Master of Science Program in Civil Engineering

Academic year 2022/2023

Graduation Session December 2023

Hydraulic efficiency of a Sustainable Urban Drainage System in Turin.

Supervisor:

Prof. Fulvio Boano

Candidate:

Lucas Valentín, Ludueña Soulé

Abstract

As urban environments continue to expand to accommodate the increasing global population, there is an ongoing necessity to measure and characterize the effects of urbanization on natural processes. Particularly, the development of impervious surfaces disrupts natural hydrologic cycle as well as affecting the efficiency of drainage systems. Consequently, modifications in slopes, soils, and land cover will result in dramatic alterations in runoff peak, maximum volume involved, flow routes and timing related.

Because of the mentioned changes, there is an increase of possible flooding, pollution, and erosion problems. Therefore, it is of paramount importance to find solutions not only to reduce surface runoff effects, but also to do so at a sustainable level. Hence, Sustainable Urban Drainage Systems (SUDS) rise as a significant alternative to counteract some of the mentioned impacts on the water cycle. The philosophy of these systems relies on slowing down and reducing the quantity of surface water runoff by infiltrating, storing, and conveying water excess.

In the framework of urban drainage issues, the present thesis aims to model the hydraulic response of an urban basin, represented by a half-block street located in Turin, Italy; in order to determine the efficiency of an existing SUDS. To do so, Hydrologic Modeling System (HEC-HMS) software was required to simulate precipitation-runoff process. Throughout the model construction, the mentioned software allows to consider the most significant and influencing factors involved in the surface runoff process such as: elevations and slopes, through the utilization of a Digital Surface Model (DSM), soil characteristics, using specific loss methods considering infiltration rates as well as impervious areas, and including different options for representing the transformation of precipitation into surface runoff.

Once finished the hydraulic modeling, and after choosing appropriate precipitation data according to IFD curves from Turin involved area, a base scenario without the contribution of the SUDS was set as a reference point. Therefore, the desired efficiency was obtained comparing the base scenario with the ones under the influence of the existing SUDS, which were represented considering specific infiltration rates and impervious area.

Acknowledgments

I would like to express my deepest gratitude to any person and institutions who have contributed throughout my educational journey. First, to Universidad Nacional de Córdoba for providing me with the required tools and knowledge for facing professional needs, as well as Politecnico di Torino, whose support and commitment to excellence have significantly contributed for my final academic purposes.

My sincere regards to my academic supervisor, Prof. Engr. Fulvio Boano. who generously provided guidance and expertise from the very beginning of this process. His supervision and invaluable feedback allowed me to overcome multiple obstacles in order to achieve this priceless educational goal.

A special thanks go to my beloved friends: I want to thank each of my friendships that were present in every moment I went through. A very important acknowledgment to my friends from San Luis, who, beyond the distance of all these years of study, who always unconditionally supported me. To the excellent individuals and classmates I had the privilege of getting to know during my university years in Córdoba, who over time became cherished friends, without whom everything would have been much more complicated. Finally, a special mention to the excellent group of persons with whom I had the honor of sharing these beautiful two years of study in Turin, as well as to each of the wonderful individuals I met in these lands from academic and work fields; their contribution to my professional/personal development has left an important, unmatched mark on me for the rest of my life.

Furthermore, to each person who has contributed, directly or indirectly, whether present or not currently in my life, to achieve this invaluable accomplishment.

Finally, to those who always trusted on me and to who I would like to dedicate this project: my family. Without their unwavering love, encouragement, and sacrifices, none of this would have been possible. The values and principles they have provided me have been of a paramount importance to affront every difficult moment and guided me to achieve the end of this long but worthy journey.

Table of contents

List of figures

Figure 5.12: Via Cervino area IDF curves: table values [43].

List of tables

Chapter 1

Urban Drainage issues

The growth of urban areas worldwide has led to significant changes in natural processes, environmental conditions, and the consumption of natural resources. In particular, expansion of urban areas leads to an increase of impervious landscape and of artificial drainage systems, which can facilitate dramatic alterations in volume, flow routes and timing of runoff across various scales, ranging from individual structures to larger developments [1].

In the hydrological cycle, when precipitation occurs on land it follows various pathways. However, urbanization, characterized by impervious surfaces, disrupts the natural distribution of water. As a result, there is less amount of water percolating into the ground, and an associated increase in the volume of surface water as well as a decrease on its quality. For instance, in heavily urbanized regions, more than half of all rainfall transforms into surface runoff, and deep infiltration is only a fraction of what it was naturally [2].

Furthermore, the previously mentioned problematics may have possible effects on hydraulic risk since flooding events, as a result of extreme runoff increment, are frequent and widespread natural hazards. There is a higher hydraulic risk due to an increased hazard, but also due to a bigger exposure and vulnerability. The reason of this last is because there are more people-infrastructure in areas prone to floods. Consequently, resultant damage, whether direct or indirect, can hold significant implications relative to the situation [3].

1.1. Introduction to urban hydrologic issues

In March 2012 the world's population reached the quantity of 7 billion people for the first time, marking a significant event as it means that global population had doubled in less than half a century. Particularly, more than 55% of global population lives in cities, and as the world's population continues to grow up at a considerable rate, the development of urban areas represents a significant threat to natural systems, resource availability, and environmental quality. Consequently, it is of relevance importance being aware about urban hydrologic processes and its alterations [1].

Urban environment significantly influences both meteorological and hydrological processes. The physical structure of buildings can modify how rainfall is transformed into runoff, while the interconnected nature of pervious and impervious surfaces affects the efficiency of surface drainage when it rains. Conversion of undeveloped areas into urban settings leads to significant changes in the landscape. These impacts manifest through changes in topography and surfaces due to new construction, demolition, and redevelopment, occurring at various scales. Human-induced construction will affect the primary processes that generate runoff and crucial flow patterns, profoundly influencing catchment boundaries and drainage routes [1].

Modifications in slope, elevations, soils, and vegetation cover all influence how hydrological systems capture, store, and release rainfall. Conversely, elimination of natural gradients through surface smoothing, such as during road and walkway construction, results in creation of simplified drainage systems designed to swiftly transport water from urban surfaces. Additionally, individual buildings play a role in altering how water is collected, stores, and transferred, with factors like buildings materials, infrastructure (such as drainage systems), and building orientation being significant contributors to these modifications [1].

1.2. Natural hydrologic cycle

The hydrological cycle, also known as water one, describes the journey of water as it starts from how water molecules traverse from Earth's surface to the atmosphere and then they return, occasionally penetrating below the surface. This enormous system is a continuous exchange of moisture between oceans, atmosphere, and the land [4].

Water perpetually undergoes a continuous process of circulation, through and above the Earth in a natural cycle that has persisted for billions of years. As water moves between land, ocean, rivers, and atmosphere, it transforms from solid to liquid to gas. This natural water cycle represents our planet's way of recycling water, which is a crucial process for sustaining life on Earth [5].

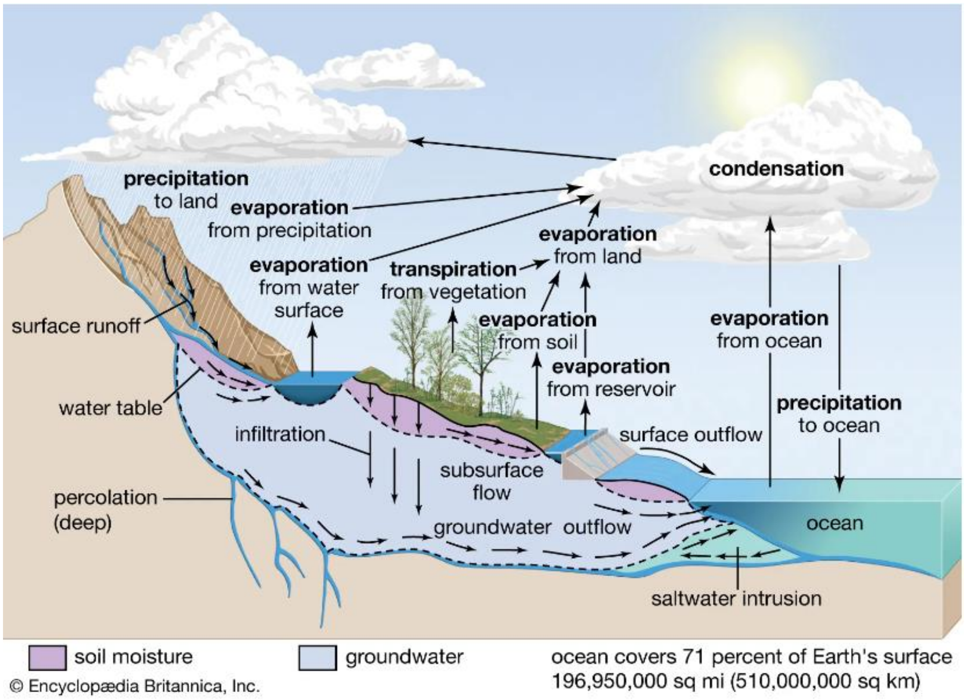


Figure 1.1: Hydrologic cycle [6].

Among many processes involved in the water cycle, the most remarkable ones are evaporation, transpiration, condensation, precipitation, and runoff. While the overall quantity of water in the cycle remains relatively constant, its distribution in the different processes constantly undergoes alterations [6].

Evaporation, one of the major processes in the cycle, entails the movement of water from the Earth's surface to the atmosphere. During evaporation, liquid water transforms into a gaseous or vapor state as individual water molecules gain enough kinetic energy to break free from water's surface. The principal factors which influence this process are temperature, humidity, wind, speed, and solar radiation. Besides having as a primary source of generation the oceans, evaporation also takes place in soils, snow, and ice. [6].

Transpiration represents the evaporation of water through minute pores, in the leaves of plants. For practical purposes, transpiration, and the collective evaporation from various surfaces like water bodies, soils, snow, ice, and vegetation are considered and referred to as evapotranspiration or total evaporation. Water vapor is the main form of atmospheric moisture. While its presence in the atmosphere is relatively modest, it plays a significant role in forming the moisture supply for dew, frost, fog, clouds, and precipitation. Nearly all atmospheric water vapor is concentrated within the troposphere, which constitutes the layer that extends to an altitude of 10 to 13km. [6].

Regarding condensation, is the transition process from the vapour state to the liquid one. It occurs when air holds more water vapor than it can receive from a free water surface through evaporation at the prevailing temperature, as a consequence of either cooling or the mixing of air masses at different temperatures. Through condensation, atmospheric water is released and forms precipitation [6].

As for the rainfall that falls to the Earth, it follows particular pathways: a portion is sent back to the atmosphere through evaporation, other infiltrates into the soil and the rest travels directly as surface runoff towards the sea [6]. Specifically, there are percentages to take into account in order to understand how precipitation is distributed in a natural vegetated terrain [7]:

40% Evapotranspiration.

10% Surface Runoff.

25% Surface Infiltration.

25% Groundwater Infiltration.

In conclusion, hydrological cycle links interactions between atmosphere, lithosphere, biosphere and anthroposphere, and it is significantly influenced by human actions and socioeconomic progress. With recent rapid changes in climate and land use, global water cycle is experiencing substantial levels fluctuations in both space and time, which has given rise to numerous water-related issues that present complex challenges for human water security. Therefore, obtaining a better understanding of hydrological cycle and water resources has emerged as a prominent priority for environmental and natural resources research, as well as having a significant knowledge about how natural water cycle’s intricate components are being influenced in various ways [8].

1.3. Surface runoff and influencing factors

After rain falls, first drops of water are caught by the leaves and stems of vegetation, which is usually referred to as interception storage. While rain continues, water that reaches the earth's surface infiltrates into the soil until it reaches a point where the rainfall rate surpasses the soil's ability to absorb it (known as infiltration capacity). Beyond this point, surface depressions like puddles and ditches start to fill up, a process referred to as depression storage, after which runoff is generated [9].

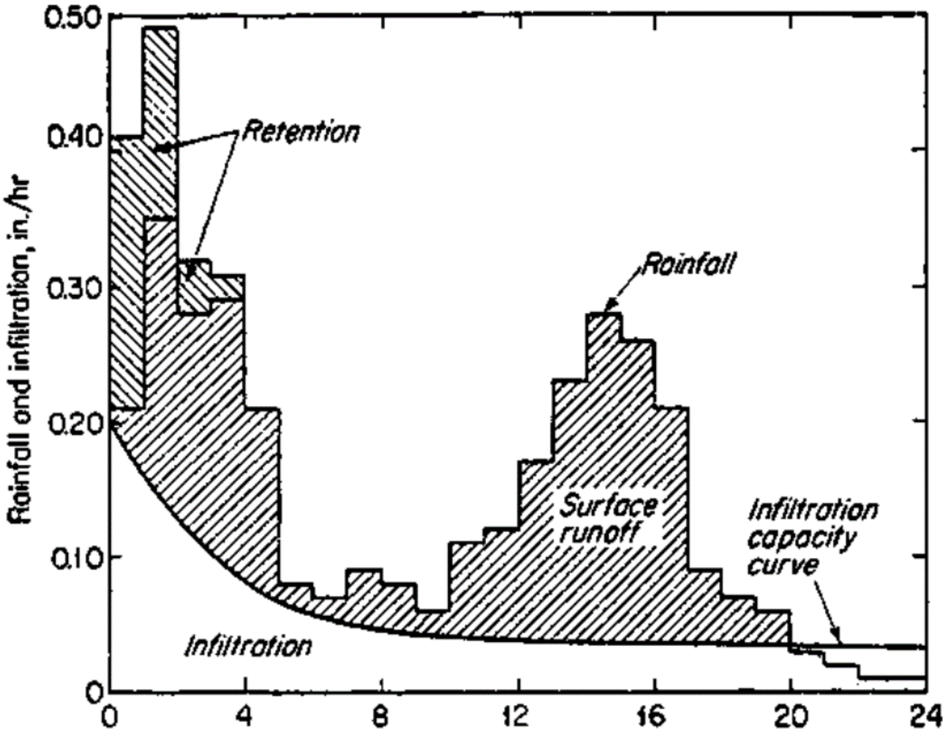


Figure 1.2: Diagram illustrating runoff process [9].

The soil's infiltration capacity depends on its texture, structure, and the previous moisture content (from previous rainfall or dry conditions). Initially, when soil is dry, its capacity is high, but as the storm continues, it decreases until it reaches a steady value termed as final infiltration rate. Runoff process generation continues as long as the rainfall intensity exceeds the actual infiltration capacity of the soil but, it stops when rainfall rate falls below it [9].

This process has been extensively documented in the literature, with numerous papers and computer simulations models developed. Nevertheless, all these require detailed knowledge of a number of factors and initial boundary conditions in a catchment area which in most cases are not readily available. Therefore, for a better understanding of the difficulties of accurately predicting the amount of runoff resulting from a rainfall event, it is essential to explain the main factors influencing rainfall-runoff process [9].

In addition to attributes of rainfall such as intensity, duration and distribution, there is a number of site-specific factors within a given area (or catchment) which have a direct influence on the occurrence and quantity of runoff [9].

I. Soil type.

Infiltration capacity, among other factors, relies on the soil's porosity, which determines its ability to store water as well as influences how water can penetrate deeper layers. It is well known that porosity varies across soil types, the highest infiltration capacities can be observed in loose, sandy soils while heavy clay or loamy soils have considerable smaller infiltration rate. Figure 3 illustrates variations in infiltration capacities observed in different soil types [9].

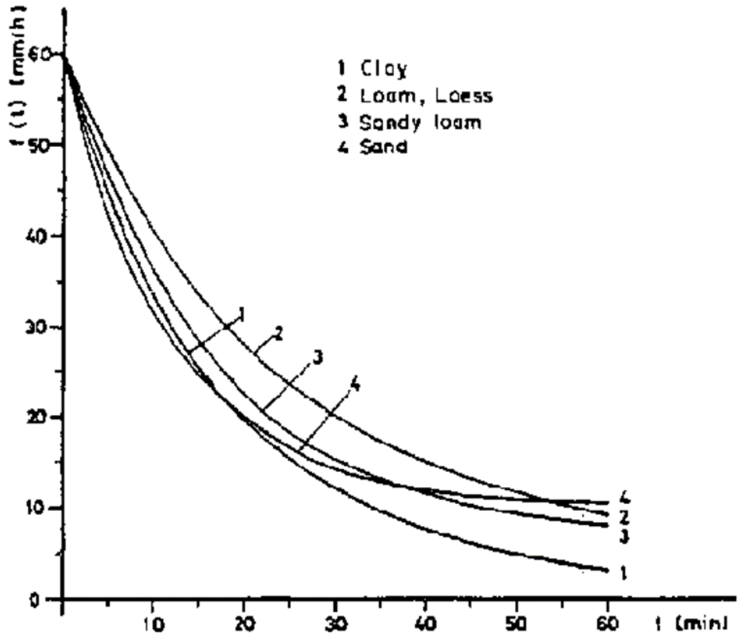


Figure 1.3: Infiltration capacity curves [9].

