simulated indices is detected, the other simulated MAE and RSR values show a substantial decrease in terms of mean errors. Therefore, the stochastic approach improves the values of key characteristics of rainfall compared with observed ones with 24 h time-step. In addition, to adjust the simulated and observed key characteristics of the rainfall series, we modified the MIT to different intra-day values. It should be noted that, in the professional practice, where only daily rainfall data are available, SuDS design considering MITs smaller than daily time-step is not possible. Thus, the use of a stochastic rainfall generator enables the use and analysis of sub-daily MIT. Moreover, different sub-daily MIT values were explored to analyze if simulated key characteristics became closer to the ones obtained from the observed series. Figure 3.2 shows the key characteristics of the rainfall series by considering MIT equal to 12 h. In addition, in Table 3.2, the three statistical indices were also calculated using a storm volume threshold of 0.5 mm and a MIT equal to 12 h. Results show that this procedure (MIT 12 h, threshold 0.5 mm) improves the values of the statistical indices compared with MIT of 24 h, except for the storm mean intensity.

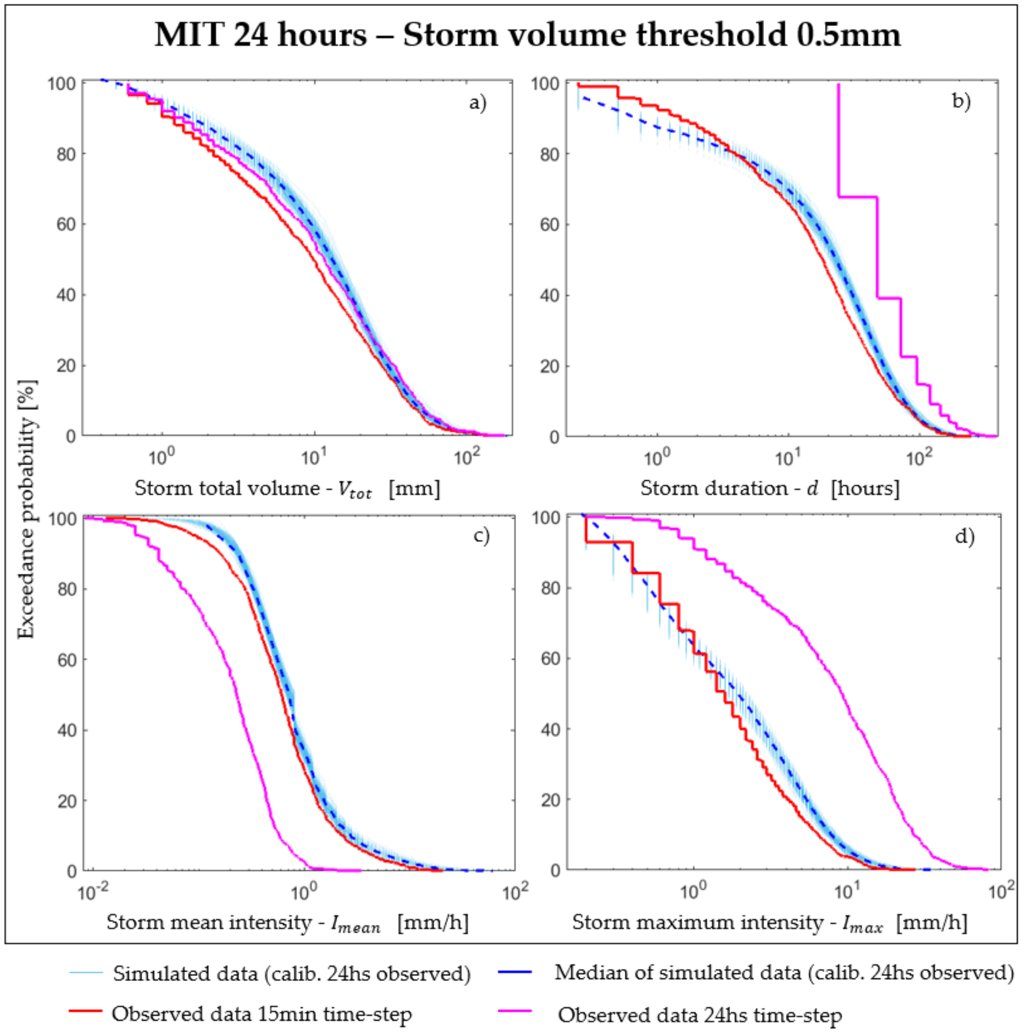

Figure 3.1. Key Characteristics of rainfall pattern calculated using a MIT of 24 h and a storm volume threshold of 0.5 mm: (**a**) storm total volume [mm]; (**b**) duration of the storm event [hours]; (**c**) storm mean intensity [mm/h]; (**d**) storm maximum intensity [mm/h].

Table 3.2. Mean absolute error (MAE), root mean square error-observations standard deviation ratio (RSR) and Percent bias (PBIAS) calculated between key characteristics of observed rainfall with 15 min time-step, observed daily (24 h) rainfall and simulated rainfall with 15 min time-step. MIT are fixed to 24 and 12 h.

	MAE [mm]	RSR [-]	PBIAS [-]
Storm Total Volume			
(MIT 24 h) Observed data 24 h time-step	2.81	0.19	−16.95
(MIT 24 h) Median of simulated data 15 min time-step	2.75	0.16	−15.95
(MIT 12 h) Median of simulated data 15 min time-step	0.44	0.09	−0.57
Storm Duration			
(MIT 24 h) Observed data 24 h time-step	36.28	1.22	−125.64
(MIT 24 h) Median of simulated data 15 min time-step	4.36	0.16	−14.33
(MIT 12 h) Median of simulated data 15 min time-step	1.33	0.15	0.19
Storm Mean Intensity			
(MIT 24 h) Observed data 24 h time-step	0.86	0.96	74.72
(MIT 24 h) Median of simulated data 15 min time-step	0.35	0.59	−30.71
(MIT 12 h) Median of simulated data 15 min time-step	0.85	0.95	−60.26
Storm Maximum Intensity			
(MIT 24 h) Observed data 24 h time-step	9.66	4.12	−361.90
(MIT 24 h) Median of simulated data 15 min time-step	0.67	0.34	−23.67
(MIT 12 h) Median of simulated data 15 min time-step	0.48	0.29	−20.27

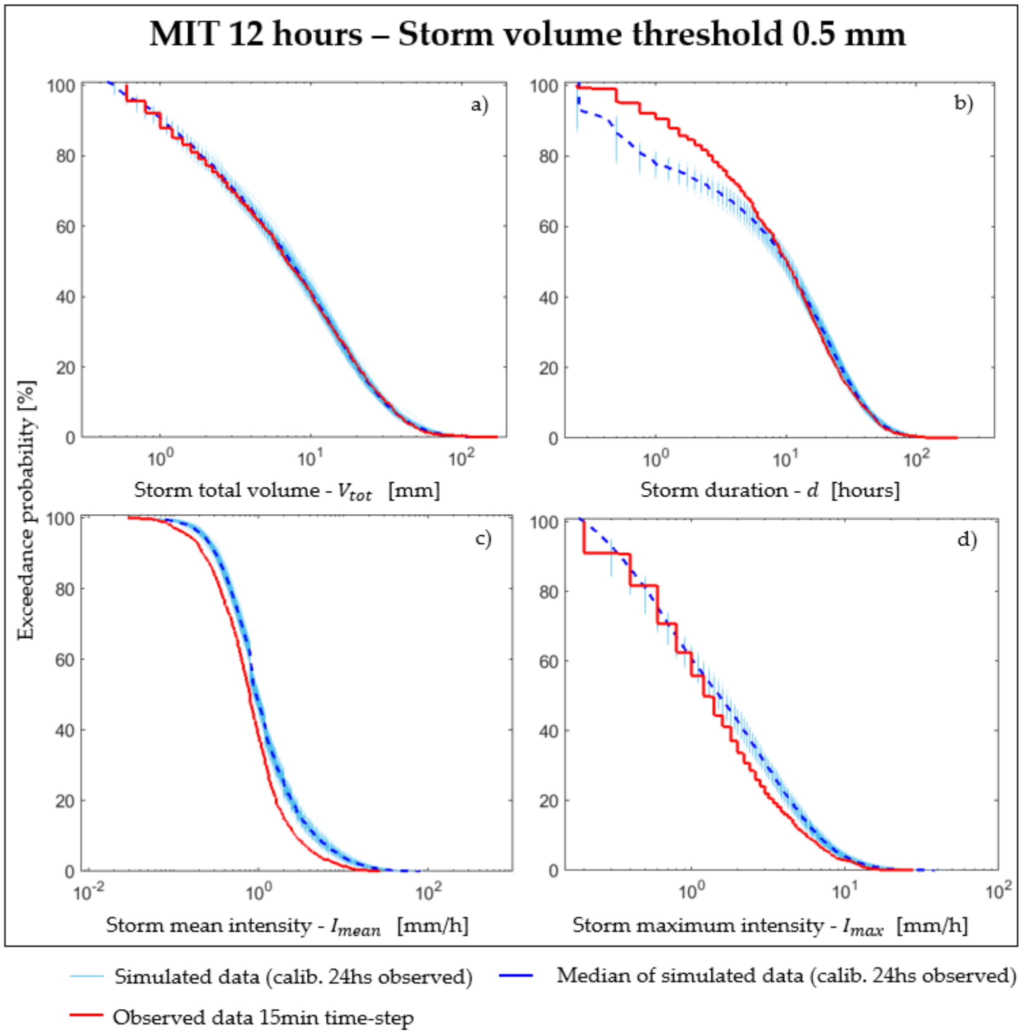

Figure 3.2. Key Characteristics of rainfall pattern calculated using a MIT of 12 h and a storm volume threshold of 0.5 mm: (**a**) storm total volume [mm]; (**b**) duration of the storm event [hours]; (**c**) storm mean intensity [mm/h]; (**d**) storm maximum intensity [mm/h].

We calculated the number of rainstorm events associated with a fixed storm volume threshold of 0.5 mm and different MIT values for simulated and observed series. Results of this procedure are reported in Table 3.3. Simulated series of rainfall in the range of 12 h produced similar number of rainstorm events compared with observed ones using 15 min rainfall time step.

Table 3.3. Number of independent rainstorm events calculated using 0.5 mm fixed Storm Volume Threshold and different MIT values.