Additionally, infiltration capacity depends on the moisture content prevailing in a soil when rainstorm begins. Initial high-capacity decreases over time (if rain does not stop) until it reaches a constant value as soil profile becomes fully saturated. However, this condition holds true only when the soil surface remains undisturbed [9].

II. Vegetation.

The quantity of rainfall that is retained in interception storage on the foliage depends on the kind of vegetation and its growth stage, where interception values range between

1 and 4mm. For instance, a cereal crop has a smaller storage capacity than a dense grass cover [9].

In high-intensity storms, raindrops possess significant kinetic energy when they strike the soil surface, which leads to the disintegration of soil aggregates causing fine soil particles to be driven into the upper soil pores. Consequently, these pores become clogged, giving rise to formation a thin yet dense and compacted layer at the surface which diminishes soil's infiltration capacity, this phenomenon is commonly referred to as capping or crusting. A dense vegetation cover acts as a shield, mitigating the impact of raindrops and reducing crusting effect [9].

Furthermore, presence of root system in the soil enhances porosity, facilitating greater water infiltration. As a result, decelerates surface runoff, specifically on gentle slopes, providing water with more time to infiltrate and to evaporate. So, to summarize, an area densely covered with vegetation yields less runoff than bare ground [9].

III. Slope and catchment size.

Investigations on experimental runoff have revealed that steeper slopes produce more runoff compared to their gentler counterparts. In addition, it was observed that runoff volume decreased as the slope length increased. This can be related mainly due to lower flow velocities and subsequently a longer time of concentration. Essentially, water remains exposed to infiltration and evaporation for a longer period before it reaches the measurement point [9].

Runoff efficiency, which is the runoff volume per unit of area, increases as the catchment size decreases, as reported in figure 1.4.

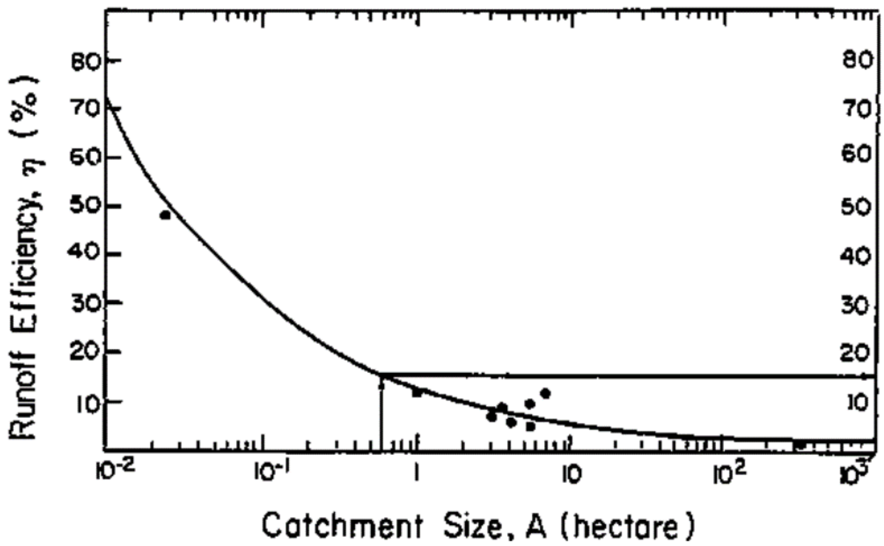


Figure 1.4: Runoff efficiency as function of catchment size [9].

So, as it is observed, larger catchment areas have a longer time of concentration and, consequently, lower runoff efficiency [9].

Besides the site-specific factors previously discussed, it is crucial to recognize that physical conditions within a catchment area are not uniform. In other words, there is a variety of slopes, soil types, vegetation covers, and other factors. As a result, each catchment possesses its unique response to the rainfall events, and so will react differently to varying rainstorm occurrences. The design of water schemes requires the knowledge of the quantity of runoff to be produced by rainstorms in a given catchment area and is commonly assumed that the quantity of runoff is a proportion of the rainfall depth. Here arises the concept of runoff coefficient, which is defined as the quantity of runoff divided by the corresponding rainfall both expressed as depth over catchment area [9].

The runoff coefficient, defined as ratio of peak runoff rate to the mean rate of rainfall, for a duration equal to the catchment time of concentration, attempts to take into account all catchment characteristics that affect runoff. This variable is the most difficult input variable to estimate, representing the interaction of many complex factors including storage of water in surface depressions, infiltrations, antecedents, moisture, ground cover, ground slopes, and soil types [10].

	FLAT	ROLLING	HILLY
Pavement & Roofs	**0.90**	**0.90**	**0.90**
Earth Shoulders	0.50	0.50	0.50
Drives & Walks	0.75	0.80	**0.85**
Gravel Pavement	**0.85**	**0.85**	**0.85**
City Business Areas	0.80	**0.85**	**0.85**
Apartment Dwelling Areas	0.50	0.60	0.70
Light Residential: 1 to 3 units/acre	0.35	0.40	0.45
Normal Residential: 3 to 6 units/acre	0.50	0.55	0.60
Dense Residential: 6 to 15 units/acre	0.70	0.75	0.80
Lawns	0.17	0.22	0.35
Grass Shoulders	0.25	0.25	0.25
Side Slopes, Earth	0.60	0.60	0.60
Side Slopes, Turf	0.30	0.30	0.30
Median Areas, Turf	0.25	0.30	0.30
Cultivated Land, Clay & Loam	0.50	0.55	0.60
Cultivated Land, Sand & Gravel	0.25	0.30	0.35
Industrial Areas, Light	0.50	0.70	0.80
Industrial Areas, Heavy	0.60	0.80	**0.90**
Parks & Cemeteries	0.10	0.15	0.25
Playgrounds	0.20	0.25	0.30
Woodland & Forests	0.10	0.15	0.20
Meadows & Pasture Land	0.25	0.30	0.35
Unimproved Areas	0.10	0.20	0.30

Note:

- ***Impervious surfaces in bold***
- *Rolling = ground slope between 2 percent to 10 percent*
- *Hilly = ground slope greater than 10 percent*

Figure 1.5: Runoff coefficient range of values [10].

In addition, the coefficient may vary with respect to prior wetting and seasonal conditions. As reported above, figure 1.5 lists runoff coefficients for various combinations of ground cover and slope [10].

1.4. Alterations in the surface runoff process due to soil impermeabilization

Urban hydrologic cycle is notably different from that of a nature area. In a natural setting, water balance primarily revolves around processes such as infiltration, subsequent percolation into groundwater, the ensuing flow of groundwater, and transpiration of water from the vegetation. However, urbanization introduces significant alterations to this water balance, leading changes or even the complete elimination of certain components, where in particular the increased impermeability resulting from urban development accelerates surface runoff [11]

Arnold and Gibbons (1996) focused their attention to the consequences of impermeable surfaces that typically accompany urban expansion. They offered a general overview about what happens with different components of the water balance with increasing urban areas on a yearly basic. Paul and Meyer (2001) in their literature review, built upon the previous mentioned worked to provide a comprehensive depiction of the effects of increasing surface impermeability, as depicted in figure 1.6. This illustration highlights that in forested areas, runoff accounts for only 10% of the water output. However, when reaching a fully developed one, with surface imperviousness ranging from 75% to 100%, runoff increases by a factor of 5.5. This surge is primarily attributed to reduced evapotranspiration and infiltration [11].

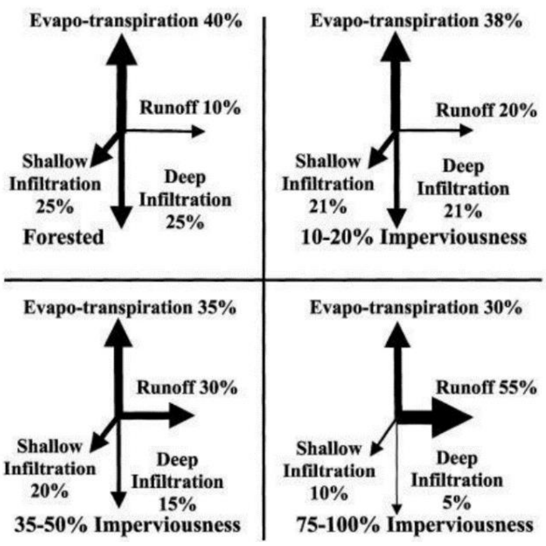


Figure 1.6: Changes in hydrologic flow with increasing impervious surface cover [11].

Niehoff et al. (2002) centred their investigation around three distinct catchments. They conducted simulations to assess the hydrological response to rainfall events under the existing conditions, as well as under various potential future land use scenarios. In all urban areas, they made a clear distinction between densely populated zones and less densely settled regions. After running the model, they observed that different types of rainfall events result in different effects of urbanization on the peak flow (figure 1.7). All rainfall events result in an increase in both flood volume and peak runoff [11].

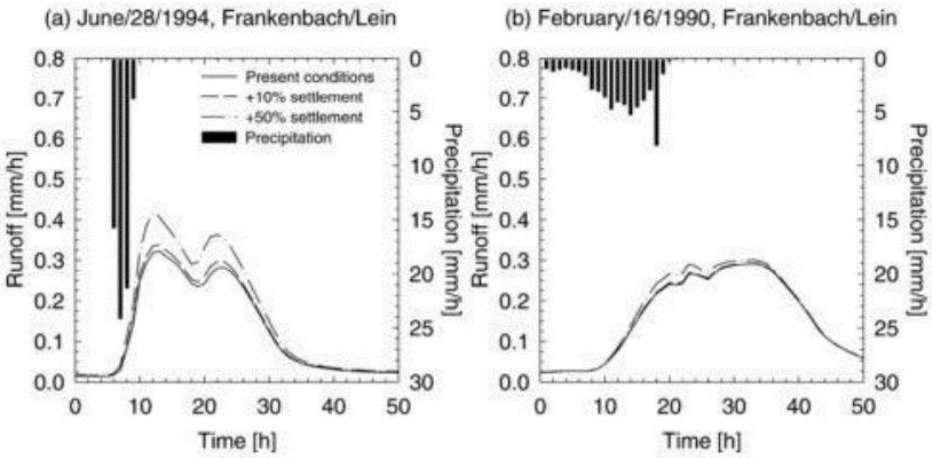


Figure 1.7: Hydrological impact of urbanization of flood events [11].

As reported above, figure illustrates the simulation of two flood events as a response to (a) a convective storm event and (b) an advective storm event under present and scenario conditions [11].

Hundecha and Bárdossy (2004) also modelled a hypothetical scenario involving two distinct land use situations. One scenario entailed doubling the existing proportion of urban land use, while the other was based on the future land use scenario based on the current trend of urbanization. In the scenario with a doubled proportion of urban areas, simulation results clearly indicate an effect on the peak flow, showing an average increase in discharge of approximately 9%. Across all rainfall events, both minimum and maximum discharge levels increased, and the average time it takes for the peak flow to occur decreased. Nevertheless, peak flow increase is higher during summer than during winter, according to the researchers this is because the summer potential evapotranspiration is slightly higher in agricultural areas than in urban ones, so if the urban share of catchment increases, the runoff will increase as well. Furthermore, storm events generally follow period of dry soil conditions, creating more potential for infiltration, particularly at the onset of a storm event. Therefore, as urban area expands, loss of infiltration capacity dure to surface sealing becomes increasingly significant [11].

Bendient and colleagues (2012) illustrate an urban hydrologic cycle, drawing upon insights from prior research. In this cycle, some surface runoff still occurs in the natural environment, but man-made drainage systems are becoming an important form of discharge as well. As the city continues to expand, is possible that natural surface runoff might even disappear, and man-made drainage systems will become the only form of water transport out of the city (subterranean sewer networks or surface-level channels). In contrast to natural streams and rivers, these man-made inventions typically follow straight trajectories. Moreover, resistance offered by concrete channels is typically lower than those in natural watercourses. These factors will shorten runoff time and increase the peak flow downstream as shown in figure 1.8 [11].

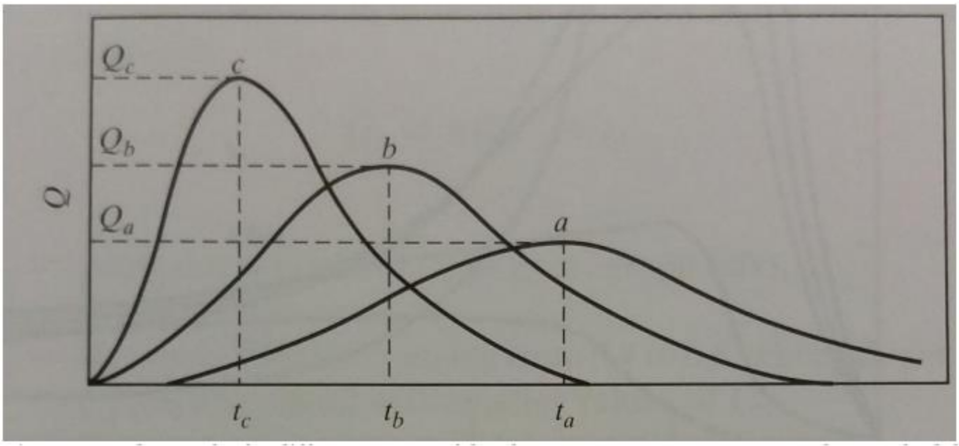


Figure 1.8: Hydrographs for different stages of development [11].

When reporting hydrographs for different stages of development, situation “a” represents a natural watershed, “b” is partially developed, and “c” is fully developed watershed. In a natural system, hydrograph displays a substantial delay before reaching its peak discharge, and the volume of water at the peak moment is relatively modes. Conversely, within a fully developed urban drainage system, conditions are reversed. The time leading up to the peak is brief, and the volume of water during the peak is notably higher compared to a natural setting [11].

1.5. Effects on urban drainage systems

The urban drainage system influences and is influenced by city expansion process. As previously explained, the rise of urbanization has resulted in a higher prevalence of impermeable surfaces like roads, parking lots, and rooftops, along with a decrease in wooded areas and other open spaces that would otherwise absorb rainwater. Consequently, this change in the water balance has brough about notable alterations in the quantity and quality of runoff [12].

As watersheds are urbanized, natural vegetation is largely replaced by impermeable surfaces, diminishing the available areas for groundwater infiltration. Consequently, there is an increase in stormwater runoff, which must be collected by extensive drainage systems that combine curbs, storm sewers, and ditches to carry stormwater directly to streams. In other words, much more water arrives to stream at a much faster rate, higher probability of more frequent and severe flooding [13].

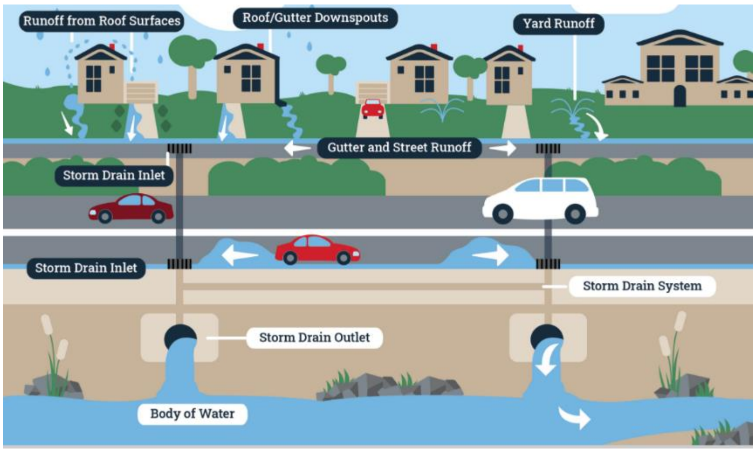


Figure 1.9: Stormwater runoff scheme [14]

Urban flooding occurs when the inflow of storm water exceeds the capacity of a drainage system to infiltrate water into the soil or to carry it away. Cities development disrupts the natural drainage patterns of the landscape, where flow gradually accumulates through small hollows and channels into local streams, is replaced by a graded landscape where streets carry surface water flow and become an important part of the drainage network. Storm sewer inlets collect water from the street system and transport it through underground pipes to release points downstream. Moreover, a combination of transmission systems, including channels, streets, and pipes, moves precipitation from within the city to larger streams or the coast. Floodwaters accumulating in larger streams can overwhelm the capacity of the stream channel and inundate surrounding aeras, particularly in downstream areas that receive floodwaters from developed regions in the upstream part of watershed. Additionally, coastal cities are vulnerable to storm surges caused by strong winds, which can lead to direct flood damage and hinder the drainage of inland flooding. Even in the absence of significant wave surges or rainfall, coastal waters can encroach on urban landscape at high tide. Older cities with combined sewer systems, which handle both stormwater and wastewater, may experience smaller but chronic floods. These systems can become overloaded during storms, resulting in sewer backups in homes and in the discharge of untreated wastewater into streams [15].

Figure 1.10: Example of drainage system flooding [16].

According to what was previously explained, to avoid urban flooding dangers, it is essential to have efficient drainage systems for collecting and conveying rainwater. Nevertheless, because of rapid urbanization and alterations in the levels of rainfall intensity, linked to climate change, have the potential impacts to overburden drainage networks. This strain might result in flooding, substantial harm to infrastructure, disturbance of economic and social services, and increased risk of human safety. [17]

Stormwater drainage systems, initially designed based on existing urban development and historical rainfall patterns, are generally failing due to impacts of urbanization and climate change. As mentioned before, urban hydrological cycle is undergoing significant disruption since natural land covers are being transformed into impermeable surfaces, which contributes to the worsening of severity and risk of flooding. Furthermore, the growing population in unplanned urban areas exacerbates these adverse effects, including urban flooding, erosion and deteriorating water quality. Consequently, expansion urban areas, effects of climate change, and inadequate drainage systems designed without considering future conditions collectively impact on runoff and flooding volumes.

Similarly, these elements have led to reduced infiltration rated, amplified runoff and a surge in flooding incidents in various cities [17].

Figure 1.11: Flash flooding case in the United Kingdom [18].

It is of a paramount importance recognizing the impacts of urbanization process on hydrological processes, taking into accounts aspects such as peak runoff, flooding volume, and drainage system efficiency. In particular, the assessment of land use and land cover serves as an indicator of the interaction between humans and their environment. Moreover, a comprehensive understanding of the varying climatic conditions, achieved by integrating urban settlement areas, is essential to manage daily, seasonal, yearly, and regional water balance [17].

Analyzing flooding issues, it is well-known its potential in causing destruction of residences, disruption of transportation, and financial ruin for businesses. It can overload sewers and contaminate flood water, spreading diseases. Just a six-inch depth of fast-flowing water can knock a person over, while two feet can carry away a car. Furthermore, emergency services could be overstretched [18].

Flood consequences can affect people basic needs such as food, shelter, medication, and money. Therefore, individuals' homes and communities may be affected by this flooding event, causing the requirement of support. So, millions of people are at risk of this possible tragic event, and even worse, according to recent research majority of population is not prepared for facing these issues [18].

Figure 1.12: Urban area flooding risk [19].

Considering the mentioned several problematics, as well as the magnitude of the possible effects, it is vital to understand that no city, town, or village is immune to flooding event, and it is necessary to take hard action in order to prevent undesired impacts [18].

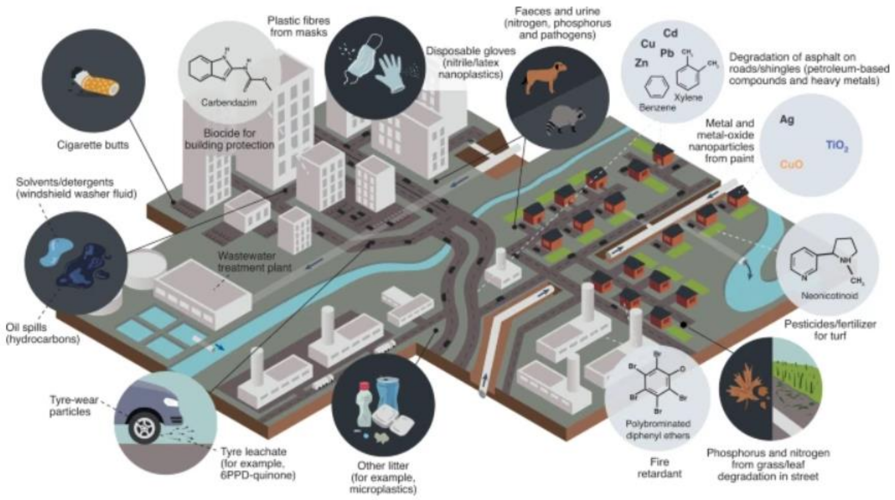
1.6. Pollutants and watercourse quality

Globally, cities serve as the epicenters for anthropogenic environmental inputs. Specifically, urban runoff represents a major route for pollution to contaminate aquatic ecosystems. In particular, as it flows over the land surface, stormwater collects possible pollutants as it moves across the land surface, among which we can find metals from rooftops and roads, bacteria from animal and human waste, nutrients from lawn fertilizers, sediment, pesticides from lawn and garden chemical, and petroleum by products from leaking cars. So, as urban areas expand, characterized mainly by impermeable surfaces like asphalt and concrete, so does urban runoff which directly influences on the equality and capacity of surface water [25].

Several millions of tons of non-treated and hazardous contaminants constitute commonly the so-called urban runoff. Among its components it is possible to mention plastic waste, hydrocarbons, detergents, solvents, pathogens, pesticides, heavy metals, and engineered nanomaterials. As a result, urban runoff is composed by a high quantity of human-made pollutants, some of which can affect aquatic organisms, while others may threat ecosystems and people through their consumption[25].

It is important to remark that the mixture found in urban runoff which is released to natural waters encompasses more than just the traditional water quality parameters usually examined, which could be suspended solids, metals, phosphorus and nitrogen. Many other contaminants are discharged into natural waters through urban stormwater runoff and stormwater sewer systems on a daily basis, with some of these substances posing an immediate threat to aquatic organisms, as previously said [25].

Fig. 1: Mapping global anthropogenic pressures from conventional and emerging contaminants.



Audrey Desaulniers (Orceine).

Figure 1.13: Mapping global anthropogenic pressures from conventional and emerging contaminants [25].

Numerous additional human-made pollutants find their way into natural water bodies following heavy rain or precipitation events, with most of these substances often going unnoticed. To take as an example of this last, it is possible to mention salts and de-icing chemicals case applied in winter, or solvents and detergents. Furthermore, the significant presence of urban-adapted and domestic animals, among which we can find birds, skunks, squirrels, cats, etc. may contribute to the release of pathogens, organic phosphorus, and nitrogen into natural waters [25].

Significantly, there is a lack of systematic measurement of concentrations of these pollutants and its toxic effects, which are potentially underestimated. So, it is of paramount importance to acquire a more comprehensive understanding of contaminant levels so as to evaluate risk to aquatic ecosystems but also to determine sites where mitigation strategies are needed. Indeed, to correctly address the complexity of hydrology including effects of rainfall intensity and local topography on flooding, it is crucial to increase the prevalence of urban runoff storage and treatment processes. In particular, this is very important for densely populated cities where natural landscape is insufficient to naturally manage, absorb, and purify stormwater. So, new and strategically geolocalized infiltrated areas, collection systems and treatment processes with a certain flexibility for expansion can collaborate in mitigating both flooding and influx contaminants. Moreover, it is imperative to develop large-scales, sustainable solutions, for storing and passively treating urban runoff, as it will be appropriately discussed in chapter 2 [25].

1.7.Groundwater recharge modifications

A mere 1.2% of Earth's fresh water is surface one, and two-third exits of this resource is locked away in glaciers and ice caps, with groundwater accounting for the remaining 30%. So, groundwaters accounts for the world's most important reserve to available fresh water, and so managing this resource in a sustainable way is critical for water resource management. For instance, given the abundance of groundwater compared to surface one, farmers and ranchers often heavily depend on this resource to sustain their operations [26].

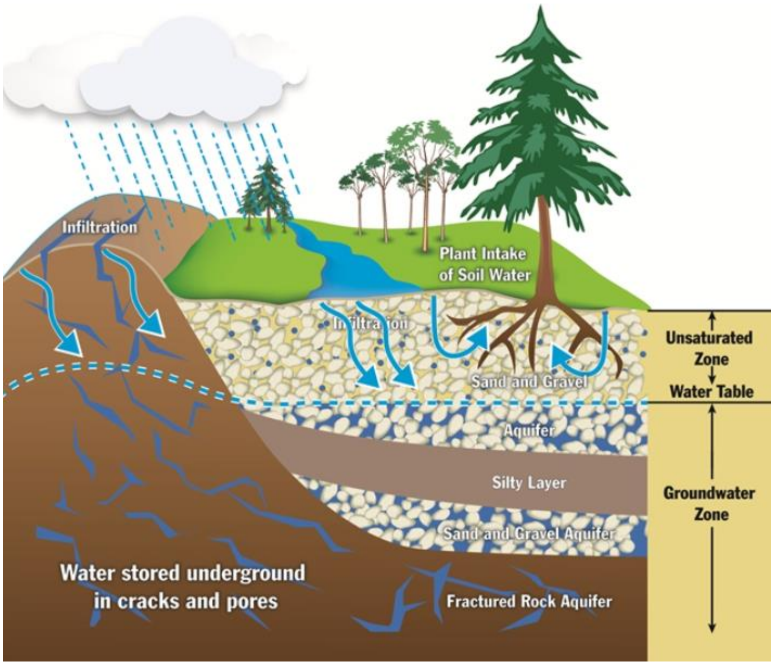


Figure 1.14: Natural groundwater recharge scheme.

So as explained, majority of Earth's liquid freshwater is stored underground in aquifers rather tan in lakes and rivers. Aquifers also serve as the primary source of base flow for rivers when there is a lack of rainfall. This natural process of water infiltration plays an important role in terms of economic and social health of urban population of the developing world. In particular, cities need to supply water in various combinations to meet the diverse needs of private, public, industrial, and commercial users. Nevertheless, urbanization process consistently leads to changes in both quality and quantity of local aquifer systems. So, given the alteration in the hydrological cycle cause by the development of impermeable surfaces, it is essential to investigate impact of urban development on local water resources [28].

Urbanization typically results in four immediate consequences for the hydrological cycle: increased flooding (often due to greater soil sealing), water scarcity stemming from higher consumption rates, alterations in river and groundwater patterns, and increased water pollution. Urban areas are sources of both nonpoint and point contaminants. Point sources that impact groundwater quality include issues like leaks from underground storage facilities and occasional accidental releases of organic or inorganic substances. The rapid expansion of urban areas has two primary effects on groundwater resources. First, it disrupts the natural recharge of aquifers due to extensive ground sealing with concrete. Second, it contaminates groundwater through the seepage from drainage systems, industrial waste, and effluents. As a consequence, the management of water in an urban aquifer is a complex process to consider due to the introduction additional sources of groundwater recharge, and the widespread establishment of new extraction points within the urbanized region [28].

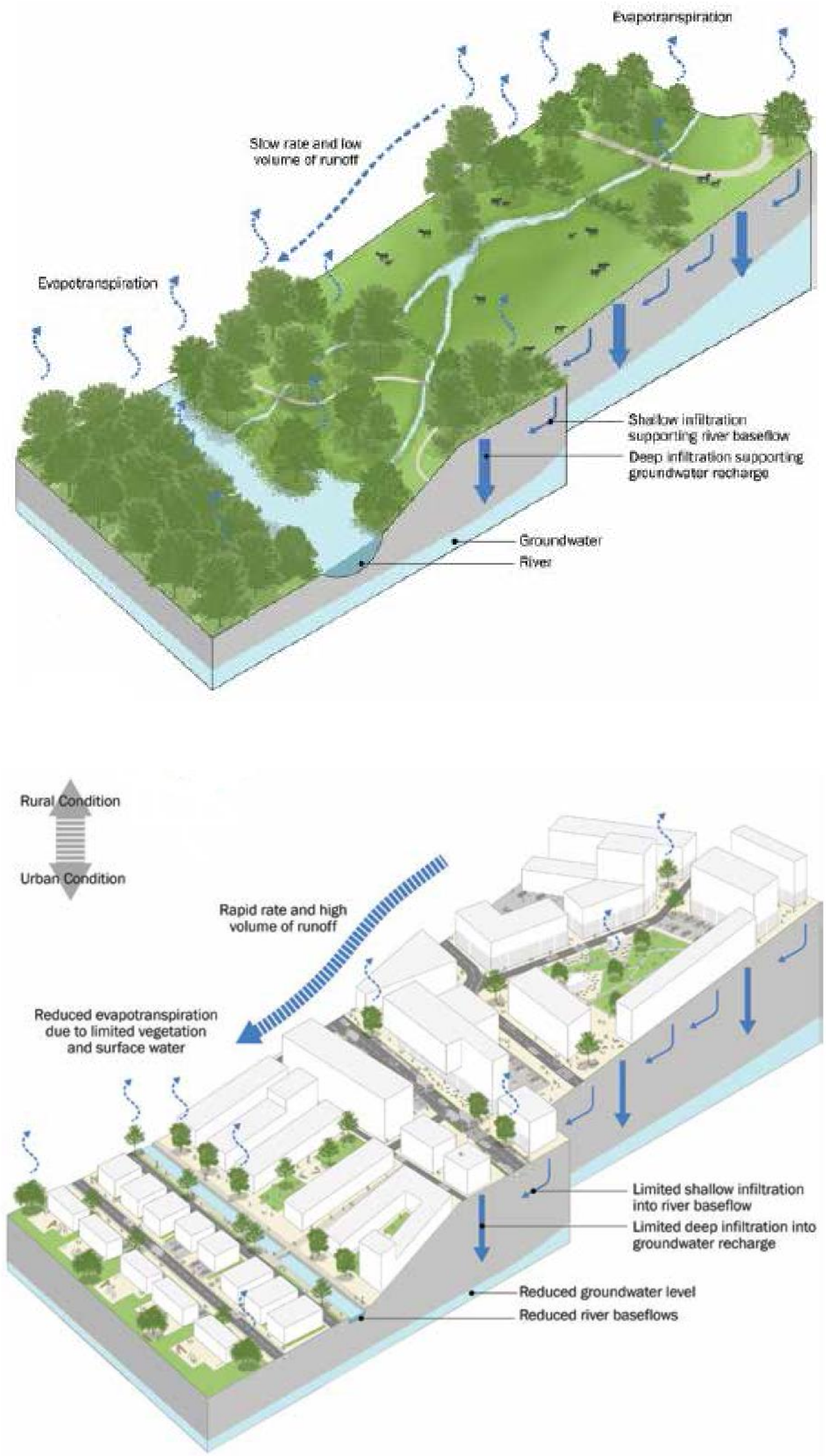


Figure 1.15: Impacts of urbanization on a catchment [20].

Chapter 2

Sustainable Urban Drainage Systems

Due to the urbanization-induced rise in runoff leading to potential water excess problems, it becomes imperative to seek remedies for mitigating the previously explained drainage issues. Multiple research studies have been undertaken to explore potential strategies for addressing this issue to assess the impacts of integrated urban water cycle management. Moreover, considering aspects related to sustainable development goals, the focus should be extended beyond merely reducing stormwater runoff, but also encompassing low impact structures to face these problems, more sustainable water utilization in cities and the reduction of contamination. This holistic approach is essential for curbing downstream bank erosion, flooding, and ecosystem degradation [11].

According to this new perspective, the reduction of stormwater runoff can be achieved through the establishment of hydrological balance. In this way, there are several practices to take into account such as bolstering natural processes like infiltration and evapotranspiration, or even the reuse of rainwater. It is important to highlight that this sustainable strategy, also referred to as Low Impact Development (LID), strives to replicate the predevelopment hydrology of an area. For instance, this emulation can be obtained using techniques such as clustering buildings and implementing features like grassed swales, rain gardens, and pervious pavements. By doing so, these techniques collectively reduce the overall impervious footprint, helps to decentralize water treatment, and enhance water infiltration into the soil [11].