Storm Volume Threshold	MIT [hours]					
0.5 mm	**3**	**6**	**12**	**24**	**48**	**72**
Median of simulated data	2690	1904	1242	828	586	486
Observed data 15 min. time-step	2149	1718	1324	1009	724	558
Observed data 24 h time-step	-	-	-	663	633	520

3.1.2. Stochastic Representation of Rainfall Volumetric Percentiles for SuDS Design

Figure 3.3 presents the results in terms of relative frequencies of N_{80}, N_{85}, N_{90} and N_{95} calculated for MIT 24 h and 0.5 mm storm volume threshold. To create histograms of relative frequencies, values of rainfall percentiles were calculated for each of the 100 simulated rainfall series with 15 min time-step and then grouped in 8 statistical bins according with the Sturges' rule [102]. Red and magenta lines represent respectively rainfall percentiles of observed series with time-step 15 min and 24 h. As can be seen, the 25th and the 75th percentiles of the distribution of simulated volumetric percentiles are systematically closer to the volumetric percentiles calculated using observed rainfall series with 15 min time-step than to those using observed values with 24 h time-step. For instance, considering the N80 percentiles of Figure 3.3, the 15-min observed value is 27.9 mm, the 25th and 75th simulated values are 29.4 mm and 31.1 mm respectively (median 30.3 mm), while the observed value with 24 h time-step is 33.6 mm. Moreover, the median values are always greater than values of percentiles of observed series with 15 min time-step, being the hydrological design on the safe side. Therefore, for the Florence rain gauge in the period under analysis, the stochastic rainfall generation of sub-hourly rainfall series by using observed daily rainfall, produce design parameters for SuDS more reliable than using directly observed 24 h data. Similar results and considerations were obtained when calculating the relative frequencies of V_{80}, V_{85}, V_{90} and V_{95} (Figure 3.4).

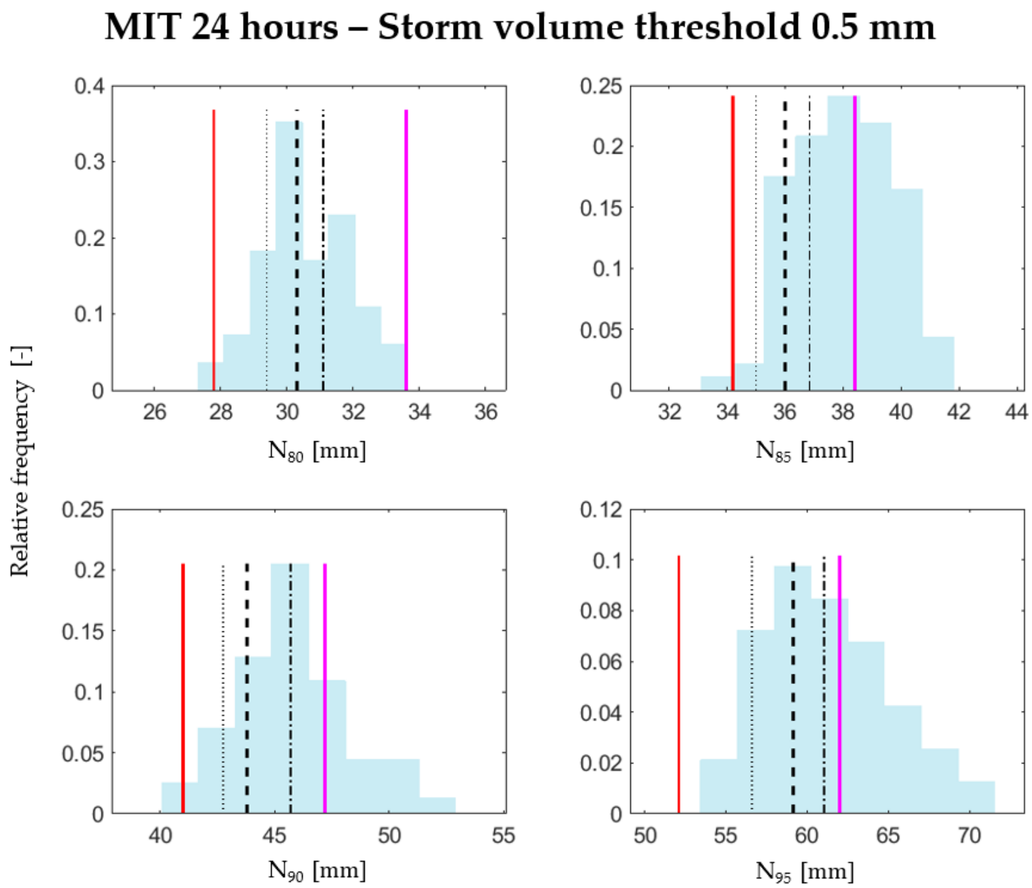

Figure 3.3. Relative frequency of volumetric percentiles that treat a percentage of the total number of rainfall events, for MIT 24 h and storm volume threshold 0.5 mm. Red and magenta lines represent respectively observed rainfall series with time-step 15 min and 24-h. Black dashed, dotted and dash-dotted lines represents respectively the median, 25th and 75th percentiles of simulated data (light cyan histograms).

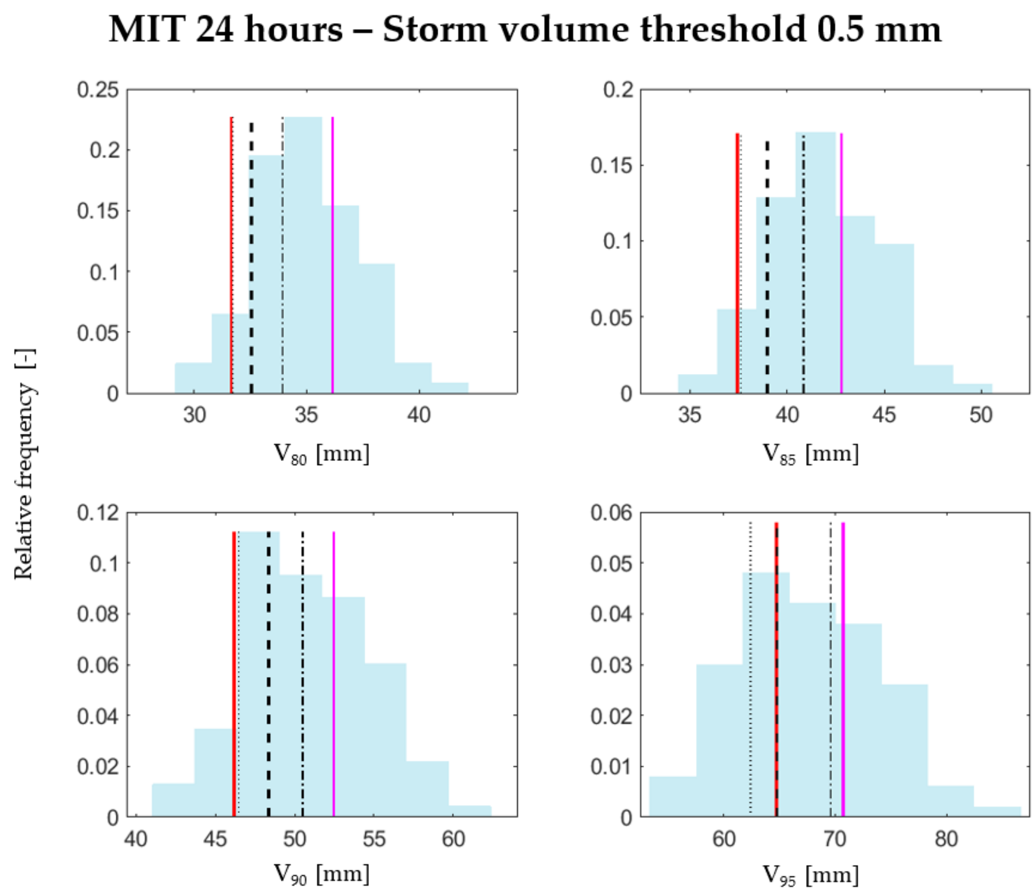

Figure 3.4. Relative frequency of volumetric percentiles that treat a percentage of the total volume of accumulated rainfall series, for MIT 24 h and storm volume threshold 0.5 mm. Red and magenta lines represent respectively observed rainfall series with time-step 15 min and 24-h. Black dashed, dotted and dash-dotted lines represents respectively the median, 25th and 75th percentiles of simulated data (light cyan bars).

3.1.3. Sensitivity Analysis of Hydrologic Design Parameters by Considering Different MIT and Threshold Values

The proposed stochastic disaggregation methodology permits to perform analyses at fine time resolution. Consequently, sub-daily and sub-hourly MIT values can be considered. Therefore, we tested the sensitivity of the calculation of SuDS design parameters based on stochastic rainfall simulation by using different MIT values (assuming a storm volume threshold of 0.5 mm): 3, 6, 12, 24, 48 and 72 h. In addition, we also performed a sensitivity analysis by considering different threshold values (fixing MIT at 24 h): 0.2, 0.5, 1 and 2 mm. To assess the sensitivity of N_x (Figure 3.5) and V_x (Figure 3.6) to MIT and storm threshold values variation, boxplots were presented for simulated rainfall series. Figures 3.5 and 3.6 show the effect of different MIT values on N_x and V_x volumetric percentiles. Both N_x and V_x values are highly sensitive to MIT values. Median values of simulated N_x and V_x percentiles follow a growing trend as the MIT value is increased from 3 to 72 h. The absolute differences among median values of simulated volumetric percentiles when varying MIT from 3 to 72 h are: 42, 49, 59 and 77 mm from N_{80} to N_{95}, respectively; analogously, 37, 43, 53 and 65 mm ranging from V_{80} to V_{95}. Considering volumetric percentiles calculated using observed rainfall series with 15 min time-step, the same differences are 37.5, 41.2, 48.8 and 66.4 mm ranging from N_{80} to N_{95} and 42.1, 51.6, 69.2 and 102.5 from V_{80} to V_{95}. It can be also noted that when MIT varies from 3 to 72 h, simulated median values increase by 81%, 82% and 83% when moving respectively from N_{80} to N_{95}. These results are higher compared with V_x ones, that are respectively 68%, 71% and 72%. For both design parameters, N_x and V_x, larger dispersion is obtained for higher MIT values. In general, this is especially significant for MIT ≥ 24 h. However, this effect is more pronounced for N_x. Regarding these results, N_x provides higher values than V_x and shows higher sensitivity to MIT.

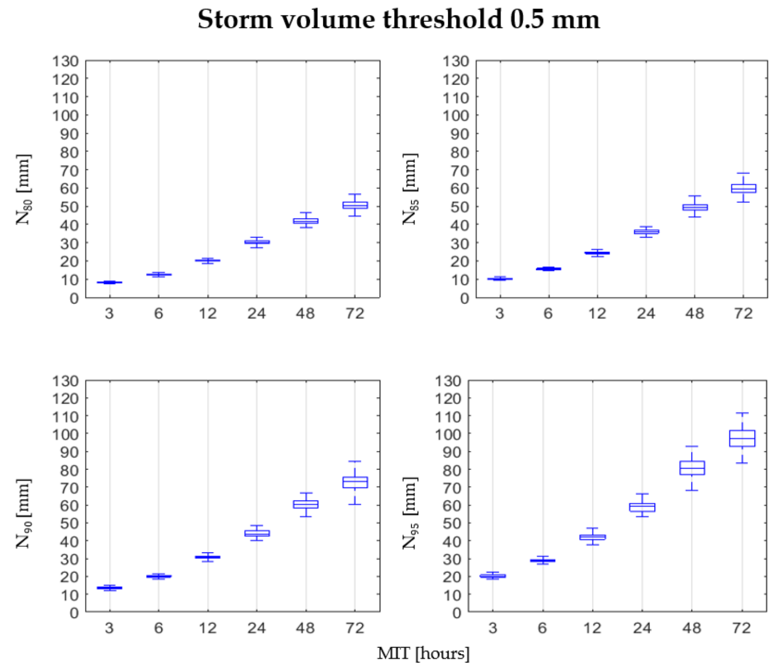

Figure 3.5. Effect of different MITs on values of volumetric percentiles that treat a percentage of the total number of rainfall events, for simulated rainfall series and a fixed 0.5 mm value of storm volume threshold.