2.1. Importance of managing surface water runoff

As previously said, in a natural setting precipitation falls on land and infiltrates into the soil. It then evaporates into the atmosphere, gets absorbed by vegetation through evapotranspiration, and eventually some of it runs into streams and rivers. Nevertheless, these fundamental stages of water cycle can face disruptions when land is altered by urban development. Inside these areas, there is less vegetation available for evapotranspiration and less permeable ground for infiltration required process. Because of this, a much greater amount of precipitation that falls on impermeable surfaces is converted into surface water runoff, which raises previously explained issues [20].

Studies suggest that these problems will get worse if we do not modify our urban planning and implement more effective strategies for managing surface water runoff. Indeed, climate change forecasts suggest a higher probability of more frequent occurrences of intense rainfall and flooding. As a result, persisting in the expansion of sewer capacity to manage these growing risks is economically unsustainable [20].

Figure 2.1: Problems related to the increase of impermeable land [20].

In the framework of stormwater management, Sustainable Urban Drainage Systems (SuDS) are intended to optimize the advantages and opportunities within the context of stormwater management. Specifically, these systems can lead to four main categories of benefits:

- Water Quantity: to support the management of flood risk and maintain and protect the natural water cycle.
- Water Quality: to manage the quality of the runoff to prevent pollution.
- Amenity: to create and sustain better places for people.
- Biodiversity: to create and sustain better places for nature [20].

2.2. General aspects related to SuDS

Both above and below ground, SuDS can take on a variety of configurations. Among the possible solutions, it is possible to find natural features like planting, and others include proprietary/manufactured products. Typically, these systems are often made to manage and use rainfall close to where it falls, often incorporating surface vegetation which tend to provide greatest benefits [20].

Some illustrations of SuDS might encompass systems for collecting rainwater, such as rainwater harvesting, which gathers rain from roofs and paved surfaces for on-site use. Another example is green roofs, where a planted soil layer is established on the roof, creating a living surface that can reduce surface runoff. Pervious pavements represent another alternative which provide a solid surface suitable for pedestrians or vehicles while allowing rainwater to permeate through to the soil or underground storage; while bioretention systems capture runoff, temporarily retaining it on the surface before it filters through vegetation and the underlying soils. Trees also capture rainwater, promoting evapotranspiration, biodiversity, and providing shade. Swales, detention basins, ponds, and wetlands play a role in slowing down the flow of water, storing runoff, and treating it as it traverses the site, encouraging biodiversity [20].

Regarding the advantages of SuDS, it is possible to mention their ability to provide effective drainage solutions and to help urban areas in adapting more effectively to periods of high precipitation both now and in the future. These systems also contribute to mitigating the effects of urbanization on the water cycle, such as reduced infiltration leading to reduced groundwater resources. Indeed, SuDS have the potential to enhance the quality of life in urban developments, rendering them more dynamic, visually appealing, sustainable, and adaptable to challenging conditions. In addition, they are able to enhance air quality, regulate building temperatures, reduce noise levels, and offer recreational and educational opportunities.Furthermore, well-designed SuDS that are seamlessly integrated into the overall development plan can attract tourism and investments, thereby stimulating economic growth in the local area. Additionally, in cases where SuDS make efficient use of available space, they often present a more cost-effective option compared to traditional underground piped systems [20].

When considering the suitable locations for implementing SuDS, the answer is quite versatile. They can be employed almost everywhere, for instance in new construction projects, in redevelopment initiatives, and can even be integrated into pre-existing urban areas. Their adaptability extends to small spaces as well, as their designs are adept at making the most of available land, delivering efficient drainage while simultaneously fulfilling other site-specific objectives. For example, pervious pavements which can be used for parking, rain gardens can be integrated into traffic calming measures, detention basins can offer recreational opportunities, and trees and green roofs contribute to the regulation of building temperatures [20].

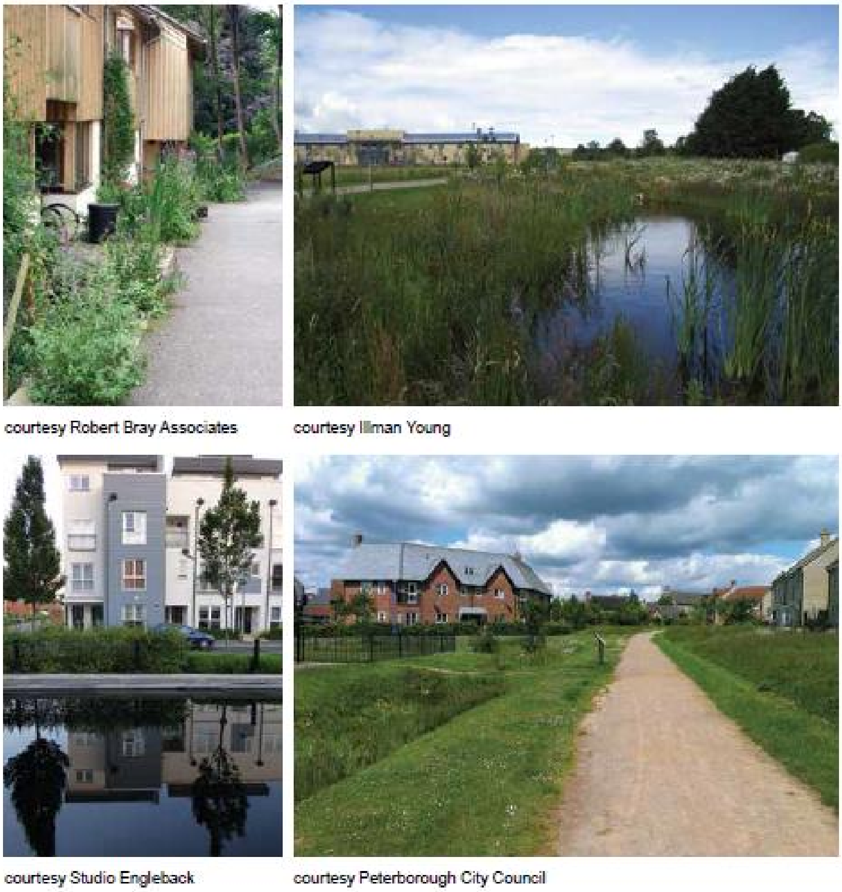


Figure 2.2: Common examples of SuDS implementation [20].

The majority of sites present some sort of challenge but given the variety of SuDS components and solutions available, all developments can benefit from an efficient SuDS scheme provided the appropriate expertise. This comprises sites with high development densities, steeply sloping sites, flat ones, or with high groundwater levels, with floodplains, contaminated lands, low infiltration capacity areas, and unstable soils conditions [20].

To have a successful SuDS implementation, there are three keys to consider:

- Take into account how surface water runoff will be managed on site from the beginning and consider it as an integral part of the design.

- Assemble the appropriate team early on the process to enable the consideration of environmental factors, drainage design, landscape characteristics, and urban planning as a whole.
- Relevant importance has the consultation with pertinent parties, such as local planning authorities, environmental regulators, and those in charge of approving and maintaining SuDS [20].

2.3. Sustainable Urban Drainage Systems framework

As is widely acknowledged, surface water is a precious resource, and this should be reflected in the way water is managed and used in the built environment. In addition to improving biodiversity, buildings, locations, and landscapes' inherent beauty and tranquility, it can also strengthen their resistance to climate change. The idea behind sustainable drainage systems is to maximize the benefits and minimize the negative impacts of runoff from populated areas. [20].

In order to manage the risk of flooding downstream and lower the likelihood of pollution from surface water runoff, SuDS approach involves slowing down and reducing the quantity of surface runoff. To do so, excess water must be collected, infiltrated, slowed down, stored, conveyed, and treated on site. By applying this, SuDS has the opportunity to create and enhance green spaces within developments as well as connect to the wider green network. The public benefits of using SuDS are also many, including improving the health, well-being and quality of life of individuals and communities [20].

There are different ways to apply SuDS to ensure effective surface water management. Depending on the opportunities and constraints of the site, the type of development expected and the characteristics of the surrounding environment, this can be accomplished through a combination of components: open water areas, vegetation and landscape, on the surface or underground. Even the smallest spaces can be used by SuDS, therefore the apparent lack of space should not be an excuse to avoid using these systems. In crowded urban settings, where space is limited, designing SuDS to serve multiple purposes is especially crucial [20].

Concerning the advantages of implementing SuDS, the most significant ones are:

- Preserving assets and people from elevated risk of flooding.

- Protecting surface and groundwater quality by shielding them from contaminated runoff.
- Preserving morphology and related ecology of rivers, lakes, and streams by maintaining their natural flow regimes.
- Encouraging increased biodiversity and establishing connections between habitats and related ecosystems.
- Increasing soil moisture content and recharging drained groundwater reserves.
- Supplying a valuable supply of water to society.
- Using water and green spaces to integrate with the built environment to create appealing places where people want to live, work, and play.
- Raising public awareness of the advantages of more sustainable practices and the management and utilization of runoff from development projects.
- Supporting the creation of structures better equipped to withstand climate change.
- Providing affordable infrastructure with lower whole-life carbon footprint than conventional drainage and with fewer natural resource requirements.

Figure 2.3: The Circle, Uptown Normal, Illinois [20].

As an example of previously explained concept, we can take as an example The Circle in Uptown Normal, Illinois, USA (figure 2.3). This award-winning, multipurpose public area is situated in a roundabout and offers green areas for a variety of community events, such as farmer's markets, blues, and arts festivals. To prevent flooding downstream, it collects runoff from nearby streets, filters, stores, and cools the water before recycling it into a public fountain that cools the neighbourhood and even reduces noise pollution from vehicles [20].

So as to maximize its benefits, SuDS design should focus on the following aspects in particular: treating runoff to reduce the risk of urban contaminants causing environmental pollution, promoting evapotranspiration, managing runoff above ground and close to the source, allowing rainwater to soak into the ground, reducing pollution through runoff prevention and source control, and treating runoff to reduce pollutants causing environmental pollution [20].

The goal of the SuDS approach aims to mimic natural hydrologic processes. As such, system performance is assessed using this natural reference as a baseline. By removing the water as soon as possible from its source, the conventional technique of drainage surface water runoff from populated areas through subterranean pipe and tank storage system was meant to safeguard public health and avoid local flooding. In many cities, water runoff is drained into a combine sewer, where it mixes with sewage. Consequently, this can put a heavy and unpredictably burden on wastewater treatment facilities causing some untreated sewage to overflow into receiving watercourses in the form of Combined Sewer Overflows (CSOs). Flooding from surcharged manholes can also result in sewage-contaminated flooding. The foul and surface water systems typically have their own separate sewerage networks in more recent developments, where surface water is piped to the closes watercourse, and foul water is transported to wastewater facility. However, although the likelihood of CSO spills is decreased by these divided surface water sewers, pollutants found in urban runoff are still transferred from urban surface to receiving waters. Increased peak flow rates can sometimes be reduced using attenuation tanks and flow controls, but changes in discharge frequencies and volumes are typically ignored, which can have negative physical effects like eroding habitats and disrupting ecosystems [20].

Natural "sponges" in the landscape are habitats like peat bogs, heather moorland, broadleaved woodland, wildflower meadows, and reed beds. They absorb rainfall and remove pollutants from the environment. Well-planned SuDS landscapes that incorporate drainage features like wetlands, green roofs, bioretention systems, and ponds that make use of the same natural processes can provide some of the same opportunities even in developed areas [20].

SuDS are particularly good at reestablishing natural base flows, soil moisture, and water balance. Under various flow conditions ranging from minor to major rainfall events, they seek to maintain or restore the ecologically significant components of the pre-development runoff process. A developed catchment surface is washed over by surface water runoff, which also mobilizes litter, oils, grits, metals, fertilizers, pesticides, animal wastes, salts, and pathogens, among other pollutants linked to human activity. These eventually find their way into rivers, groundwater, and the ocean without human intervention, endangering the environment and the general public's health. SuDS offer an opportunity to reduce the amount of potentially contaminated material in runoff by capturing, filtering, and degrading pollutants runoff [20].

A significant point to remark is defined by the fact that SuDS offer a valuable alternative to managing rainfall events that overpass design conditions, that is to say when a rainfall is more severe than the system design capacity. So, by using this low impact developed systems, excess runoff can be conveyed from within the drainage system into defined safe exceedance conveyance pathways and storage zones. In addition, this alternative represents a more adaptable way of draining surfaces taking into account the threat of both climate change and urban intensification. The reason of this is because surface-based systems can be designed to offer a more flexible capacity, making them more likely to undergo cost-effective improvements in the future when compared to subsurface systems [20].

2.4. Into more sustainable developments

It is well-known that sustainable developments have a common objective which is improving quality of life, now and for generations to come. So, it is possible to list the following goals:

- Social progress recognizing the necessities of everyone.
- Protection of natural environments.
- Sustainable use regarding natural resources.
- Maintenance of strong and stable levels of economic growth and employment.

Particularly, considering SuDS as an alternative for the sustainable management of water excess can provide: management of flood risk controlling flow rates and volumes, protection and support of ecology and biodiversity, indeed the creation of sustainable habitats through utilization of vegetated SuDS, prudent use of water resources by establishing rainwater harvesting systems, preservation of hydric reserves by protecting the ground and surface water quality, as well as sustainable use of natural resources reducing its utilization; and the decrease of embodied and operational carbon in drainage systems within manufacture and through the reduced use of pumping [20].

It is important to remark that previously mentioned strategies are in agreement with a broad range of national and European requirements in the framework of legislation and regulations [20].

Considering design philosophy, SuDS should not be taken as an individual component (such as a filter strip, swale or detention pond), but instead as an interconnected system designed to manage, treat and make the best use of surface water, considering the way where it falls as rain to the place where it is discharged into the receiving environment. Moreover, to better understand the philosophy of these alternatives, remarkable considerations should be considered regarding its specific functions according to its components, which are not independent, and are summarized ahead [20]:

- Rainwater harvesting systems: include the elements that collect rainwater and facilitate its utilization within the building or local place.
- Pervious surfacing systems: encompass the structural areas which permit water to penetrate, and so reduce the runoff quantity which is conveyed to the drainage system. For instance, green roofs, pervious paving (may include subsurface storage and treatment).
- Infiltration systems: parts that simplify the water infiltration, which usually include temporary storage where to accommodate water volumes before the slow release into the ground.
- Conveyance systems: components which transport flows to downstream storage systems, may also supply flow and volume control and treatment, for instance swales.
- Storage systems: responsible for controlling flows and, if it is possible, volumes of water excess being discharged from the site by storing water and releasing it slowly, which represents the attenuation concept. In particular, could present further treatment, for example ponds, wetlands, and detention basins.
- Treatment systems: constituents able to remove or to easy the degradation of pollutants present inside the runoff [20].

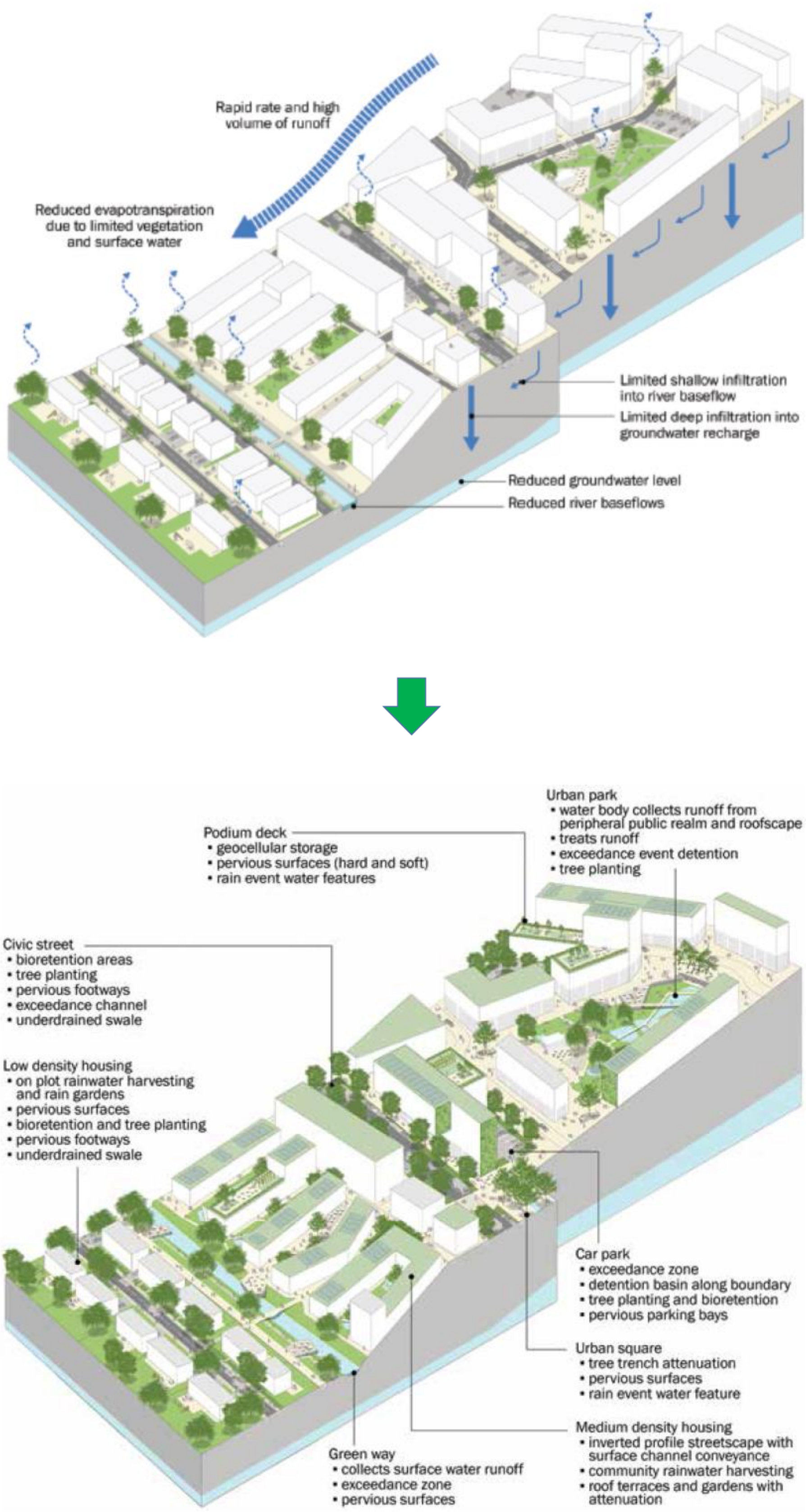


Figure 2.4: Examples of commonly used types of SuDS for different purposes [20].

There are many types of SuDS components, which means that sustainable drainage can be delivered anywhere. The designer can choose a number of different SuDS components and tailor the overall composition of a SuDS scheme to the local context (figure 2.4). The designer can create green corridors, link habitats together and add fun, education, and amenity value [20].

2.5. Water quantity design objective

To prevent harmful effects on people, property, and the environment resulting from surface water runoff on a developed site, it is crucial to manage both the rate at which runoff is released from the site (peak runoff) and the quantity of runoff that is discharged from the site (runoff volume) [20].

SuDS perform better at lowering risk for short- to medium-sized events with relatively high intensities. Their importance lies in their ability to reduce the likelihood of surface water flooding, sewer flooding, and flooding from small and medium-sized watercourses that may arise from development. Rather, they have less of an effect on the risk of flooding linked to large rivers, which are more vulnerable to events that last a long time. However, this does not mean that SuDS are not required. For instance, flow characteristics and local hydraulic constraints may require the use of flow and volume controls. SuDS may also be shown to have little effect at a single location; rather, the overall effect of all development within the catchment should be taken into account [20].

If left uncontrolled, the peak rates of surface water runoff discharged from a developed (relatively impermeable) site are typically much higher than from a site in its greenfield state. This is because there is significantly more runoff and it drains off the surface of the developed site much faster than it does on the greenfield site because less water can seep through the ground or be caught in other ways. Peak rates may be at least an order of magnitude higher on sites that are overlaid by sandy, well-drained soils. By raising flow rates and the chance of flooding and bank erosion, this may have serious effects on the receiving watercourse. The risks are typically higher when sites discharge to an existing piped drainage system because pipes have limited capacities and are more sensitive to change in flow rate [20].

As we can see in figure 2.5, there is a pre-development or green field discharge rate (green line) which is compared to the uncontrolled post one discharge rate (blue line).

This last has a runoff peak which is much higher and arrives much earlier than the green field condition [20].

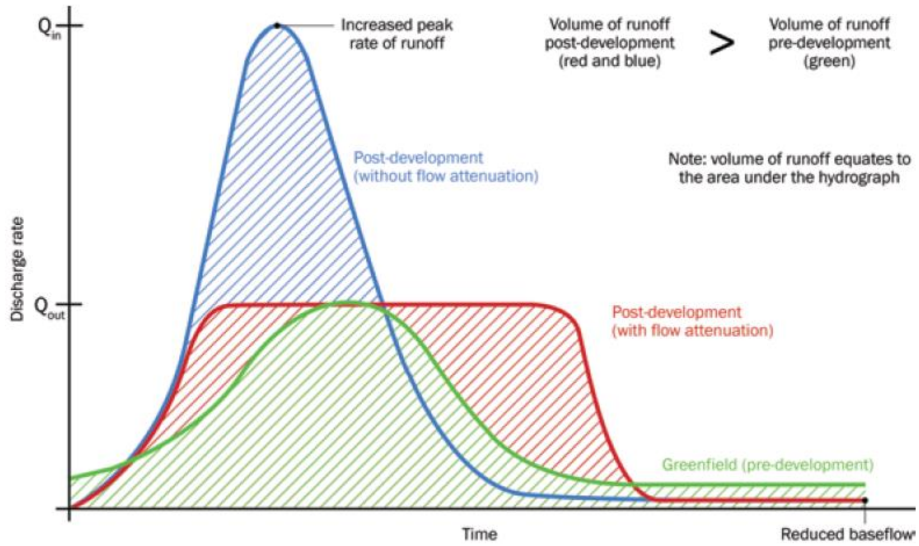


Figure 2.5: Pre and post-development runoff hydrographs [20].

Limiting the post-development runoff rate to that which would have existed pre-development is the aim of peak runoff rate control. The process of attenuation, which involves storing and slowing runoff on site before releasing it into the receiving watercourse at a set maximum rate, can be used to accomplish this [20].

Because of the additional runoff volume, attenuation controls the peak runoff rate by extending the hydrograph. As a result, even though the peak runoff rate may not increase, the duration over which it occurs will be significantly longer than it was prior to development [20].

The post-development discharge rate with attenuation is shown in red in figure 2.5. Under the graph is the volume of runoff. Due to increased erosion and sediment movement, this prolonged period of peak flows in the receiving watercourse may be detrimental to the morphology and ecology. Controlling the peak runoff rates from significant storm events is therefore crucial, but it is insufficient to lessen the impact of development on the downstream catchment on its own. Furthermore, the issues arising from a development site producing runoff from all of the smaller rainfall events are not addressed by attenuation, which is limited to controlling only relatively large rainfall events. Most of these events' runoff would have been lost through evapotranspiration and/or infiltration in naturally occurring soil. Usually, attenuation systems only allow runoff from these recurrent little rainfall events to "pass through" with little to no control.

However, the possible drawbacks of relying just on attenuation are also apparent at the catchment scale. Because of the greater total volumes being discharged from each sub-catchment, even though the runoff from each sub-catchment is attenuated to limit flows to pre-development conditions, the peak flow downstream will continue to rise. This implies that there is still a chance of flooding downstream [20].

2.6. Types of SuDS

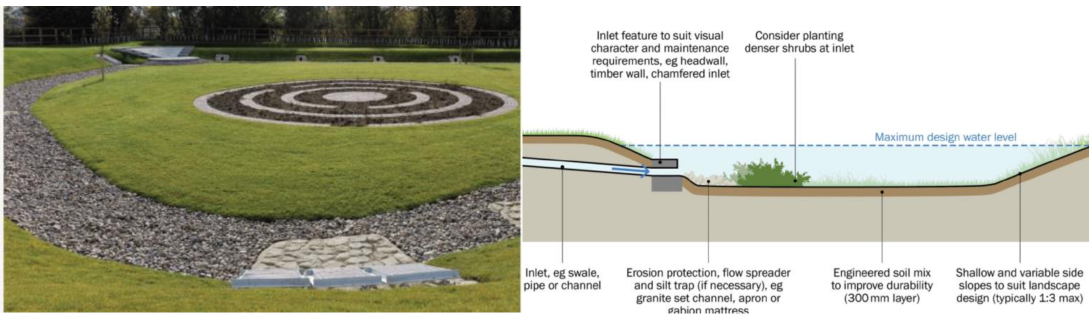
As previously mentioned, there are several alternatives to consider when planning a sustainable urban drainage system according to specific necessities or availabilities. For instance, the ones we can take into account are:

- Green roofs.

Figure 2.6: Green roof SuDS [20].

On these systems, a planted soil layer construction takes places on the roof of a building. Therefore, water is stored in the soil layer and absorbed by vegetation. A particular case are the so-called blue roofs that store water at roof level, without the use of vegetation [20].

- Infiltration systems.



Systems that gather and store runoff, then allow it to infiltrate into the soil. Both vegetation on the surface and the one underlying, being non-saturated, can offer protection to potential pollution towards groundwater [20].

Figure 2.7: Infiltration systems SuDS [20].

- Pervious pavements.

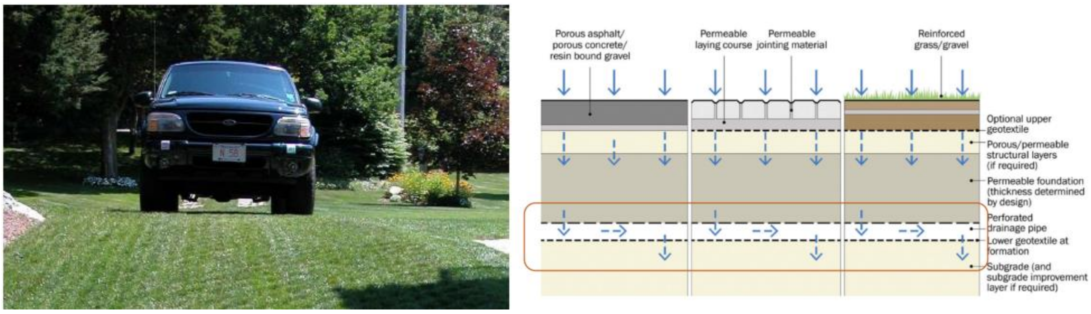


Figure 2.8: Pervious pavement SuDS [20].

By using this alternative, water excess is allowed to soak through specialized structural paving, which may include paving blocks with spaces between solid blocks or permeable paving where water permeates through the block material itself. Here water can be retained in the sub-base and possibly seep into the soil. Water can be stored in the sub-base and potentially allowed to infiltrate into the ground. Nevertheless, we may pay attention because risk of soil compaction if traffic is high can be present, then infiltration rate capacity can be reduced due to clogging [20].

- Ponds and wetlands.

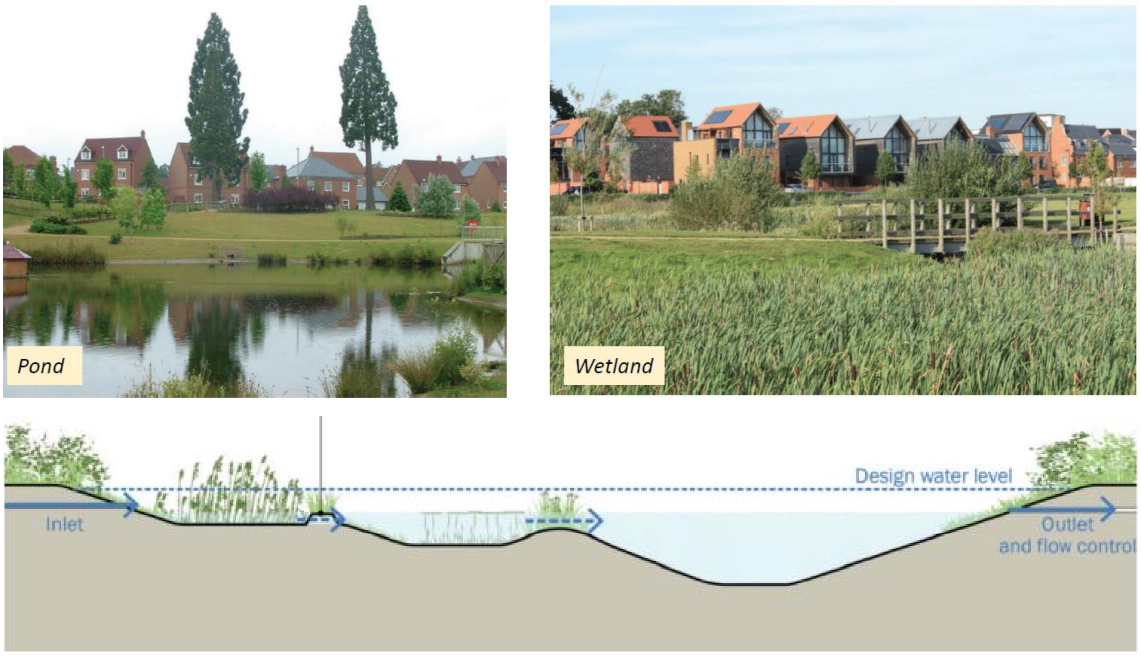


Figure 2.9: Ponds and wetlands SuDS [20].

On this type of SuDS, structures with a permanent pool of water can be used to supply attenuation and treatment of runoff. These aeras regulate the release of water and permit rising water levels after rainfall [20].

- Detention basins.

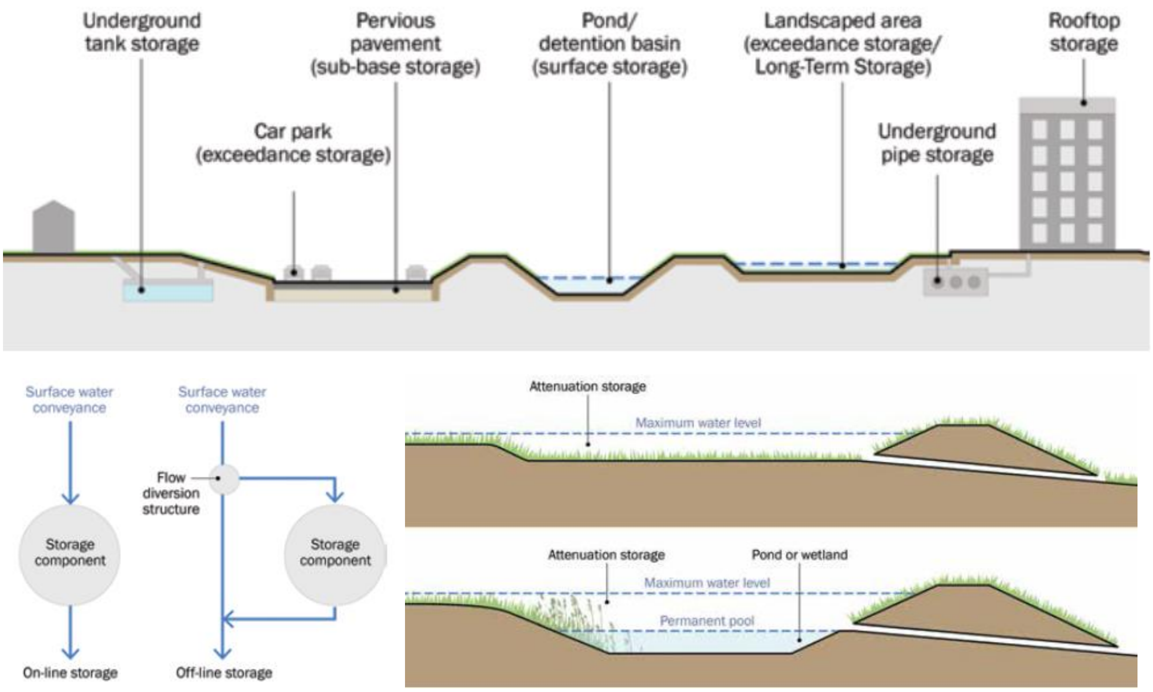


Figure 2.10: Attenuation storage tanks SuDS [20].

By using these systems during precipitation event, water flows to a landscaped depression which has an outlet that controls flows, resulting in a basin fil and attenuation. Moreover, if there is vegetation presence, runoff undergoes a treatment while being carried and filtered [20].

- Filter strips.