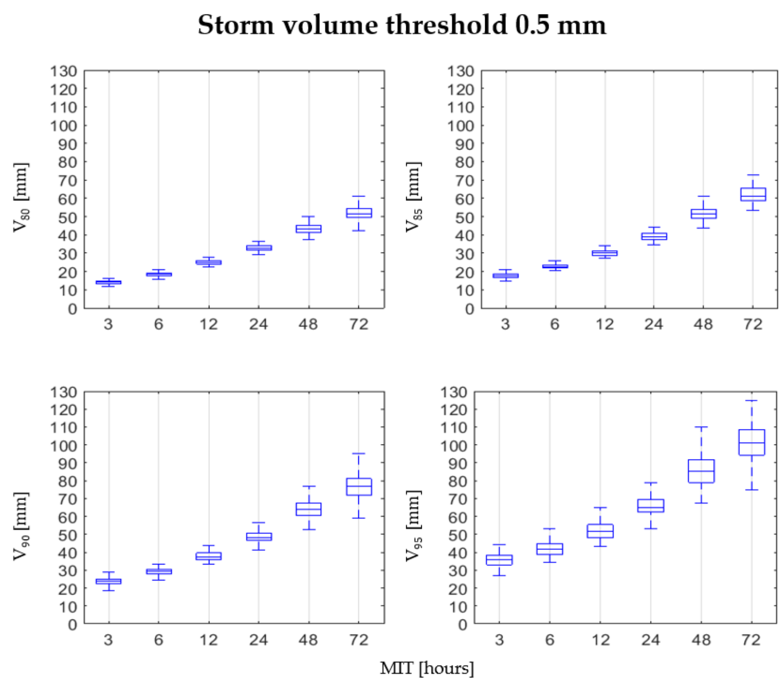

Figure 3.6. Effect of different MITs on volumetric percentiles that treat a percentage of the total volume of accumulated rainfall series, for simulated rainfall series and a fixed 0.5 mm value of storm volume threshold.

The high sensitivity of N_x and V_x to MIT is to be expected, since the required time to consider two events as independent clearly affects the distribution of relevant storm characteristics, like number of storms or storm depth. This indetermination on the proper value for design parameters may be resolved in two ways. First, we could apply objective criteria to establish the proper MIT value based on the statistical independence of sequential storm events, such as the procedure proposed by Restrepo-Posada and Eagleson, 1982 [55]. This would lead to an intrinsic design parameter, independent from the element to be designed. The alternative procedure would be based on the expected performance of the element under design. Under this approach, the MIT value chosen for the computation of the design parameter should be, at least, equal to the time required by the element to recover fully operational capability after the previous storm event. For instance, in elements designed to temporarily store a given volume of water, MIT should be at least equal to the time required to empty the water reservoir. This would lead to an element-specific design parameter and the MIT would be established by functional requirements of such element. In accordance with Sordo Ward et al., 2019 [39] (rainfall series of Retiro rain gauge located in Madrid, Spain), simulated values of N_x percentiles are conditioned by the storm volume threshold considered (Figure 3.7), while V_x percentiles are more stable (Figure 3.8). The median values of simulated N_x percentiles show a growing trend when threshold is altered from 0.2 to 2 mm, while median values of V_x percentiles remain almost constant. As an example, median values of simulated percentile N_{80} are 29.3, 30.3, 31.5 and 32.9, while V_{80} values are 32.5, 32.6, 32.6 and 32.7 mm moving from threshold 0.2 mm to 2 mm. The variations of differences between the highest and the lowest values of simulated N_x percentiles in the boxplots are negligible when storm volume threshold increase. Nevertheless, same differences for simulated V_x remain constant. Therefore, simulated median values of N_x percentiles are less sensitive regarding storm volume thresholds than MITs, while simulated median values of V_x percentiles are very sensitive regarding MITs but not sensitive regarding storm volume thresholds. In the case of storm volume threshold, the proper value for design parameters could be based on climate characteristics. The threshold should be set to a value of rainfall depth that is directly evaporated from vegetation or the soil surface, without entering the drainage facilities. With this criterion, humid climates with low potential evapotranspiration would require lower threshold values than dryer climates with high evapotranspiration.

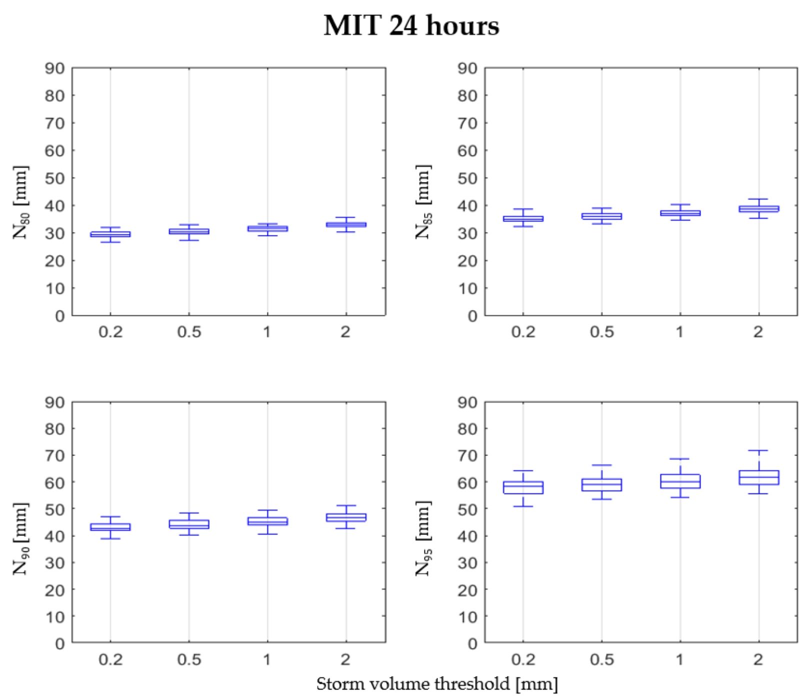

Figure 3.7. Effect of different storm volume thresholds on values of volumetric percentiles that treat a percentage of the total number of rainfall events, for simulated rainfall series and a fixed 24 h MIT value.

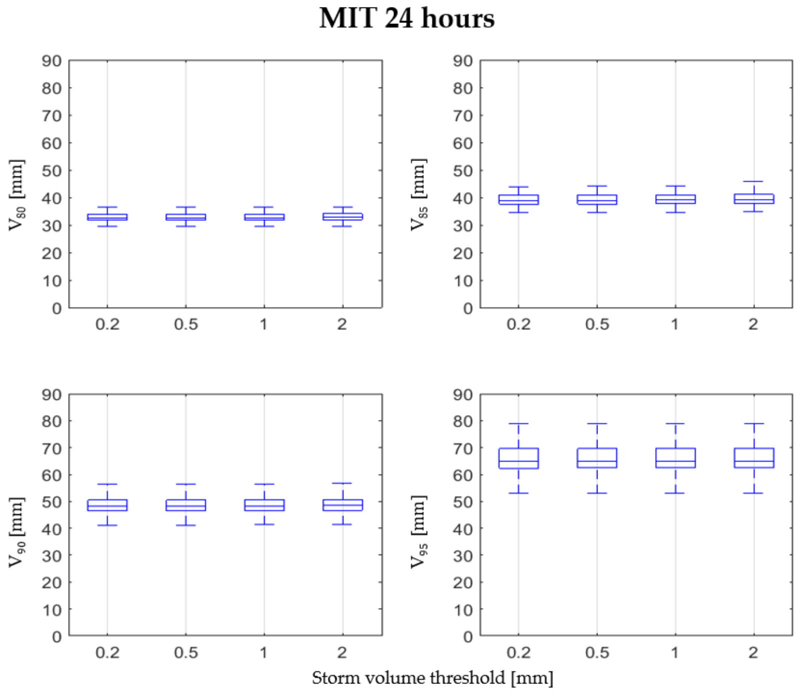

Figure 3.8. Effect of different storm volume thresholds on values of volumetric percentiles that treat a percentage of the total volume of accumulated rainfall series, for simulated rainfall series and a fixed 24 h MIT value.

3.2 Long-Term effects of Low Impact Development of watershed hydrology in an urban system

3.2.1. Peak Flow Reduction by flow and rainstorm events analysis

The potential PFR of every LID scenario was quantified based on flow events and corresponding rainstorm events which were identified from the LID module outputs and stochastic rainfall series, respectively. Figure 3.10 presents the PFR effects depending on different percentages of impervious area treated when LID types and MITs are fixed. It shows only the results for MIT 6 hours. Nevertheless, as can be seen in Figure 3.9, the effects of every MIT (3, 6 and 12 h) on PFR are negligible when percentages of impervious area treated, and LID type are fixed. Results reported in Figure 3.9 concern the rain garden, but results of MIT sensitivity analysis on the other three LID type show the same behavior. The behavior of PFR with respect to the rainstorm event intensities is the same for every percentage of area treated as MIT varies. Therefore, curves representing different MITs are strictly closed together. The graphs in Figure 3.10 were generated by fitting the mean peak reduction percentage and the total rainstorm volume, calculated in each rainstorm intensity class, to a polynomial curve. Every intensity class has a range of 3 mm/h. Figures 3.10a and 3.10b show runoff reduction capability of single GR and RG combination, respectively. It can be noticed that, when green roofs are used without cisterns, the trend of runoff reduction, which depends on rainstorm event intensity, is similar from lower to higher percentages of impervious treated area.

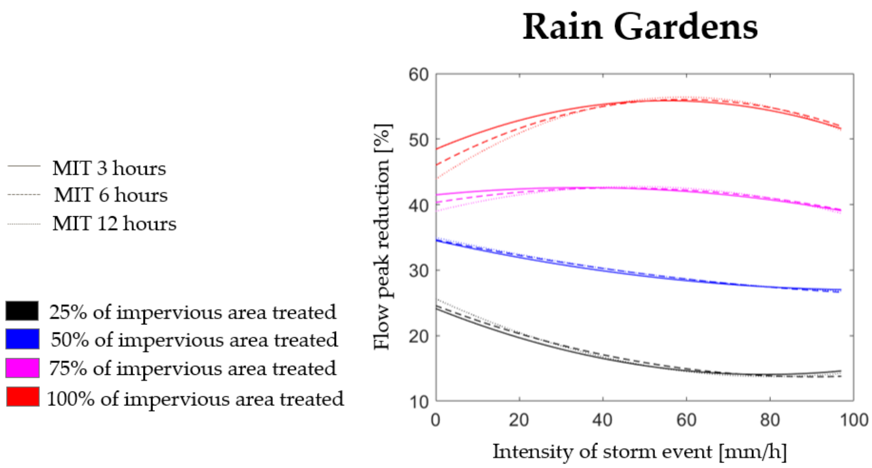

Figure 3.9. MIT sensitivity analysis on rain garden's percentages of flow peak reduction associated with classes of rainstorm event intensities.