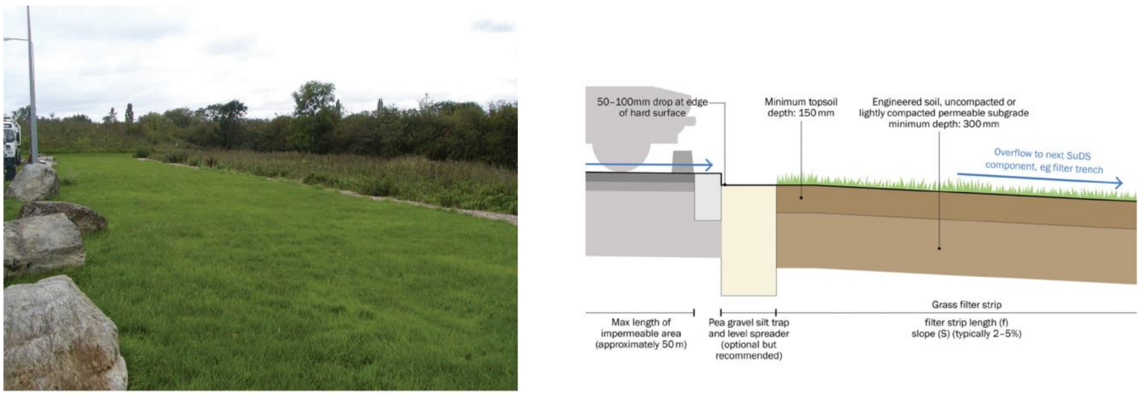


Figure 2.11: Filter strips SuDS [20].

In this case, water excess from an impermeable area is allowed to flow across a grassed planted area to boost sedimentation and filtration. They are characterized by mild slopes and dense vegetation, having a typical length of 2,5-5m [20].

- Swales.

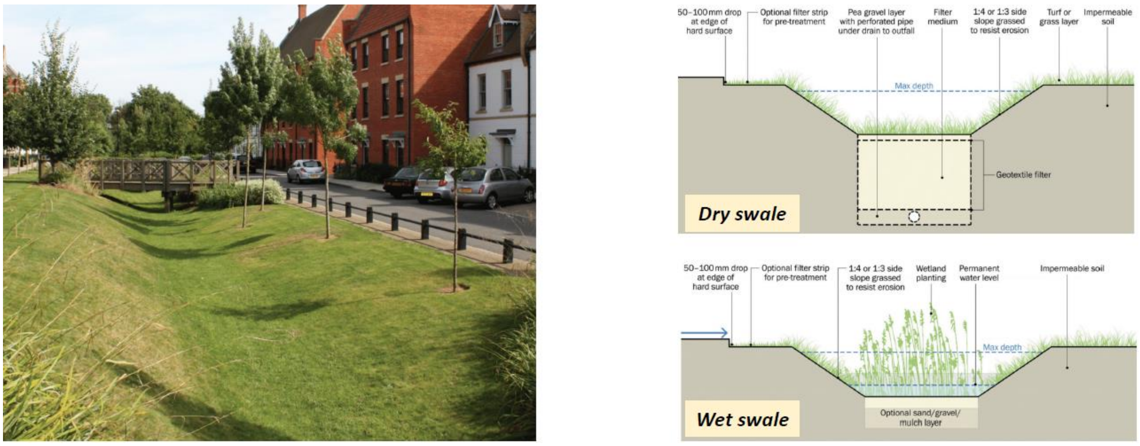


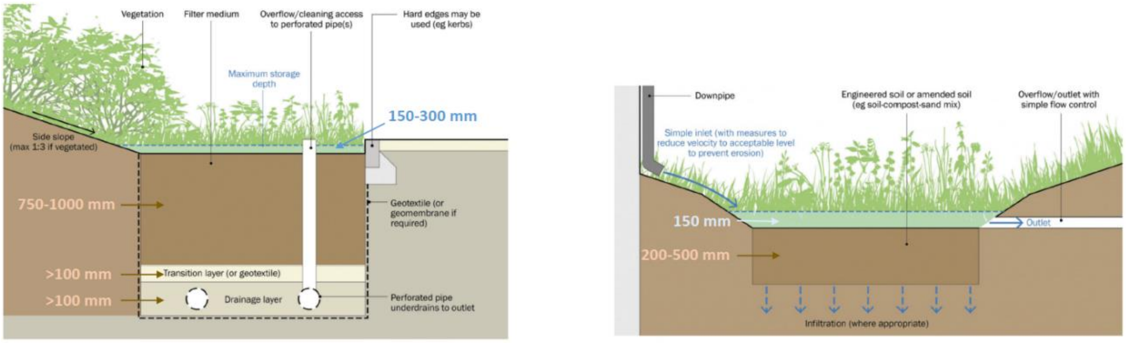
Figure 2.12: Swales SuDS [20].

Swales have a vegetated channel that is used to convey and treat runoff by using filtration. The possible typologies of channels can be "wet", where water is designed to remain permanently at the base of the swale, or "dry" where water is only present in the channel after rainfall events [20].

- Bioretention systems and rain gardens.

Figure 2.13: Bioretention systems and rain gardens SuDS [20].

On these types of systems, a flat landscaped depression allows water excess to pond temporarily on the surface, then it filters through vegetation and underlying soils prior to collection or infiltration. Among its contributions, they can decrease both speed and quantity of runoff, as well as treating pollution through the use of engineered soils and vegetation. Comparing both, rain gardens are particularly small systems that serve part of a single property, they are likely to be less engineered, so less complex in design compared to complete bioretention systems [20].



BIORETENTION SYSTEMS
- **Surface water ponding** during/after rain
- **Soil filter layer** (sand+organic) retains fines and support plants.
- **Transition layer** avoids fine transport
- **Drainage layer** (gravel) may also store water

RAIN GARDENS
- **Surface water ponding** during/after rain
- **Soil filter layer** is thinner than for bioretention systems.

Figure 2.14: Different SuDS scheme characteristics [20].

They represent a significant alternative for intercepting water and providing attractive landscape features, which are self-irrigating and fertilizing, as well as promoting habitat and biodiversity, and cooling of the local microclimate thanks to evapotranspiration [20].

Chapter 3

HEC-HMS Software

After discussing about the main issues related to the actual ongoing development of impermeable surfaces as a result of urbanization problems, such as flooding, erosion, pollution and many other alterations to the natural hydrological cycle, it was required to understand how to manage it. Therefore, the main alternative introduced on the present work is focused on the advantages represented by the use of Sustainable Urban Drainage Systems as a mechanism to counteract the mentioned problem. It was also explained the importance of the design criteria, key factors for an efficient performance as well as the different systems available for particular goals.

Once understood the main issue and the chosen strategy to face it, it is time present the selected software in order to proceed with the desired hydraulic modelling. In particular, it was necessary to find a software which was able to consider and to represent the most significant and influencing factors involved in the surface runoff process such as: elevations and slopes, through the utilization of a Digital Surface Model (DSM), soil characteristics, using specific loss methods considering infiltration rates as well as impervious areas, and including different options for representing the transformation of excess precipitation into surface runoff.

3.1. Introduction to HEC-HMS

Dendritic watershed systems' precipitation-runoff processes are modeled by the Hydrologic Modeling System (HMS), which is a product of the Hydrologic Engineering Center within the United States Army Corps of Engineers (USACE). It is intended to be used to solve the broadest range of problems across a variety of geographic locations. This covers runoff from small urban or natural watersheds, as well as flood hydrology and large river basin water supply. For studies of water availability, urban drainage, flow forecasting, future urbanization impact, reservoir spillway design, flood damage reduction, floodplain regulation, and systems operation, hydrographs generated by the program are used either directly or in conjunction with other software [21].

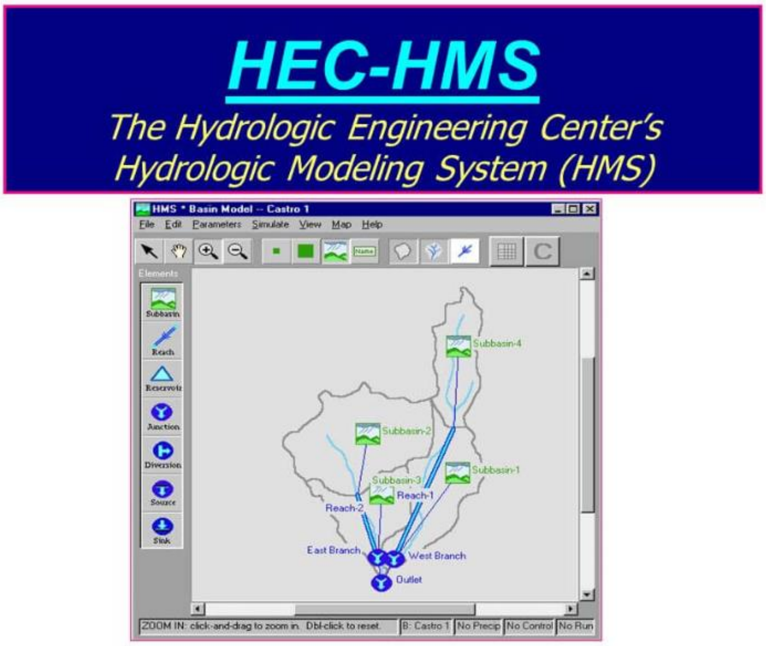


Figure 3.1: Hydrologic Modelling System software [22].

The software is a generalized modeling system that can simulate a wide range of watershed types. By breaking down the hydrologic cycle into smaller, more manageable components and drawing boundaries around the watershed of interest, a model of the watershed is created. After then, a mathematical model can be used to represent any mass or energy flux in the cycle [21].

Most of the time, there are multiple model options available to represent each flux. Each of the mathematical model inside the program can be used in a variety of settings and circumstances but is significantly important to understand the watershed of interest, to define appropriate objectives, and applying engineering criterion to make the right decision. The various components of the program can be moved between with ease thanks to a graphical user interface. All supported platforms have the same program appearance and functionality. The software offers a wide range of features for simulating hydrologic processes. Numerous widely used techniques in hydrologic engineering are included in a user-friendly manner. The user can focus on accurately representing the watershed environment, as the program handles the laborious tasks. [21].

It is widely used in the field of hydrology and hydraulic engineering for various practical and engineering purposes. Here are some of the key practical and engineering uses of HEC-HMS, in particular requiring Watershed Modeling [29]:

- Flood Risk Management.
- Environmental Restoration.
- Flood Forecasting.
- Hydrologic Hazard Curve Development for Dam and Levee Safety.
- Development of Probable Maximum Flood or Inflow Design Flood for Dam Safety.
- Determination of Pump Station/ Interior Drainage Adequacy for Levee Safety.
- Reservoir Storage Reallocation or Water Control Manual Updates.

Figure 3.2: USACE Key Mission Areas [30]

The mission of USACE is broad, and within the scope of that broad mission, information about watershed and channel behavior must be available for decision making for planning, designing, operating, permitting, and regulating [31].

3.2. Modeling framework

Hydrological engineers are tasked with supplying data for a range of water resource investigations, including:

- Designing and planning new infrastructure for water conveyance and control.
- Assessing and managing the operation of existing water conveyance and control structures.
- Preparing for and responding to flood and drought situations.
- Enforcing regulations for activities within floodplains.
- Formulating strategies that harness resources to improve environmental functionality.

In some rare instances, historical records of flow, stage, or precipitation can fulfil the required information. However, more frequently, the need for information necessitates the prediction of watershed runoff. For instance, in a study focused on reducing flood damage, an estimation of the increased runoff volume due to proposed land use changes within a watershed may be required. Yet, no existing data can provide this information because the changes have not occurred. Similarly, when determining reservoir release strategies in the event of a tropical storm altering its course over a watershed, waiting to observe the flow is not a viable option. Instead, the solution is to employ a model to generate the necessary information. A model establishes a relationship between something unknown (the output) and something known (the input). In the case of the models incorporated in the program, the known inputs consist of factors like precipitation, temperature, and potentially other meteorological data. The unknown output typically pertains to runoff. In applications beyond watershed runoff estimation, the known input might be upstream flow, with the unknown output being downstream flow [32].

There are several types of models. Physical models are simplified representations of systems found in the real world. A physical representation of a watershed consists of a sizable surface with overhead sprinklers that replicate the precipitation input. In addition to controlling the rate of rainfall, the surface can be changed to replicate different land uses, soil types, surface slopes, and other characteristics. Since the system is closed, the runoff can be measured. HEC-HMS software uses models which are defined by mathematical formulations, which defines an equation that illustrate the response of a hydrologic system component to a change in hydrometeorological conditions. Various criteria can be employed to categorize mathematical models, including those found in the program. These concentrate on the model's mechanics, including how it handles time, randomness, and other issues. Understanding this classification is useful in selecting which model to use for different applications, even though it is not required to use the program [32]. In the following part, a brief description of the possible models:

Event or Continuous: this distinction mostly applies to baseflow, surface runoff, and infiltration models. A single storm is simulated by an event model. The storm could last anywhere from a few hours to several days. The primary characteristic that sets the model apart is its limited ability to simulate the watershed response during and immediately following a storm. The redistribution of the wetting front in between storms and the transpiration and evaporation of soil moisture are not taken into account by event infiltration models. Surface runoff unit hydrograph models are all categorized as event models due to their ability to react to excessive precipitation. Instead, a continuous model simulates a longer period, ranging from several days to many years. The majority of models in HEC-HMS are event models [32].

Spatially-Averaged or Distributed: applies mostly to models of infiltration and surface runoff. In contrast to a spatially-averaged model, which averages or ignores these spatial variations, a distributed model explicitly takes into account the spatial (geographic) variations of characteristics and processes. It is frequently the case—though not always—that distributed models depict the watershed as a collection of grid cells. Every grid cell has a separate set of calculations. It is important to remember that spatial averaging is done by distributed models as well. The majority of the models included in HEC-HMS are based on differential equations, written at the so-called point scale are these equations. By point scale, we mean that the equation holds true over a very small (differential) length Δx in relation to the watershed's size. HEC-HMS primarily includes spatially-averaged models [32].

Empirical or Conceptual: this differentiation centers on the foundational knowledge used to construct mathematical models. A conceptual model is constructed establishing a control volume and formulating equations for conserving mass, as well as either momentum or energy within that volume. Conversely, an empirical model relies on observations of input and output without attempting to explicitly represent the conversion process. A common approach to constructing empirical models involves gathering field data, which is then subjected to statistical analysis to establish a mathematical relationship between the input and output. Once this relationship is established, it becomes possible to predict output for a given input. HEC-HMS incorporates both empirical and conceptual models [32].

Deterministic or Stochastic: a deterministic model assumes that the input is known with absolute precision. Furthermore, it presumes that the process described by the model is free of any random fluctuations. In reality, there is always some degree of variability. Deterministic models, in essence, overlook input variability by assuming that the input remains constant. In contrast, stochastic models embrace random variation by making explicit attempts to describe it. Unlike deterministic models, which rely on a single input value, stochastic models incorporate statistical information about the variability in both the input and the underlying process. It's important to note that all the models integrated into HEC-HMS are deterministic [32].

Measured-Parameter or Fitted-Parameter: the difference between measured and fitted parameters plays a crucial role in the selection of models for use in situations where there are no available observations of input and output. A model with measured parameters is one in which the model's parameters can be established based on system properties, either through direct measurement or through indirect methods that rely on these measurements. In contrast, a model with fitted parameters contains parameters that cannot be directly measured. Instead, these parameters must be determined by adjusting the model based on observed values of both the input and the output. HEC-HMS encompasses both models with parameters that can be directly measured and models with parameters that are determined through fitting based on observed data [32].

3.3. Model's constituents and components

The mathematical models included in the program describe how a watershed reacts to precipitation or upstream water flowing into it. While the equations and solutions differ, all of the models share the same components [32]. The constituents of a model are:

- State Variables:

The terms within the equations of the model describe the condition of the hydrological system at a specific time and place. For example, in the deficit and constant-rate loss model, this approach monitors the average amount of water stored naturally within the watershed [32].

- Parameters:

These are numerical measures of the real-world system's properties. They govern the relationship between system input and system output. The curve number, which is a component of the SCS curve number runoff model, is an example of this. This parameter, which is specified as a single number when using the model, represents complex properties of the real-world soil system. It is important to remark that parameters are adjusted in order to have a model which accurately predicts physical response [32].