This can be explained since every GR unit is built independently to others, and water treatment is governed by slowly infiltration and quickly evapotranspiration caused by the amended soil layers thus they do not interact with hydrological processes of other GRs. In agreement with Guan et al., 2015 [103], GR practices performed better in a monthly rainstorm scenario than a single hourly event, and PFR generally diminished during rainfall events of high magnitude. On the contrary, Figure 3.10b shows that the relation between PFR and rainfall intensity in RG has a different behavior as the percentage of impervious treated area increases. In a single RG unit, storage and treatment of water occurred by: (i) high infiltration rate due to the amended soil layer properties, (ii) surface ponding, (iii) orifice pipe installed in the surface storage. Once the stage of ponding water is higher than that of an orifice installed in the surface storage, the ponding water starts to drain toward the orifice.

Two or more connected RG units can work synergically resulting in more treats rainfall volume and less ponding and flow excess across adjacent areas. Nevertheless, the water excess from adjacent RG units can be treated by the neighboring RGs. Therefore, for smaller to medium percentages of impervious treated area (25% - 50%), isolated RGs are demanded to treat water that directly drops from surrounding impervious areas. Likewise, ponding is counteracted and PFR efficiency increases until a higher rainstorm intensities event occurs. After that, the amended soil layers reach again field capacity and ponding becomes predominant. In this case, water ponding excess and a slow infiltration are frequently observed thus, PFR capability reduces. This behavior is more pronounced as rainstorm event intensities increases; its effect in an impervious treated area is less pronounced in 50% than 25% (Figure 3.10b).

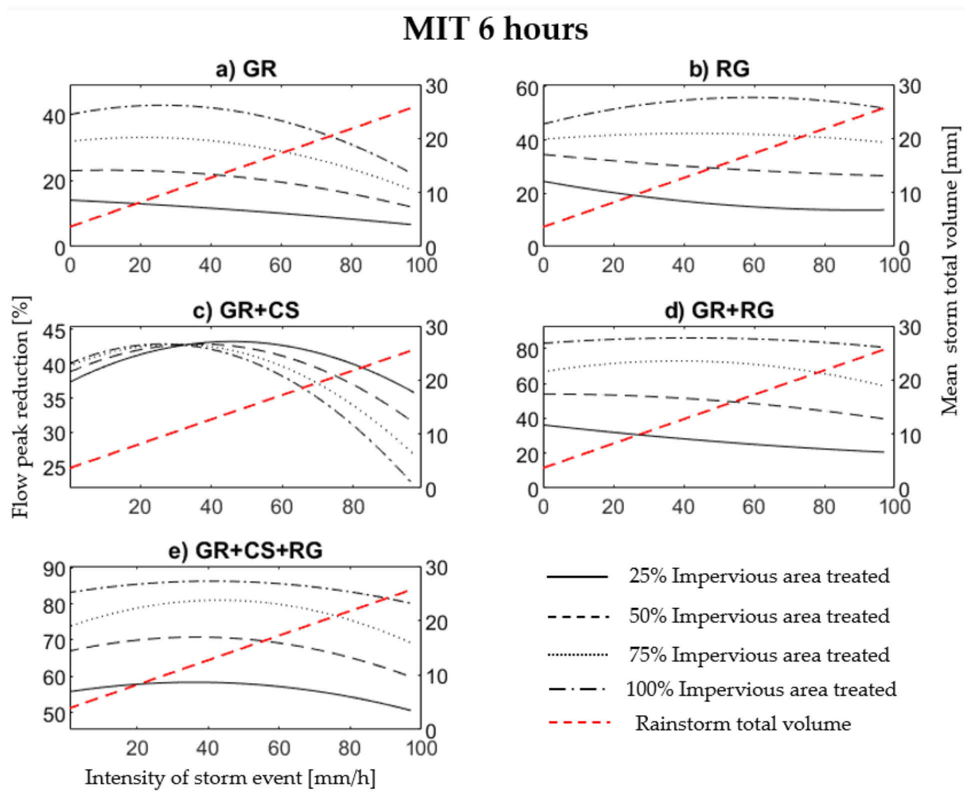

Figure 3.10. Percentages of Flow Peak Reduction associated with classes of rainstorm event intensities calculated with a MIT of 6 hours. The effects of increasing percentages of impervious treated area inside every HRU are shown for the five LID combinations analyzed. The mean rainstorm total volume trend of every intensity of storm event class is also shown.

Otherwise, when percentages of impervious treated areas are higher than 50%, synergy between every RGs and PFR increases with rainstorm intensities.

If a cistern is connected to a green roof, it works retaining water from the building until the maximum storage capacity is reached. As shown in Figure 3.10c, peak flow treatment and storage increase proportionally to the percentages of impervious treated area and moves from smaller to higher rainstorm intensities, until a given rainfall intensity is reached. In the one hand, for smaller rainstorm intensities, the higher the number of cisterns coupled with GRs, the higher storage capacity. For the value of rainfall intensity, the maximum PFR capability is achieved (~44%) which is the same value for every percentage of impervious treated area. On the other hand, for higher rainstorm intensities, the performances reduced. Indeed, the higher the percentage of impervious treated area with GRs and cisterns, the lesser the PFR effect, since cisterns reach the maximum storage capacity, and the water excess increases the bypass and drained water. The performance of single LID types at watershed scale may not be proportional to what it was observed for the single infrastructure, due to hydrological processes on HRUs. Combinations of different LID types increases the reduction of flow peak percentage, and it increases further when LIDs area increases (Figure 3.10d, 3.10e). As can also be noticed in Table 3.4, for high percentages of impervious treated area, the GR+RG and GR+RG+CS configurations produce the same treatment capacity. For smaller percentages of treated area, the effect of CS highly increases the overall capacity of LID combinations from 40.8% to 59.6%. As can be also seen in Table 3.4, the maximum PFR increases since the number of LID types are added in a configuration. Considering the maximum PFR percentage of single LID type combinations, the potential of GR configurations is the worst (15% to 44% and moves from GR-25 scenario to GR-100 scenario). This agrees with Cipolla et al., 2016 [104], that GRs can have an annual average runoff removal rate of 51.9%, whereas it drops from 6.4% to 50% for single rainfall events. On the contrary, RG configurations

Table 3.4. Maximum flow peak reduction percentages associated with rainstorm intensities for every LID scenario analyzed, using MIT 6 hours. Values refer to the mean peak flow reduction of flow events belonging to each rainstorm intensity class.

LID SCENARIO	MAX PEAK FLOW REDUCTION [%]	ASSOCIATED RAINSTORM INTENSITY [mm/h]
GR – 25	15.3	1.5
GR – 50	23.6	19.5
GR – 75	34.2	16.5
GR – 100	44.2	22.5
RG – 25	30.8	1.5
RG – 50	37.9	1.5
RG – 75	43.3	28.5
RG – 100	55.9	37.5
GR+CS – 25	43.3	52
GR+CS – 50	43	47.5
GR+CS – 75	42.7	35.5
GR+CS – 100	42	28.2
GR +RG – 25	40.8	1.5
GR+RG – 50	55.6	1.5
GR+RG – 75	74.4	37.5
GR+RG – 100	87.9	44.5
GR+CS+RG – 25	59.6	28.5
GR+CS+RG – 50	72.2	37.5
GR+CS+RG – 75	82.2	37.5
GR+CS+RG – 100	88.1	64.5

performance almost doubled for smaller percentages of impervious treated area and remains higher than GR as the treated area increases (up to 55%).

In Figure 3.11, a sensitivity analysis of PFR percentages to LID types was showed, again for a MIT of 6 hours and percentages of impervious treated area. A comparison between LID scenarios must be performed to highlights which LID combination provide the best performance. In this case, the comparison was achieved by analyzing the PFR capability for unit of impervious treated area. The results in Figure 3.11 were shown only for one single LID type at time (GR and RG), except for the scenario GR+CS. The runoff reduction of multiple LID combinations (GR+RG, and GR+CS+RG) cannot be compared because single LID types are installed in different land uses and refer to different HRU areas. Indeed, SWAT-LID module allows to assign only one LID type in a single HRU at a time, i.e. in a single land use type. Only GRs and CS can refer to the same land use area but with different design elevations.

Therefore, only the combination of GR, RG, and GR+CS can be considered, and the PFR percentages of every scenario need to be divided over the whole impervious area where the LID combinations install. First, the PFR percentages per unit of HRU area decreases in every graph as the percentage of impervious treated area increases. The maximum PFR is 1.3% for the GR+CS configuration if the 25% of the impervious is treated (Figure 3.11a). The maximum PFR reduces to 0.35% in Figure 3.11d, where the GR+CS combination is introduced on the 100% of the impervious area. The PRF reduces because, as similar rainstorm intensity, the increasing percentages of impervious area within the treated HRU plays a bigger role than increasing the PFR capability. Second, up to 50% of impervious area treated (Figure 3.11a, 3.11b), the GR + CS scenario produces higher PFR effects than RG and GR used alone.

MIT 6 hours

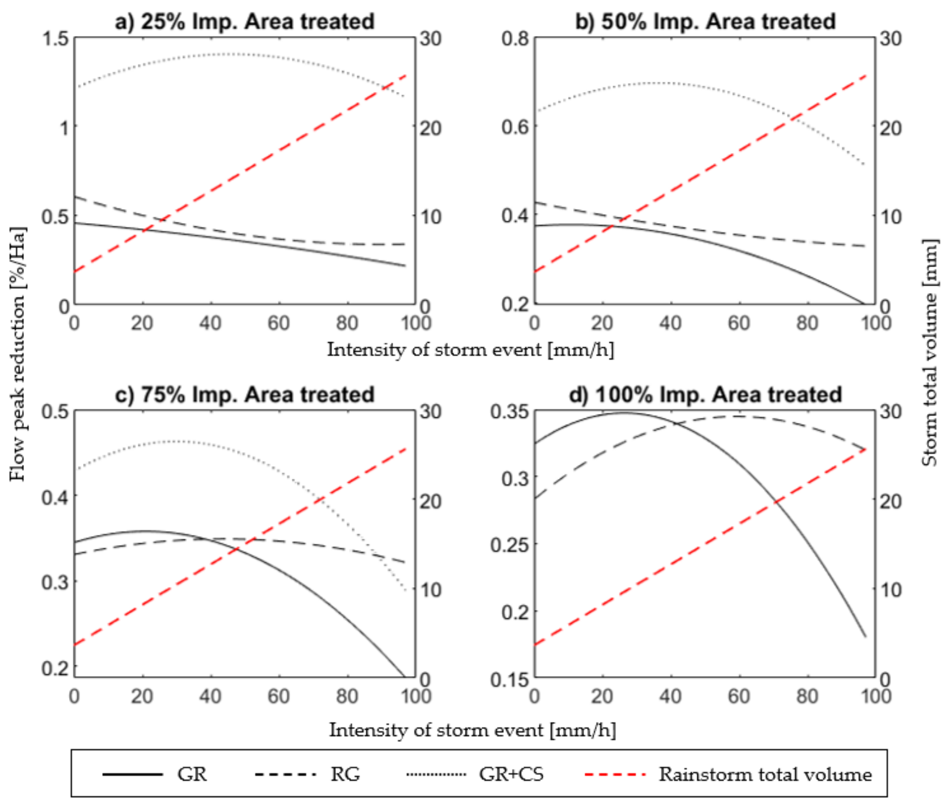

Figure 3.11. Percentages of flow peak reduction for unit of impervious HRU treated area, associated with classes of rainstorm event intensities that were calculated with a MIT of 6 hours. Effects of increasing percentages of impervious treated area within an HRU are shown for the studied LID types. The mean rainstorm total volume trend with respect to the intensity of each storm event is also shown.