- Boundary Conditions:

These are the system input values—the forces acting on the hydrologic system and causing it to change. Precipitation is the most common boundary condition in the program; applying this boundary condition results in runoff from a watershed. The upstream (inflow) flow hydrograph to a channel reach is another example; this is the boundary condition for a routing model [32].

All of the models in the program are unsteady-flow models, which describe changes in flow over time. They accomplish this by solving differential equations that describe a component of the hydrologic system in some form. Solving differential equations involving time always necessitates knowledge of the system's state at the start of the simulation. The solution to any differential equation is a report on how much the output changes as the input, parameters, and other critical variables in the modeled process change [32].

- Method:

A mathematical model is a set of equations that represents the behavior of the components of a hydrologic system. The method contains all of the details of the equations, initial conditions, state variables, boundary conditions, and method of solving the equations [32].

After discussing about the modeling main constituents, in the next part the program components will be developed. So, is described how methods included in the program conceptually represent watershed behavior; and also identifies and categorizes these methods based on the mathematical models that underlie [32].

Watershed Processes.

Figure 3.3 depicts a systems diagram of the watershed runoff process at a scale consistent with the scale well modeled by the program. The depicted processes begin with precipitation. Precipitation could be either rain or snow. Precipitation can fall on the vegetation, land surface, and water bodies such as streams and lakes in the simplified conceptualization shown [32].

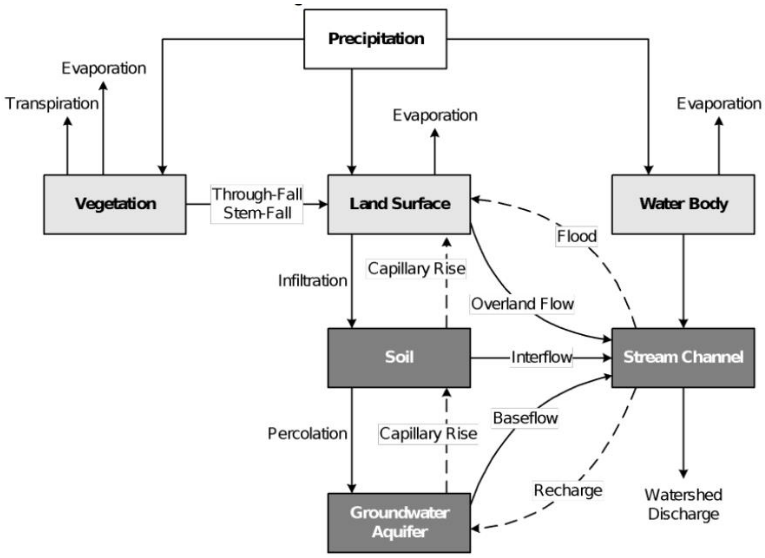


Figure 3.3: System diagram of the runoff process at local scale [32].

As it is well-known, most of water that falls as precipitation returns to atmosphere by evaporation from vegetation, land surfaces, and water bodies, as well as through transpiration and vegetation. However, these last two processes are limited during a storm event because meteorological conditions resulting in precipitation often reduce evaporation almost to zero (decreasing solar radiation and increasing relative humidity). Then, the short time window of a storm event prevents evaporation and transpiration processes from having significant impact on total water balance. Precipitation falls between leaves or runs down stems, branches, and trunks to the land surface, where it joins precipitation which felt directly on surface. Moreover, water may pond once it reaches land surface, and depending on soil type and moisture, may infiltrate. This last is temporarily stored in soil's upper, partially saturated layers, and may rise to surface again thanks to capillary action. Then, after sufficient water has infiltrated to form saturated zones, it begins to move vertically and horizontally. In particular, saturation point at which this takes places is called field capacity. Water percolates into groundwater aquifer beneath watershed, and water in stream channel may indeed recharge the mentioned aquifer [32].

Overland flow transports water that does not pond on the land surface or infiltrate into the soil to a stream channel. The stream channel serves as a confluence point for overland flow, precipitation that falls directly on water bodies in the watershed, interflow, and baseflow. As a result, the total watershed outflow is the resultant streamflow [32].

Representation of Watershed Processes.

The appropriate representation of the system previously depicted is determined by the information requirements of a hydrologic-engineering study. For instance, in some required analysis, a detailed accounting of the movement and storage of water through all system components is necessary. However, such a detailed information isn't essential for many of the motivations behind conducting a water resources investigation. In situations like this, the perspective of the hydrological process can be more straightforward. As depicted in Figure 3.4, only the elements required for predicting runoff are meticulously depicted, while other components are streamlined or excluded entirely [32].

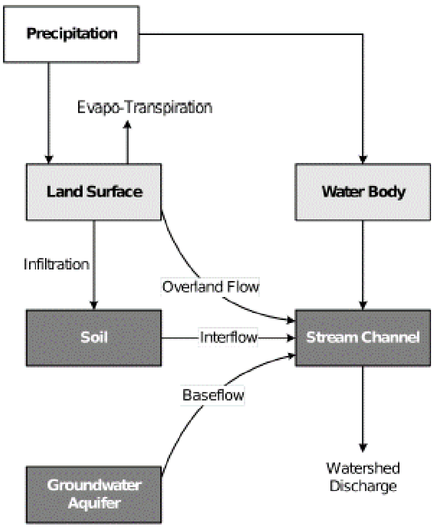


Figure 3.4: Simplification of watershed runoff[32].

As an example of this possible simplification, a common application is that the detailed information regarding movement of water within the soil can be omitted, and by doing so the program is set to consider the infiltration method but does not model storage and water movement vertically withing soil layer. So, does not include a model of interflow or flow to the groundwater aquifer, but instead represents only the combined outflow as baseflow [32].

3.4. Programs methods and setup

In order to represent each component of the runoff process illustrated in figure 2.4, the program uses separate methods, among which there are [32]:

- Methods for analyzing meteorological data related to precipitation, snowfall, and potential evapotranspiration.
- Methods for calculating infiltration and the consequent runoff volume.
- Methods for modeling direct runoff, encompassing overland flow and interflow.
- Methods for characterizing baseflow.
- Methods for estimating channel flow.

Model	Categorization
Deficit and constant	continuous, spatially averaged, conceptual, measured parameter
Exponential	event, spatially averaged, empirical, fitted parameter
Green and Ampt	event, spatially averaged, conceptual, measured parameter
Gridded deficit and constant	continuous, distributed, conceptual, measured parameter
Gridded SCS curve number	event, distributed, empirical, fitted parameter
Gridded SMA	continuous, distributed, empirical, fitted parameter
Initial and constant	event, spatially averaged, conceptual, fitted and measured parameter
SCS curve number	event, spatially averaged, empirical, fitted parameter
Smith Parlange	event, spatially averaged, conceptual, measured parameter
Soil moisture accounting (SMA)	continuous, spatially averaged, conceptual, fitted and measured parameter

Figure 3.5: Loss methods for computing infiltration [32].

The techniques responsible for calculating infiltration and the consequent runoff volume can be found in Figure 3.5. These methods tackle inquiries regarding the precipitation volume that descends onto the watershed: What portion permeates through non-porous surfaces? What amount flows from impermeable surfaces? When does this runoff occur? [32].

Model	Categorization
User-specified unit hydrograph (UH)	event, spatially averaged, empirical, fitted parameter
User-specified s-graph	event, spatially averaged, empirical, fitted parameter
Clark's UH	event, spatially averaged, empirical, fitted parameter
Snyder's UH	event, spatially averaged, empirical, fitted and measured parameter
SCS UH	event, spatially averaged, empirical, fitted parameter
ModClark	event, distributed, empirical, fitted parameter
Kinematic wave	continuous, spatially averaged, conceptual, measured parameter

Figure 3.6: Transform methods for computing surface runoff [32].

The procedures concerning surface runoff are documented in Figure 3.6. These methods elucidate the processes occurring when water that hasn't seeped into the ground or been retained within the watershed traverses across or right beneath the watershed's surface [32].

Model	Categorization
Bounded recession	event, spatially averaged, empirical, fitted parameter
Constant monthly	continuous, spatially averaged, empirical, fitted parameter
Exponential recession	event, spatially averaged, empirical, fitted parameter
Linear reservoir	continuous, spatially averaged, empirical, fitted parameter
Nonlinear Boussinesq	event, spatially averaged, conceptual, measured parameter

Figure 3.7: Baseflow methods for computing subsurface flow[32].

Figure 3.7 presents the different options for modelling the baseflow, in particular these ones simulate the slow subsurface drainage of water from the system into the channels [32].

Model	Categorization
Kinematic wave	continuous, spatially averaged, conceptual, measured parameter
Lag	continuous, spatially averaged, empirical, fitted parameter
Modified Puls	continuous, spatially averaged, empirical, fitted parameter
Muskingum	event, spatially averaged, empirical, fitted parameter
Muskingum-Cunge	continuous, spatially averaged, quasi-conceptual, measured parameter
Straddle-stagger	continuous, spatially averaged, empirical, fitted parameter
Confluence	continuous, conceptual, measured parameter
Bifurcation	continuous, conceptual, measured parameter
Reservoir	Continuous, empirical or conceptual, measured parameter

Figure 3.8: Routing methods for computing open channel flow [32].

The different alternatives for modelling channel flow are shown in figure 3.8. These methods simulate one-dimensional open channel flow, an exception is the kinematic wave method which is a simplified hydraulic routing model [32].

Furthermore, the program has been created to be as adaptable as possible. The program will connect infiltration and excess precipitation from the loss method to the transform method for computing surface runoff. To compute watershed discharge, most methods can be successfully combined with one another. The applicability of any particular method, however, is dependent on the characteristics of the watershed, and some methods may be inappropriate for some hydrologic-engineering studies [32].

Chapter 4

Model Construction

In the previous chapters, it was introduced the main issue of the present thesis which is the so-called urban drainage issues. It was explained how its alteration to natural hydrologic cycle affects in several ways surface runoff and generates related problems to this last fact. As a consequence, it was required to analyze measures to counteract these several issues, among which Sustainable Urban Drainage Systems rise as a low development impact to contribute to this goal in terms of reduction of surface runoff quantity, but also considering facts regarding water quality and pollution. Moreover, it was presented the software tool of interest called HEC-HMS to simulate precipitation-runoff processes. In this last section, plenty characteristics of this program were presented to emphasize its capacity to reproduce surface runoff phenomena with its correlated hydrologic methods: loss, transformation, baseflow, and routing techniques.

After establishing the required concepts and defining the appropriate methodology for practical application, is time to define the thesis case study. In the following section, the area of interested will be presented, its main features and the process of hydrologic model construction will take place. Hence, it will be detailed the step-by-step development in order to build the mentioned model with its considerations, level of precision, used tools, chosen hydrologic methods and the appropriate precipitation data involved.

4.1. Case study

As discussed in Chapter 2, there are many alternatives to consider when thinking about implementing a SuDS solution on an urban area. Particularly, a common solution usually observed on streets are the so called bioretention areas or rain gardens systems. In the city of Turin, Piedmont Region, the mentioned systems can be observed in many places. Among them all, the present thesis is focused on a specific street called Via Cervino, in the district named Barriera di Milano, Circoscrizione VI.

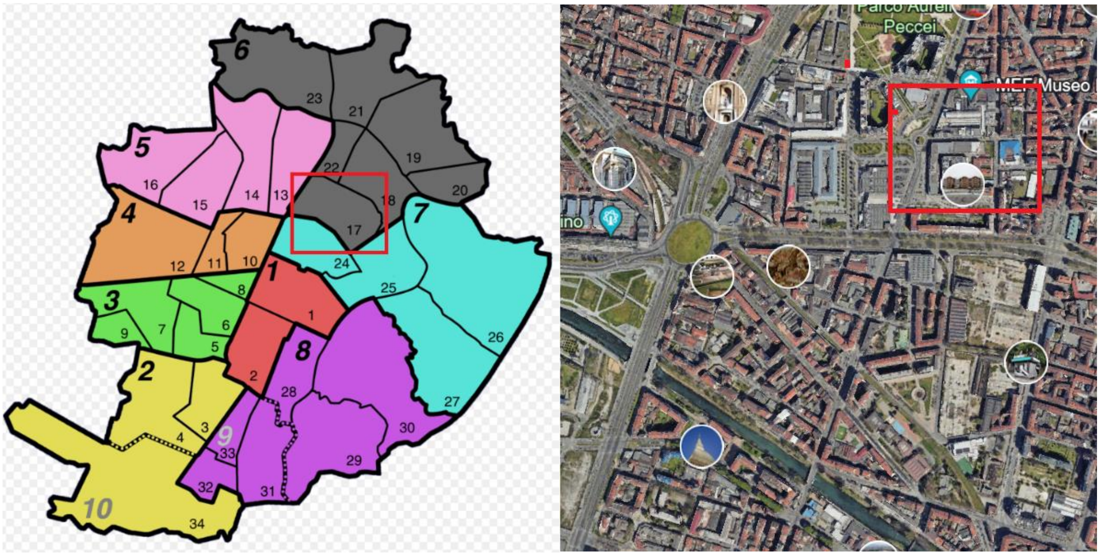


Figure 4.1: Localization of the study area within Turin [42].

The mentioned area is located in the upper part of one of the rivers that reaches the city: Fiume Dora Riparia, as reported in Figure 4.1. The portion of interest of Via Cervino is limited by Via Francesco Cigna and Via Antonio Banfo.

In order to describe the area of the city in which the street of interest is located, among the principal features in the surrounding area it is possible to mention:

- Parco Aurelio Peccei.
- Corso Vigevano.
- MEF Museo Ettore Fico.
- FACIT Headquarters.
- Brico Center.

To better visualize the street under consideration, an aerial view of it is presented in Figure 4.2:

Figure 4.2: Aerial view of Via Cervino 16 [42].

Regarding street geometry, the considered block has a length of around 150m, with a width of about 8m. It is characterized by an asphalt pavement with the already mentioned presence of bioretention areas/rain gardens as sustainable urban drainage systems. In the following section, a set of images are presented to improve the knowledge of the area of interest.

Figure 4.3: Street corners with Via Francesco Cigna (left) and Via Antonio Banfo (right).

Considering the drainage system elements, it is important to remark the presence of a slight slope with the highest elevation in the corner with Via Francesco Cigna, while the lowest in the corner with Via Antonio Banfo. So, if analyzing figure 4.2, the slope direction of the flow would be from left to right.

Figure 4.4: Storm drains characteristics of the street.

Moreover, presence of several storm drains was detected throughout the street development, as a reference of the drainage system entrance as shown in Figure 4.4.

Figure 4.5: Generic view of the street of interest.

A site visit was performed in order to better understand the main features influencing the place. As shown in Figure 4.5, street is characterized by significant impermeability because of the asphalt pavement and related man-made surfaces, with an exception represented by the SuDS presence, with a visible example reported also in the previous mentioned image.

The criteria to model the presented street in order to obtain its hydraulic response and characterize the efficiency of the SuDS system was to encompass only the half of the total street. That is to say, from the mid-block position towards the corner with Via Antonio Banfo, as reported in Figure 4.6, with an approximate area of 650 m2.

Figure 4.6: Mid-block street selected for model construction.

In the chosen area, 6 SuDS were identified, with their corresponding characteristics presented in the following section:

Figure 4.7: SuDS N°1.

Figure 4.8: SuDS N°2.

Figure 4.9: SuDS N°3.

Figure 4.10: SuDS N°4.

Figure 4.11: SuDS N°5.

Figure 4.12: SuDS N°6.

Once reported the 6 samples of the mentioned systems, which are going to be considered in the model construction, some of their characteristics to take into account are listed below:

- Average of every single SuDS area of 3 m2.
- Height of the asphalt surrounding kurb of 12 cm.
- Presence of vegetation and soil with infiltration capacity.
- As shown in the reported pictures, every single system has an entrance connecting the pavement with the infiltration system. This particular fact is observed in the frontal and lateral perimeter of the SuDS system in relation to the surrounding impermeable surface. The purpose of this entrance is to collect water in storm events in order to collaborate with drainage system, as specifically explained in Chapter 2.

4.2. Digital Elevation Models (DEMs) and Raster data

Geospatial data, and the insights derived provides advancement in terms of digital terrain modeling, as well as expanding computational capabilities. Consequently, dimensional elevation models of the Earth's surface can be rapidly generated, shared, and integrated with other products [33].