Moreover, RG works better than GR for all rainstorm intensities. Third, the treatment gap between every LID combination decreases continuously as the percentage of treated area increases. For percentages of treated area above 50%, the PFRs for unit of treated area are higher in GR than RG for small rainstorm event intensities, and the way around. Again, as cistern storage areas are progressive filling, the GR+CS curve of PFR become closer to the one of a single GR configuration. Likewise, between 75% and 100% or impervious treated area, GR, and GR + CS combinations show similar effect on runoff reduction (Figure 3.11d).

3.2.2. Peak Flow Reduction by return period analysis

This part analyzes the long-term PFR capabilities provided by different LID scenarios, with an approach based on return periods of annual maximum peak flow. Figure 3.12 shows the results from the approach followed in this study by fixing every LID combination and making a sensitivity analysis regarding the percentages of impervious treated area.

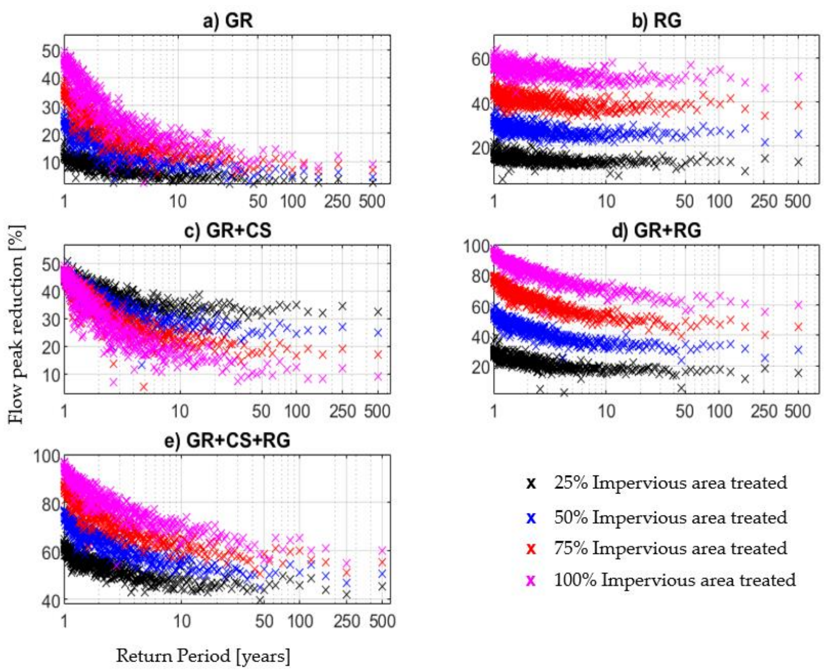

Figure 3.12. Percentage of Flow Peak Reduction associated to the maximum annual runoff with different Return Periods. Effects of increasing percentages of impervious treated area inside every HRU are shown for the five LID combinations.

The results show that in GR the PFR capability decreases as the return periods of runoff increases, i.e., with higher annual maximum peak flows. The runoff treatment capacity increases when the fraction of impervious treated area increases except for the GR+CS configuration (Figure 3.12c), in which the opposite occurs. This can be explained as in Sub-section 3.1 for Figure 3.10c: the hydrological processes in this configuration during runoff treatment, for peak flow associated with higher rainfall intensities like the annual maximum here analyzed, decreases the potential of PFR as the HRU fraction treated increases. On the contrary, the single RG configuration (Figure 3.12b) provides peak flow treatment more stable as the return period increases. Likewise, every LID combination exhibits a PFR plateau for annual maximum peak flows with return periods above 50 years. Table 3.5 presents the mean annual peak flow reduction for 500 years and for every LID scenario. This calculation was performed since hydrological efficiency uses single short-term design storms and does not reproduce the average performances during the long-term analysis. It can be argued that the best PFR capacity, regarding annual maximum peak flows, is provided by the GR+RG and GR+CS+RG configurations. For example, when 100% of impervious area is treated, the PFR of annual maximum peak flows ranges from 98% to 65% as the return period moves from 1 to 500 years, and the mean PFR reduction of annual maximum peak flows is 80%.

Table 3.5. Mean of annual Flow Peak Reduction percentages over the 500-years period analyzed.

LID SCENARIO	MEAN ANNUAL PEAK FLOW REDUCTION [%]
GR – 25	8.4
GR – 50	15.7
GR – 75	22.7
GR – 100	29.7
RG – 25	14
RG – 50	27.4

RG – 75	40.7
RG – 100	54
GR+CS – 25	39.3
GR+CS – 50	36.2
GR+CS – 75	32.9
GR+CS – 100	29.7
GR +RG – 25	22
GR+RG – 50	43
GR+RG – 75	63.4
GR+RG – 100	80
GR+CS+RG – 25	53.5
GR+CS+RG – 50	63.7
GR+CS+RG – 75	73
GR+CS+RG – 100	82

3.2.3. Limitations and future developments

This section used a not-calibrated SWAT model. In the study area, only observed data collected by two sewer gauge stations were available for three pluvial flood events occurred in 2014 but they cannot be used to calibrate the model. Calibration processes would be needed to ensure the suitability of the assumptions and they must be incorporated if available. Nevertheless, since the study focuses on the analysis of runoff differences between different LID scenarios located across the study watershed the baseline scenario can be set as the referring state of every LID combination output and thus, the no-calibration issues can be overcome. In addition, the SWAT model does not need flow calibration to determine relative changes induced by land use modification on the main urban hydrological processes [105,106,107]. Despite these limitations, the proposed methodology may provide a useful tool for hydrological LIDs design. This study bases on a unique stochastic rainfall generator model to simulate sub-daily rainfall records from observed data. Nevertheless, RainSim V.3. is a stationary stochastic model, therefore climate change effects or possible long-term variations of the rainfall were not considered, and they would be included in further studies. In addition, an approach based on multiple not-stationary stochastic rainfall generator may be an interesting future choice since global climate change may affect the urban micro-climate and have implications for designing stormwater and flood control measures for watershed management [108,109]. Therefore, these considerations may limit the generalization of the results and conclusions.

4. CONCLUSIONS

In sub-section 3.1, a temporal disaggregation methodology of daily rainfall records was proposed by using the stochastic spatial-temporal model RainSim V.3. The study provides a methodology to calculate volumetric percentiles N_x and V_x based on definition of independent rainstorm events according to different minimum inter-storm time (MIT) and storm volume threshold values. The ability of the stochastic disaggregation methodology to estimate rainfall volumetric percentiles commonly used in hydrological design of SuDS, was analyzed. The effect of different MIT and storm volume threshold values on simulated rainfall volumetric percentiles was also investigated. The stochastic model was validated based on key characteristics of sub-hourly observed rainfall patterns using three quantitative indices for objective comparison. Despite the obtained results and conclusions are restricted to the selected rain gauge, the study clearly highlights that:

- Using a MIT and a storm volume threshold equal to 24 h and 0.5 mm respectively, simulated sub-hourly rainfall series show better performance than observed daily rainfall for the Florence dataset. Results are compared in terms of key characteristics of rainfall patterns and rainfall volumetric percentiles.
- The stochastic disaggregation model allows the use of sub-hourly MIT values in the process. Therefore, the issue of being able to consider only MIT values equal to 24 h multiples in engineering practice can be overcome. By using a MIT equal to 12 h and a storm volume threshold of 0.5 mm, results in terms of key characteristics of rainfall series and number of rainstorm events, improve comparing with the observed ones obtained with 24 h MIT.
- N_x simulated percentiles are very sensitive to MIT and storm volume threshold values. Consequently, these parameters should be carefully selected to ensure the representativeness of the study. Nevertheless, V_x simulated percentiles show dependence regarding MIT values but not regarding storm volume threshold.

These outcomes can be used in the hydrological design of different types of SuDS facilities that deals with different water treatment purposes.

- The proposed methodology produces a probability distribution of design parameters rather than one single deterministic value. This opens the field for doing probabilistic design (for instance, based on percentiles of the design parameters) and for doing uncertainty analysis (by exploring the sensitivity of the design to different values in the probability distribution of the design parameters).

The study of influence of different climates on results using a considerable amount of rain gauge stations, should be the subject of a specific study. Nevertheless, non-stationarity in stochastic generation of rainfall series, considering effects of global warming and climate change, should be considered for future developments.

In sub-section 3.2, a long-term analysis of LID effects at urban watershed scale was carried out by coupling the stochastic spatial-temporal model RainSim V.3. and the Soil and Water Assessment Tool (SWAT). The study provides a methodology to i) implement several LIDs scenarios by using the SWAT-LID module, changing the type of facilities, and varying the percentage of impervious area retrofitted; ii) analyze the maximum peak flow reduction of every LID scenario both using a flow event and an annual approach over a 500-year hydrological simulation. In the flow event analysis, the peak flow reduction percentages of every LID combination were associated with corresponding rainstorm event intensity classes. The capability of LID scenarios to reduce the annual peak flow was analyzed using a return period approach of annual maximum flow events. The stochastic model used to generate the long-term rainfall data input was validated based on key characteristics of sub-hourly observed rainfall patterns. Independent rainstorm and flow events were extracted according to different minimum inter-storm time (MIT). In addition, a sensitivity analysis of peak flow reduction to different LID types and percentages of impervious area treated was explored. Despite the obtained results and conclusions are restricted to the selected rain gauge and urban watershed area, the study clearly highlights that:

- The stochastic methodology allows to use sub-daily MITs to separate independent rainstorm and flow events. Nevertheless, for every LID type analyzed, the curves of peak flow reduction associated with rainstorm event intensity classes are not sensitive to different sub-daily MIT values when percentages of impervious area treated changes.
- Hydrological benefits of LIDs at watershed-scale can be proportional or not to what observed for single facilities, depending on several synergically physical process that occurs in multiple LIDs joined together. For rainstorm events of small and medium intensity: (i) single LID configurations GR and RG offers lower peak flow reduction capacity compared with combinations of LIDs, and the treatment capacity increase with number of LIDs added; (ii) the configurations GR+RG and GR+RG+CS produce comparable peak flow reduction capacity when higher percentages of impervious area treated are reached. Otherwise, for rainstorm events of higher intensities: (a) the RG scenarios offer better performances compared with GR; (b) performances of the configuration GR+CS drops down; (c) configuration GR+RG and GR+RG+CS produce comparable treatment capacity for higher percentage of area treated.
- The proposed methodology allows also to associate the sampling return period of every annual maximum flow peak event among the entire long series analyzed, with corresponding peak flow reduction percentage. For every LID combination, peak flow reduction percentages decrease moving from lower to higher return periods. Higher percentages of impervious area treated exhibits growing peak flow reduction except for the GR+CS combination.

These outcomes can be used to overcome short-term rainfall data input issue in the hydrological design of different LID types that deals with peak flow reduction. The stochastic methodology proposed can offer then a contribution to the analysis of several LID scenarios hydrological behavior in watershed-scale over hundred years of discontinuous wet and dry periods. Nevertheless, for future development it is necessary to consider non-stationarity in the stochastic generation of sub-hourly rainfall series to take into consideration climate change effect.

To conclude, the results achieved in the first part of the thesis demonstrate that the proposed stochastic temporal disaggregation methodology generates key characteristics of rainfall patterns and rainfall numeric and volumetric percentiles N_x and V_x, statistically closer to the ones calculated with observed sub-hourly rainfall series than using directly daily observed rainfall data. The potentiality of the proposed methodology to use sub-daily MIT (Minimum Inter-event Time) values during the independent rainfall events extraction from rainfall series was also demonstrated and tested by a sensitivity analysis of N_x and V_x to several MIT and storm volume threshold values.

Moreover, in the second part of the thesis the stochastic disaggregation approach achieved during the first part was coupled to the urban hydrological model SWAT to simulate SUDs impact on urban hydrological processes. The thesis quantified the hydrological performance of 20 LID scenarios, composed as combinations of different LID types (green roofs, cisterns, and rain gardens) and percentages of impervious area retrofitted. Moreover, the peak flow reduction of every single flow event, as well as the peak flow reduction of annual maximum flow event extracted from the long-term stochastic analysis, were analyzed for every scenario. A method to quantify them was shown based on statistical analysis of long-term continuous simulations.

Results showed that, during a 500-years long hydrological simulation of various LID scenarios, spatial effects of green infrastructures on peak flow reduction are not directly related to the ones obtained with at site single LID application. This is due to synergies and hydrological connections that occurs between multiple facilities when the percentage of impervious area treated increase. Nevertheless, the correct representation of several dry and wet period during the 500-year long simulation plays of a big role in hydrological connection of increasing retrofitted area.

This works gives a novelty contribution on using a downscaling methodology in SUDs design and investigation of hydrological behavior in long-term analysis.

This thesis has shown that SUDs are useful technologies for controlling urban stormwater and runoff. However careful design is necessary if optimal results are to be achieved and good engineering design is critical when unexpected outcomes such as increased groundwater flooding should be avoided.

REFERENCES

1. Ivanov, D.V. Post-globalization, super-urbanization and prospects of social development. *Res. Result. Sociol. Manag.* **2020**, *6*, 72–79, doi:10.18413/2408-9338-2020-6-1-0-6.
2. Liu, Y.; Engel, B.A.; Flanagan, D.C.; Gitau, M.W.; McMillan, S.K.; Chaubey, I. A review on effectiveness of best management practices in improving hydrology and water quality: Needs and opportunities. *Sci. Total Environ.* **2017**, *601*, 580–593, doi: 10.1016/j.scitotenv.2017.05.212.
3. Bengtsson, L., 2005. Peak flows from thin sedum-moss roof. Nord. Hydrol. 36 (3), 269–280.
4. State of the Nation, 2012. FRI publikation 10/12. Foreningen af Rådgivende Ingeniører, FRI. Sundkrogskaj 20, 2100 København Ø.
5. Larsen, A.N., Gregersen, I.B., Christensen, O.B., Linde, J.J., Mikkelsen, P.S., 2009. Potential future increase in extreme one-hour precipitation events over Europe due to climate change. Water Sci. Technol. 60 (9), 2205–2216.
6. Zhou, Q., Mikkelsen, P.S., Halsnæs, K., Arnbjerg-Nielsen, K., 2012. Framework for economic pluvial flood risk assessment considering climate change effects and adaptation benefits. J. Hydrol., 414–415(0): 539-549.
7. Bornstein, R., Lin, Q., 2000. Urban heat islands and summertime convective thunderstorms in Atlanta: three case studies. Atmospheric Environment 34, 507–526.
8. Morris, B., Lawrence, A., Foster, S. D., 1997. Sustainable groundwater management for fast-growing cities: Mission achievable or mission impossible? Congress on Groundwater in the Urban Environment. Vol. 1. Taylor & Francis, Nottingham, UK.

9. Foster, S., Morris, B., Lawrence, A., 1994. Effects of urbanization on groundwater recharge. In: Wilkonson, W. (Ed.), Groundwater.
10. Lerner, D. N., 1986. Leaking pipes recharge ground water. Ground Water 24 (5), 654–662.
11. Lerner, D. N., 1990. Groundwater Recharge In Urban Areas. Atmospheric Environment Part B-Urban Atmosphere 24 (1), 29–33.
12. Carcia-Fresca, B., 2004. Urban-enhanced groundwater recharge: review and case study of Austin, Texas, USA. Selected papers from the 32nd International Geological Congress (IGC), Florence, Italy, August 2004.
13. Carcia-Fresca, B., Sharp, J. M. J., 2005. Hydrogeological considerations of urban development: Urban-induced recharge. Reviews in Engineering Geology. Vol. 16. Geological Society of America Inc., Boulder, Colorado, USA, pp. 123–136.
14. Zhou, Q. A review of sustainable urban drainage systems considering the climate change and urbanization impacts. *Water* **2014**, *6*, 976–992, doi:10.3390/w6040976.
15. Raymond, C.M.; Frantzeskaki, N.; Kabisch, N.; Berry, P.; Breil, M.; Nita, M.R.; Geneletti, D.; Calfapietra, C. A framework for assessing and implementing the co-benefits of nature-based solutions in urban areas. *Environ. Sci. Policy* **2017**, *77*, 15–24, doi: 10.1016/j.envsci.2017.07.008.
16. Zhang, D.; Gersberg, R.M.; Ng, W.J.; Tan, S.K. Conventional and decentralized urban stormwater management: A comparison through case studies of Singapore and Berlin, Germany. *Urban Water J.* **2017**, *14*, 113–124, doi:10.1080/1573062X.2015.1076488.
17. Li, Jiake, Chenning Deng, Ya Li, Yajiao Li, and Jinxi Song. "Comprehensive Benefit Evaluation System for Low-Impact Development of Urban Stormwater Management Measures." Water Resources Management 31, no. 15 (December 2017): 4745–58. https://doi.org/10.1007/s11269-017-1776-5.

18. Bai, Yiran, Yuhong Li, Ruoyu Zhang, Na Zhao, and Xiaofan Zeng. "Comprehensive Performance Evaluation System Based on Environmental and Economic Benefits for Optimal Allocation of LID Facilities." Water 11, no. 2 (February 18, 2019): 341. https://doi.org/10.3390/w11020341.
19. Rezaei, Abdul Razaq, Zubaidah Ismail, Mohammad Hossein Niksokhan, Muhammad Amin Dayarian, Abu Hanipah Ramli, and Sharif Moniruzzaman Shirazi. "A Quantity–Quality Model to Assess the Effects of Source Control Stormwater Management on Hydrology and Water Quality at the Catchment Scale." Water 11, no. 7 (July 10, 2019): 1415. https://doi.org/10.3390/w11071415.
20. Gong, Yongwei, Xianwei Zhang, Haiyan Li, Xiaoran Zhang, Song He, and Yuhong Miao. "A Comparison of the Growth Status, Rainfall Retention and Purification Effects of Four Green Roof Plant Species." Journal of Environmental Management 278 (January 2021): 111451. https://doi.org/10.1016/j.jenvman.2020.111451.
21. Hoghooghi, Nahal, Heather Golden, Brian Bledsoe, Bradley Barnhart, Allen Brookes, Kevin Djang, Jonathan Halama, Robert McKane, Christopher Nietch, and Paul Pettus. "Cumulative Effects of Low Impact Development on Watershed Hydrology in a Mixed Land-Cover System." Water 10, no. 8 (July 27, 2018): 991. https://doi.org/10.3390/w10080991.
22. Ahiablame, Laurent M., Bernard A. Engel, and Indrajeet Chaubey. "Effectiveness of Low Impact Development Practices in Two Urbanized Watersheds: Retrofitting with Rain Barrel/Cistern and Porous Pavement." Journal of Environmental Management 119 (April 2013): 151–61.
23. Roy-Poirier, Audrey, Pascale Champagne, and Yves Filion. "Review of Bioretention System Research and Design: Past, Present, and Future." Journal of Environmental Engineering 136, no. 9 (September 2010): 878–89. https://doi.org/10.1061/(ASCE)EE.1943-7870.0000227.

24. Ballard Woods, B.; Wilson, B.; Udale-Clarke, H.; Illman, H.; Scott, T.; Ashley, R.; Kellagher, R. *The SUDS Manual*; CIRIA: London, UK, 2015; ISBN 9780860176978.
25. Charlesworth, S.M.; Booth, C.A. *Sustainable Surface Water Management: A Handbook for SUDS*. John Wiley & Sons, Ltd. **2016**, Print ISBN:9781118897706, Online ISBN:9781118897690, doi:10.1002/9781118897690.
26. Charlesworth, S.M.; Harker, E.; Rickard, S. A Review of Sustainable Drainage System (SUDs): A Soft option for Hard Drainage Questions? *JSTOR Geogr. Assoc.* **2015**, *88*, 99–107.
27. Green, A. *Sustainable Drainage Systems (SuDS) in the UK*; Springer: Cham, Switzerland, 2019; ISBN 9783030118181.
28. Sörensen, J.; Persson, A.; Sternudd, C.; Aspegren, H.; Nilsson, J.; Nordström, J.; Jönsson, K.; Mottaghi, M.; Becker, P.; Pilesjö, P.; et al. Re-thinking urban flood management-time for a regime shift. *Water* **2016**, *8*, 1–15, doi:10.3390/w8080332.
29. Morales, J.A.; Cristancho, M.A.; Baquero-Rodríguez, G.A. Trends in the design, construction and operation of green roofs to improve the rainwater quality. *State of the Art. Ingeniería del Agua* **2017**, *21.3*, 179–196, doi:10.4995/ia.2017.6939.
30. Huber, W.C.; Dickinson, R.E. *Storm Water Management Model, Version4 : User's Manual*; EPA/600/3-88/001a; Environmental Protection Agency: Washington, DC, USA, 1992; p. 720.
31. Andersen, S.; Maria, S.; Danielsen, H.J.; Andersen, J.S.; Lerer, S.M.; Danielsen, H.J.; Backhaus, A.; Jensen, M.B. Characteristic Rain Events–A tool to enhance amenity values in SUDS-design. *Aide à la Décision/Decis. Mak.* **2016**, 9, 1–4.
32. Gulliver, J.S.; Anderson, J.L; Asleson, B.C; Baker, L.A; Erickson, A.J.; Hozalski, R.M.; Mohseni, O; Nieber, J.L; Riter, T; Weiss, P; Wilson, B.N; Wilson, M.A. *Assessment of Stormwater Best Management Practices*. Report University of Minnesota, **2008**.

33. Rivard, G. Small Storm Hydrology and BMP Modeling with SWMM5. *J. Water Manag. Modeling* **2010**, R236-10, doi:10.14796/jwmm.r236-10.
34. Pitt, R.E. Small Storm Hydrology and Why it is Important for the Design of Stormwater Control Practices. *J. Water Manag. Modeling* **1999**, R204-04, DOI: 10.14796/JWMM.R204-04.
35. Fratini, C.F.; Geldof, G.D.; Kluck, J.; Mikkelsen, P.S. Three Points Approach (3PA) for urban flood risk management: A tool to support climate change adaptation through transdisciplinarity and multifunctionality. *Urban Water J.* **2012**, *9*, 317–331, doi:10.1080/1573062X.2012.668913.
36. Geldof, D.G.; Kluck, J. The Three Points Approach. In Proceedings of the 11th ICUD–International conference on urban drainage, Edinburgh, UK, 31 August–5 September 2008.
37. Damodaram, C.; Giacomoni, M.H.; Prakash Khedun, C.; Holmes, H.; Ryan, A.; Saour, W.; Zechman, E.M. Simulation of combined best management practices and low impact development for sustainable stormwater management. *J. Am. Water Resour. Assoc.* **2010**, *46*, 907–918, doi:10.1111/j.1752-1688.2010.00462. x.
38. City of Portland. *Stormwater Management Manual;* Portland Bureau of Environmental Services: Portland, OR, USA, 2016.
39. Sordo-ward, A.; Gabriel-martin, I.; Perales-Momparler, S.; Garrote, L. Influencia de la precipitación en el diseño de SUDS. Revista de Obras Públicas: Organo profesional de los ingenieros de caminos. *Canales y Puertos* **2019**, *166*, 28–31.
40. Hirschman, D.J.; Kosco, J. *Managing Stormwater in Your Community a Guide for Building an Effective Post-Construction Program*; No: 833-R-08-001; Environmental Protection Agency, Center for Water-shed Protection; EPA: Washington, DC, USA, 2008.

41. Paquet, E.; Garavaglia, F.; Garçon, R.; Gailhard, J. The SCHADEX method: A semi-continuous rainfall-runoff simulation for extreme flood estimation. *J. Hydrol.* **2013**, *495*, 23–37, doi: 10.1016/j.jhydrol.2013.04.045.
42. Guo, Y. Hydrologic design of urban flood control detention ponds. *J. Hydrol. Eng.* **2001**, *6*, 472–479.
43. Arnbjerg-Nielsen, K.; Willems, P.; Olsson, J.; Beecham, S.; Pathirana, A.; Bülow Gregersen, I.; Madsen, H.; Nguyen, V.T.V. Impacts of climate change on rainfall extremes and urban drainage systems: A review. *Water Sci. Technol.* **2013**, *68*, 16–28, doi:10.2166/wst.2013.251.
44. Brigandì, G.; Aronica, G.T. Generation of sub-hourly rainfall events through a point stochastic rainfall model. *Geosciences* **2019**, *9*, 11–14, doi:10.3390/geosciences9050226.
45. Sordo-Ward, A.; Bianucci, P.; Garrote, L.; Granados, A. The influence of the annual number of storms on the derivation of the flood frequency curve through event-based simulation. *Water* **2016**, *8*, 335, doi:10.3390/w8080335.
46. Ailliot, P. ; Allard, D.; Monbet, V.; Naveau, P.; Ailliot, P.; Allard, D.; Monbet, V.; Naveau, P. Stochastic weather generators: An overview of weather type models Titre: Générateurs stochastiques de condition météorologiques : Une revue des modèles à type de temps. *J. la Société Française Stat.* **2015**, *156*, 101–113.
47. Cowpertwait, P.S.P.; O'Connell, P.E.; Metcalfe, A.V.; Mawdsley, J.A. Stochastic point process modelling of rainfall. I. Single-site fitting and validation. *J. Hydrol.* **1996**, *175*, 17–46, doi:10.1016/S0022-1694(96)80004-7.
48. Rodriguez-Iturbe, I.; Febres De Power, B.; Valdes, J.B. Rectangular pulses point process models for rainfall: Analysis of empirical data. *J. Geophys. Res.* **1987**, *92*, 9645–9656, doi:10.1029/JD092iD08p09645.

49. Burton, A.; Kilsby, C.G.; Fowler, H.J.; Cowpertwait, P.S.P.; O'Connell, P.E. RainSim: A spatial-temporal stochastic rainfall modelling system. Environ. *Model. Softw.* **2008**, *23*, 1356–1369, doi: 10.1016/j.envsoft.2008.04.003.
50. Fowler, H.J.; Kilsby, C.G.; O'Connell, P.E.; Burton, A. A weather-type conditioned multi-site stochastic rainfall model for the generation of scenarios of climatic variability and change. *J. Hydrol.* **2005**, *308*, 50–66, doi: 10.1016/j.jhydrol.2004.10.021.
51. Cowpertwait, P.S.P. A spatial-temporal point process model with a continuous distribution of storm types. *Water Resour. Res.* **2010**, *46*, Issue 12, W12507, doi:10.1029/2010WR009728.
52. Wu, S.J.; Tung, Y.K.; Yang, J.C. Stochastic generation of hourly rainstorm events. *Stoch. Environ. Res. Risk Assess.* **2006**, *21*, 195–212, doi:10.1007/s00477-006-0056-3.
53. Wenzel, H.G.; Voorhees, M.L. *Evaluation of the Urban Design Storm Concept*. Res. Rep. Univ. Illinois Urbana Champaign Water Resour. Cent. **1981**, Report nr.164, Water Resources Center, University of Illinois.
54. Bonta, J.V.; Rao, A.R. Factors affecting the identification of independent storm events. *J. Hydrol.* **1988**, *98*, 275–293, doi:10.1016/0022-1694(88)90018-2.
55. Restrepo-Posada, P.J.; Eagleson, P.S. Identification of independent rainstorms. *J. Hydrol.* **1982**, *55*, 303–319, doi:10.1016/0022-1694(82)90136-6.
56. Shamsudin, S.; Dan'azumi, S.; Aris, A. Effect of storm separation time on rainfall characteristics-a case study of Johor, Malaysia. *Eur. J. Sci. Res.* **2010**, *45*, 162–167.
57. Balistrocchi, M.; Grossi, G. Predicting the impact of climate change on urban drainage systems in northwestern Italy by a copula-based approach. *J. Hydrol. Reg. Stud.* **2020**, *28*, 100670, doi: 10.1016/j.ejrh.2020.100670.
58. Ercolani, Giulia, Enrico Antonio Chiaradia, Claudio Gandolfi, Fabio Castelli, and Daniele Masseroni. "Evaluating Performances of Green Roofs for Stormwater

Runoff Mitigation in a High Flood Risk Urban Catchment." Journal of Hydrology 566 (November 2018): 830–45. https://doi.org/10.1016/j.jhydrol.2018.09.050.

59. Zhang, Shouhong, and Yiping Guo. "Explicit Equation for Estimating Storm-Water Capture Efficiency of Rain Gardens." Journal of Hydrologic Engineering 18, no. 12 (December 2013): 1739–48. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000734.
60. Zubelzu, Sergio, et al. "Design of water reuse storage facilities in Sustainable Urban Drainage Systems from a volumetric water balance perspective." Science of The Total Environment 663 (2019): 133-143.
61. Yang, Wenyu, Kurt Brüggemann, Kiwanuka David Seguya, Ehtesham Ahmed, Thomas Kaeseberg, Heng Dai, Pei Hua, Jin Zhang, and Peter Krebs. "Measuring Performance of Low Impact Development Practices for the Surface Runoff Management." Environmental Science and Ecotechnology 1 (January 2020): 100010. https://doi.org/10.1016/j.ese.2020.100010.
62. Andrés-Doménech, Ignacio, Sara Perales-Momparler, Adrián Morales-Torres, and Ignacio Escuder-Bueno. "Hydrological Performance of Green Roofs at Building and City Scales under Mediterranean Conditions." Sustainability 10, no. 9 (August 31, 2018): 3105. https://doi.org/10.3390/su10093105.
63. Kim, Heenyun, and Gunwoo Kim. "An Effectiveness Study on the Use of Different Types of LID for Water Cycle Recovery in a Small Catchment." Land 10, no. 10 (October 8, 2021): 1055. https://doi.org/10.3390/land10101055.
64. Huang, Yijing, Zhan Tian, Qian Ke, Junguo Liu, Masoud Irannezhad, Dongli Fan, Meifang Hou, and Laixiang Sun. "Nature-based Solutions for Urban Pluvial Flood Risk Management." WIREs Water 7, no. 3 (May 2020). https://doi.org/10.1002/wat2.1421.
65. Catalano de Sousa, Maria Raquel, Franco Andre Montalto, and Patrick Gurian. "Evaluating Green Infrastructure Stormwater Capture Performance under

Extreme Precipitation." Journal of Extreme Events 03, no. 02 (June 2016): 1650006. https://doi.org/10.1142/S2345737616500068.

66. Wadzuk, Bridget M., Conor Lewellyn, Ryan Lee, and Robert G. Traver. "Green Infrastructure Recovery: Analysis of the Influence of Back-to-Back Rainfall Events." Journal of Sustainable Water in the Built Environment 3, no. 1 (February 2017): 04017001. https://doi.org/10.1061/JSWBAY.0000819.
67. Stovin, Virginia, Simon Poë, and Christian Berretta. "A Modelling Study of Long-Term Green Roof Retention Performance." Journal of Environmental Management 131 (December 2013): 206–15. https://doi.org/10.1016/j.jenvman.2013.09.026.
68. Caporali, Enrica, Marco Lompi, Tommaso Pacetti, Valentina Chiarello, and Simone Fatichi. "A Review of Studies on Observed Precipitation Trends in Italy." International Journal of Climatology 41, no. S1 (January 2021). https://doi.org/10.1002/joc.6741.
69. Fatichi, Simone, and Enrica Caporali. "A Comprehensive Analysis of Changes in Precipitation Regime in Tuscany." International Journal of Climatology 29, no. 13 (November 15, 2009): 1883–93. https://doi.org/10.1002/joc.1921.
70. Yang, Wenyu, Kurt Brüggemann, Kiwanuka David Seguya, Ehtesham Ahmed, Thomas Kaeseberg, Heng Dai, Pei Hua, Jin Zhang, and Peter Krebs. "Measuring Performance of Low Impact Development Practices for the Surface Runoff Management." *Environmental Science and Ecotechnology* 1 (January 2020): 100010. https://doi.org/10.1016/j.ese.2020.100010.
71. Pampaloni, Matteo, Alvaro Sordo-Ward, Paola Bianucci, Ivan Gabriel-Martin, Enrica Caporali, and Luis Garrote. "A Stochastic Procedure for Temporal Disaggregation of Daily Rainfall Data in SuDS Design." Water 13, no. 4 (February 4, 2021): 403. https://doi.org/10.3390/w13040403.

72. Andrés-Doménech, I., A. Montanari, and J. B. Marco. “Stochastic Rainfall Analysis for Storm Tank Performance Evaluation.” Hydrology and Earth System Sciences 14, no. 7 (July 9, 2010): 1221–32. https://doi.org/10.5194/hess-14-1221-2010.
73. Burton, A., C.G. Kilsby, H.J. Fowler, P.S.P. Cowpertwait, and P.E. O’Connell. “RainSim: A Spatial–Temporal Stochastic Rainfall Modelling System.” Environmental Modelling & Software 23, no. 12 (December 2008): 1356–69. https://doi.org/10.1016/j.envsoft.2008.04.003.
74. Burton, A.; Fowler, H.J.; Kilsby, C.G.; O’Connell, P.E. A stochastic model for the spatial-temporal simulation of nonhomogeneous rainfall occurrence and amounts. Water Resour. Res. 2010, 46, 1–19, doi:10.1029/2009WR008884
75. Sordo Ward, Álvaro Francisco, et al. "Influencia de la precipitación en el diseño de SUDS." *Revista de Obras Públicas* 3607.3607 (2019): 28-31.
76. Kaykhosravi, Sahereh, Usman Khan, and Amaneh Jadidi. “A Comprehensive Review of Low Impact Development Models for Research, Conceptual, Preliminary and Detailed Design Applications.” Water 10, no. 11 (October 29, 2018): 1541. https://doi.org/10.3390/w10111541.
77. Li, Jiake, Ruisong Zhao, Yajiao Li, and Li Chen. “Modeling the Effects of Parameter Optimization on Three Bioretention Tanks Using the HYDRUS-1D Model.” Journal of Environmental Management 217 (July 2018): 38–46. https://doi.org/10.1016/j.jenvman.2018.03.078.
78. Turco, Michele, Radka Kodešová, Giuseppe Brunetti, Antonín Nikodem, Miroslav Fér, and Patrizia Piro. “Unsaturated Hydraulic Behaviour of a Permeable Pavement: Laboratory Investigation and Numerical Analysis by Using the HYDRUS-2D Model.” Journal of Hydrology 554 (November 2017): 780–91. https://doi.org/10.1016/j.jhydrol.2017.10.005.
79. Massoudieh, Arash, Mahdi Maghrebi, Babak Kamrani, Christopher Nietch, Michael Tryby, Sassan Aflaki, and Srinivas Panguluri. “A Flexible Modeling

Framework for Hydraulic and Water Quality Performance Assessment of Stormwater Green Infrastructure." Environmental Modelling & Software 92 (June 2017): 57–73. https://doi.org/10.1016/j.envsoft.2017.02.013.

80. Uniyal, Bhumika, Madan K. Jha, Arvind Kumar Verma, and Prajna Kasargodu Anebagilu. "Identification of Critical Areas and Evaluation of Best Management Practices Using SWAT for Sustainable Watershed Management." Science of The Total Environment 744 (November 2020): 140737. https://doi.org/10.1016/j.scitotenv.2020.140737.
81. Marhaento, Hero, Martijn J. Booij, T. H. M. Rientjes, and Arjen Y. Hoekstra. "Sensitivity of Streamflow Characteristics to Different Spatial Land-Use Configurations in Tropical Catchment." Journal of Water Resources Planning and Management 145, no. 12 (December 2019): 04019054. https://doi.org/10.1061/(ASCE)WR.1943-5452.0001122.
82. Seo, Mijin, Fouad Jaber, Raghavan Srinivasan, and Jaehak Jeong. "Evaluating the Impact of Low Impact Development (LID) Practices on Water Quantity and Quality under Different Development Designs Using SWAT." Water 9, no. 3 (March 7, 2017): 193. https://doi.org/10.3390/w9030193.
83. Her, Younggu, Jaehak Jeong, Jeffrey Arnold, Leila Gosselink, Roger Glick, and Fouad Jaber. "A New Framework for Modeling Decentralized Low Impact Developments Using Soil and Water Assessment Tool." Environmental Modelling & Software 96 (October 2017): 305–22. https://doi.org/10.1016/j.envsoft.2017.06.005.
84. Shannak, Sa'd. "The Effects of Green Infrastructure on Exceedance of Critical Shear Stress in Blunn Creek Watershed." Applied Water Science 7, no. 6 (October 2017): 2975–86. https://doi.org/10.1007/s13201-017-0606-5.
85. Kuhn, Catherine. "Modeling Rainfall-Runoff Using SWAT in a Small Urban Wetland," n.d., 19.

86. Jeong, Jaehak, Narayanan Kannan, Jeff Arnold, Roger Glick, Leila Gosselink, and Raghavan Srinivasan. "Development and Integration of Sub-Hourly Rainfall–Runoff Modeling Capability Within a Watershed Model." Water Resources Management 24, no. 15 (December 2010): 4505–27. https://doi.org/10.1007/s11269-010-9670-4.

87. Bianucci, P.; Sordo-Ward, Á.; Moralo, J.; Garrote, L. Probabilistic-multiobjective comparison of user-defined operating rules. case study: Hydropower dam in Spain. *Water* **2015**, *7*, 956–974, doi:10.3390/w7030956.

88. Burton, A.; Fowler, H.J.; Kilsby, C.G.; O'Connell, P.E. A stochastic model for the spatial-temporal simulation of nonhomogeneous rainfall occurrence and amounts. *Water Resour. Res*. **2010**, *46*, 1–19, doi:10.1029/2009WR008884.

89. Vrugt, J.A.; Gupta, H.V.; Bouten, W.; Sorooshian, S. A Shuffled Complex Evolution Metropolis algorithm for optimization and uncertainty assessment of hydrologic model parameters. *Water Resour. Res.* **2003**, 39(8), 1201, doi:10.1029/2002WR001642.

90. Dunkerley, D. Identifying individual rain events from pluviograph records: A review with analysis of data from an Australian dryland site. *Hydrol. Process. Int. J.* **2008**, *22*, 5024–5036.

91. Dan, S.; Shamsudin, S.; Aris, A. Modeling the Distribution of Rainfall Intensity using Hourly Data. *Fac. Civil Eng. Inst. Environ. Water Resour. Manag.* **2010**, *6*, 238–243.

92. Walker, S.; Tsubo, M.; Hensley, M. Quantifying risk for water harvesting under semi-arid conditions: Part II. Crop yield simulation. *Agric. Water Manag.* **2005**, *76*, 94–107, doi: 10.1016/j.agwat.2005.01.007.

93. Bacchi, B.; Balistrocchi, M.; Grossi, G. Proposal of a semi-probabilistic approach for storage facility design. *Urban Water J.* **2008**, *5*, 195–208, doi:10.1080/15730620801980723.

94. Voyde, E.; Fassman, E.; Simcock, R. Hydrology of an extensive living roof under sub-tropical climate conditions in Auckland, New Zealand. *J. Hydrol.* **2010**, *394*, 384–395, doi: 10.1016/j.jhydrol.2010.09.013.
95. Legates, D.R.; McCabe, G., Jr. Evaluating the use of "goodness-of-fit" measures in hydrologic and hydroclimatic model validation. *Water Resour. Res.* **2007**, *35*, 1–9.
96. Gupta, H.V.; Sorooshian, S.; Yapo, P.O. Status of automatic calibration for hydrologic models: Comparison with multilevel expert calibration. *J. Hydrol. Eng.* **1999**, *4*, 135–143.
97. Milly, P.C.D.; Betancourt, J.; Falkenmark, M.; Hirsch, R.M.; Kundzewicz, Z.W.; Lettenmaier, D.P.; Stouffer, R.J. Climate change: Stationarity is dead: Whither water management? *Science* **2008**, *319*, 573–574, doi:10.1126/science.1151915.
98. Sutherland, Roger C. "Methodology for estimating the effective impervious area of urban watersheds." *Watershed Protection Techniques* 2.1 (1995): 282-284.
99. Maharjan, Ganga Ram, Youn Shik Park, Nam Won Kim, Dong Seok Shin, Jae Wan Choi, Geun Woo Hyun, Ji-Hong Jeon, Yong Sik Ok, and Kyoung Jae Lim. "Evaluation of SWAT Sub-Daily Runoff Estimation at Small Agricultural Watershed in Korea." Frontiers of Environmental Science & Engineering 7, no. 1 (February 2013): 109–19. https://doi.org/10.1007/s11783-012-0418-7.
100. Woods-Ballard, B., Kellagher, R., Martin, P., Jefferies, C., Bray, R., & Shaffer, P. (2007). *The SUDS manual* (Vol. 697). London: Ciria.
101. Behera, Pradeep K., Yiping Guo, Ramesh S. Teegavarapu, and Travis Branham. "Evaluation of Antecedent Storm Event Characteristics for Different Climatic Regions Based on Interevent Time Definition (IETD)." In World Environmental and Water Resources Congress 2010, 2441–50. Providence, Rhode Island, United States: American Society of Civil Engineers, 2010. https://doi.org/10.1061/41114(371)251.

102. Scott, D.W. Sturges' rule. *Wiley Interdiscip. Rev. Comput. Stat.* **2009**, *1*, 303–306, doi:10.1002/wics.035.

103. Guan, Mingfu, Nora Sillanpää, and Harri Koivusalo. "Assessment of LID Practices for Restoring Pre-Development Runoff Regime in an Urbanized Catchment in Southern Finland." *Water Science and Technology* 71, no. 10 (May 1, 2015): 1485–91. https://doi.org/10.2166/wst.2015.129.

104. Cipolla, Sara Simona, Marco Maglionico, and Irena Stojkov. "A Long-Term Hydrological Modelling of an Extensive Green Roof by Means of SWMM." Ecological Engineering 95 (October 2016): 876–87. https://doi.org/10.1016/j.ecoleng.2016.07.009.

105. Zubelzu, Sergio, et al. "Multi-Objective Approach for Determining Optimal Sustainable Urban Drainage Systems Combination at City Scale. The Case of San Luis Potosí (México)." *Water* 12.3 (2020): 835

106. Niraula, Rewati, Thomas Meixner, and Laura M. Norman. "Determining the importance of model calibration for forecasting absolute/relative changes in streamflow from LULC and climate changes." *Journal of Hydrology* 522 (2015): 439-451.

107. Pacetti, T., Lompi, M., Petri, C., & Caporali, E. (2020). Mining activity impacts on soil erodibility and reservoirs silting: Evaluation of mining decommissioning strategies. *Journal of Hydrology*, *589*, 125107.

108. Ghodsi, Seyed Hamed, Zahra Zahmatkesh, Erfan Goharian, Reza Kerachian, and Zhenduo Zhu. "Optimal Design of Low Impact Development Practices in Response to Climate Change." Journal of Hydrology 580 (January 2020): 124266. https://doi.org/10.1016/j.jhydrol.2019.124266.

109. Pour, Sahar Hadi, Ahmad Khairi Abd Wahab, Shamsuddin Shahid, Md Asaduzzaman, and Ashraf Dewan. "Low Impact Development Techniques to Mitigate the Impacts of Climate-Change-Induced Urban Floods: Current Trends,

Issues and Challenges." Sustainable Cities and Society 62 (November 2020): 102373. https://doi.org/10.1016/j.scs.2020.102373.