Elevation information is gathered through various techniques, including Synthetic Aperture Radar (SAR), satellite stereo imagery, Light Detection and Ranging (LiDAR), and surveying methods. The resulting data can be presented in different formats, such as contours, a point cloud, a triangulated irregular network, or a raster surface [33]. In particular, elevation models can be classified as:

- Digital Surface Models (DSMs): represent elevations of human-made and natural features. A DSM captures the top-most surface of a region, considering all exposed objects such as treetops and buildings. They portray the bare ground where there is nothing else situated above it.
- Digital Terrain Models (DTMs): constitutes a bare-earth model devoid of human-made and natural features, such as infrastructure and vegetation. The data collected by satellites or drones are DSMs, which can be transformed into DTMs by removing non-ground objects.

Moreover, there are other derivate products of elevation models, among which we can include slope aspect, curvature, shaded relief, and normalized digital surface models (nDSMs) [33].

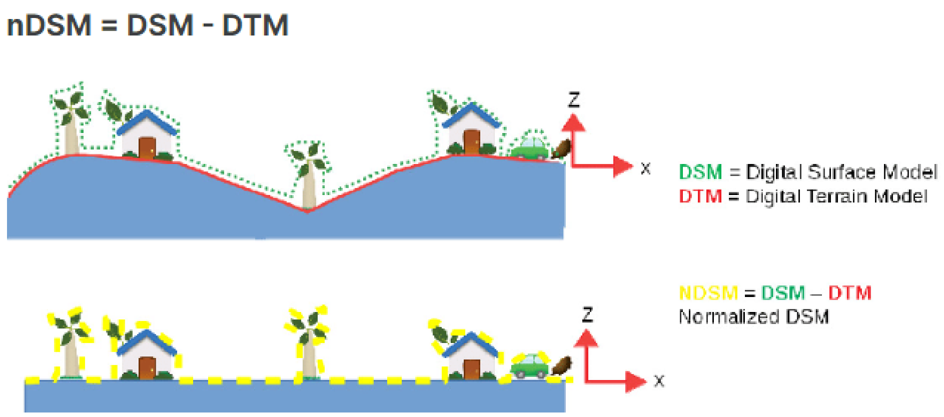


Figure 4.13: DTM vs DSM representation [33].

A Digital Elevation Model, or DEM, is a raster GIS layer that represents the Earth's surface as a grid of elevation values. This grid is referenced to the vertical datum, which is the surface of zero elevation used by scientists, insurers, and geodesists. In particular, level of detail in a DEM data file increases with smaller grid cells. As a result, if it is required to model with a high level of detail, then opting for a smaller grid spacing or cell size is recommended [34].

Since our case study is situated in an urban developed area, the type of elevation model of interest is the so called Digital Surface Model because, as already explained, it represents the bare-Earth and all of its above-ground features, being particularly important in urban planning [34].

With the wealth of online elevation data available, once identified the most suitable dataset for the specified requirements, it is time to work on it. As it was established, DEMs are files that contain either points (vector) or pixels (raster), with each point or pixel containing an elevation data value. These files come in various formats, ranging from ".csv" and ".tif" to ".flt" and ".dem". Since elevation data is not directly viewable in a browser, is necessary to take advantage of a specialized software like Geographic Information System (GIS) or other dedicated application. Some examples of software programs that recognize DEM files include ARC-GIS and Q-GIS [34].

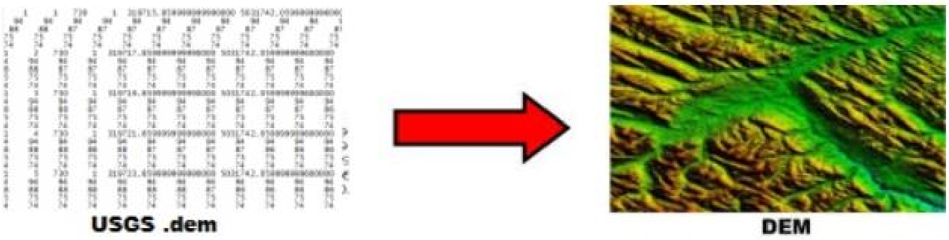


Figure 4.14: Conversion from source data to GIS visualization[34].

From the browser source, these elevation models are contained mainly by numerous areas without data, III-defined coastlines, waterbodies that may not appear flat, and other errors. So, after open and using an appropriate GIS software, it is possible to visualize the desired elevation model as shown in figure 4.14.

The diversity of applications for Digital Elevation Models (DEMs) extends beyond the methods of their acquisition. In fact, these models prove to be pertinent and valuable across a multitude of industries or sectors reliant on location DATA. Some common applications encompass [34]:

- Slope analysis.
- Aspect analysis.
- Delineating drainage networks and catchments.
- Identifying geologic structures.

- Viewshed analysis.
- 3D simulations.
- Change analysis and contour mapping.

As previously mentioned, the elevation value referred in DEMs is always normalized on a chosen reference point in the landscape, typically mean sea level. Therefore, this necessitates a well-defined and a consistent reference point in order to observe, as well as a uniform measurement technique for the assessed area. So, acquisition methodology of the elevation values will determine required corrections and how points will be interpolated [34].

Regardless of the specific application, DEMs base file will be the starting point for the model construction. So, its characteristics, accuracy and resolution are of paramount importance because of their influence in representation precision as well as results value according to reality. Hence, it is required to have a basic knowledge about this DEMs attributes to avoid undesired results.

The quality of the DEM is highly influenced by a range of interconnected factors, such as methodology for data acquisition, input data attributes, as well as methods applied during DEM development. In particular, each elevation data acquisition methodology has it own biases and potential errors. Notably, among the key factors impacting on DEM accuracy it is possible mention atmospheric and ionospheric influences, temporal decorrelation coregistration errors, phase errors, signal decorrelation, and shadow effects [34].

Another point of remarkable importance is the DEM resolution. A raster is a matrix composed by several elements, the primary element is called cell and for each cell the dimension of the cell give us the resolution of the raster, as reported in Figure 4.15 [35].

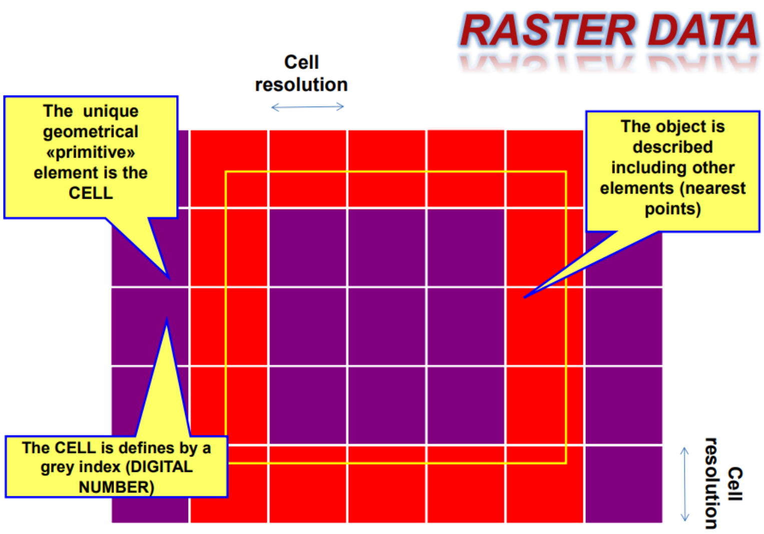


Figure 4.15: Raster data and cell resolution [35].

There are three primary resolution types that one must always take into account when evaluating the suitability of a DEM for a particular project or application [34].

- Spatial resolution: is dictated by the spacing between sample points, which may be consistently spaced, as in stereoscopic imagery, moderately uniform, as observed in RADAR and LiDAR, or highly variable, as in the case of DEMs obtained through manual methods.
- Vertical resolution: refers to the potential discrepancy in elevation between the modeled or detected elevation and the true or ground-truthed elevation of the surface. The diverse methods mentioned for acquiring elevation data produce differing accuracy levels. Among all of them, LiDAR typically provides superior spatial and vertical resolutions, however it is frequently cost-prohibitive on a larger scale.
- Temporal resolution: how recently the elevation data used for creating the DEM was collected is a significant consideration. Indeed, this is especially relevant when performing a change analysis or studying temporally dynamic phenomena such as vegetation growth or new construction, particularly if utilizing DSM.

It was already mentioned that a DEM is a raster GIS layer, but it is also important to highlight that every cell composing rata matrix has a specific value, even if it is a special value to indicate that there is "no data" or that data is "missing" at the location. Consequently, it is possible to affirm that when using raster data we are able not only to describe our elements of interest, but also we refer to what we have inside or outside the cell representing the mentioned element. On the contrary, vector data describes only the specific elements. Then, raster data represents a continuous description [35].

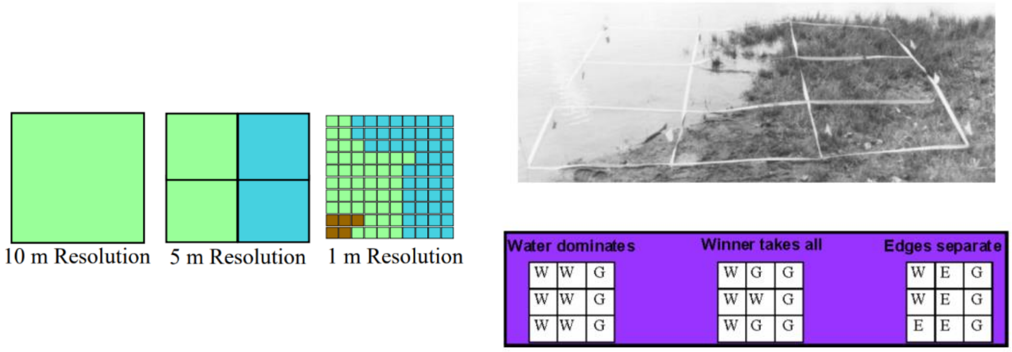


Figure 4.16: Different cell resolution on raster data [35].

The size of the cells in the raster data model determines the resolution at which features can be represented. Indeed, resolution can influence which features are represented in what locations. For instance, if we have a pixel resolution of 10m it is characterized by specific land cover, water and vegetation. However, if we increase the resolution up to 5m, for example, it could result in more water or vegetation quantities, shapes modifications, and so on as reported in Figure 4.16. Consequently, resolution is fundamental in order to analyze with more detail the phenomena. Nevertheless, if we want to use the best resolution, it also implies a lot more memory requirement and more time computation. So, according to the specific phenomena under consideration, it should be evaluated the necessity or not of using the appropriate cell resolution, taking into account time-cost factors as well [35].

4.3. Elevation Models data download

After introducing the main concepts about digital elevation models, in order to initiate the desired model construction, it was required to search for elevation data regarding the area of interest. That is to say, look for the available data source of Turin city, in particular, an elevation model which encompasses the mentioned mid-block street of Via Cervino.

Among the possible data source possessing information from Piedmont Region, undeniably Geoportale Piemonte is one of the most significant resources to take into consideration. Piedmont Region promotes, through "Geoportale Piemonte" the harmonization, dissemination, and use of geographic data, also through the collection of metadata in shared catalog.

The mentioned portal, in accordance with Regional Law dated December 1, 2017, No.21 ("Infrastruttura regionale per l'informazione geografica"), is one of the main components of the regional geographic infrastructure, serving as a point of exposure for shared geographic information. Indeed, it makes available the metadata catalog of geographic information for Piedmont territory, collected and systematized over the years by various entities. Through metadata search, it is possible to view the data using visualization services, downloading them through appropriate services, or obtain them directly as static packages [36].

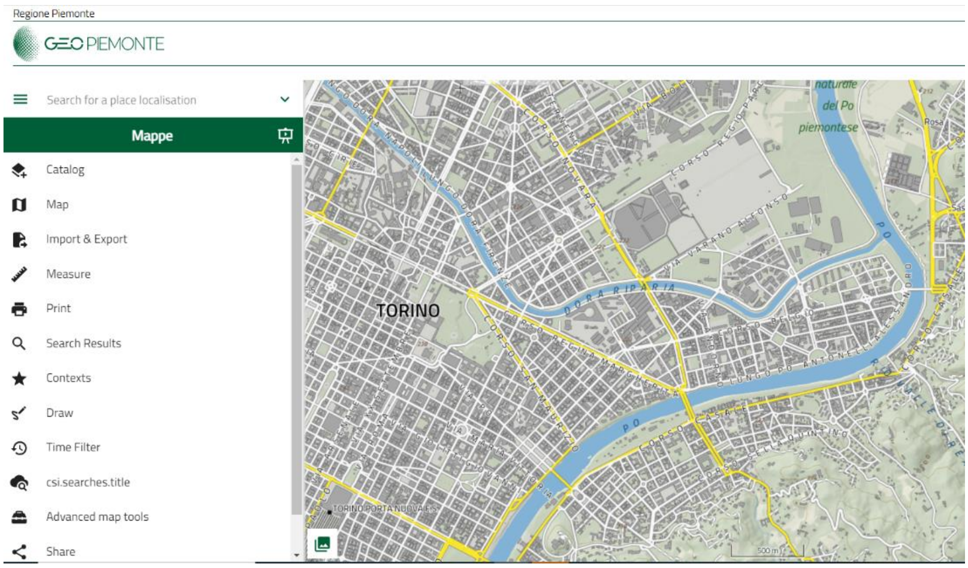


Figure 4.17: Geoportale Piemonte map viewer [36].

In addition to the catalog, within Geoportale Piemonte, it is possible to find the map viewer that allows navigation through data with configurative maps, as well as providing specific section for downloading packaged data by geographic area, as shown in Figure 4.17. This website also hosts initiatives and projects carried out in piedmont for the sharing and use of geographic data [36].

Therefore, in accordance with our case study goal, it was possible to search in the "Dati scaricabili per area geografica" the available option for DTM download. Here, zooming to the specific location of Via Cervino Street, and by clicking on a point within the mentioned desired area, is displayed the list with the available alternatives of download (Figure 4.18). A significant fact to highlight here is that, remembering the concept of DEMs resolution previously discussed, in the particular case of Geoportale Piemonte database, the provided DTM presents a resolution of 5m x 5m, so each cell composing the raster matrix on this provided elevation model has a dimension of 5m x 5m, which later will be treated and analyzed in the corresponding representation of the mid-block street basin.

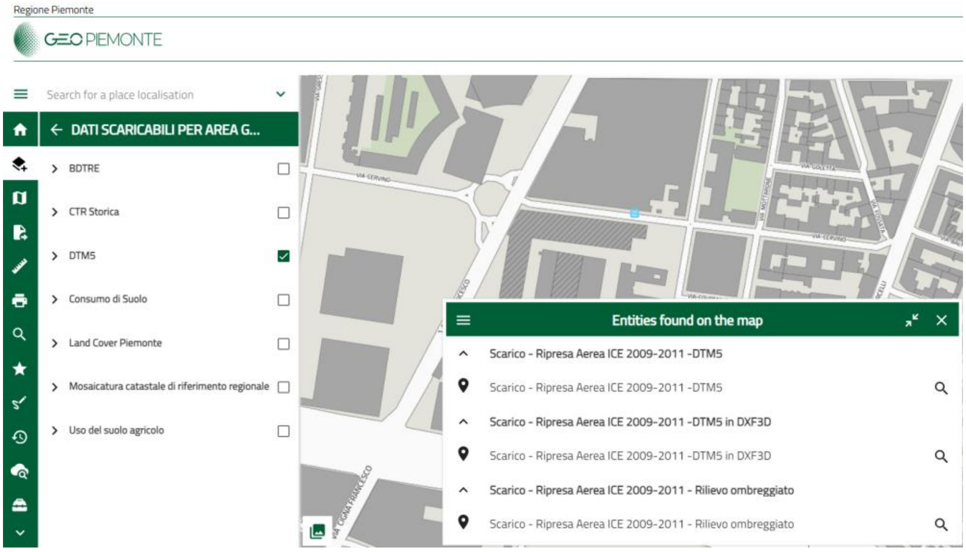


Figure 4.18: Via Cervino searched DTM in GeoPortale viewer [36].

Besides providing the required DTM5, extra information regarding and characterizing the study area was also supplied. In particular, a useful list of base maps as reported ahead with their corresponding denominatives in Italian original language:

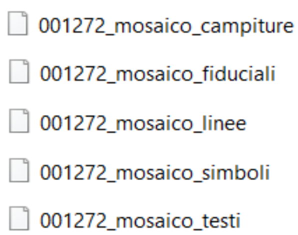


Figure 4.19: List of base maps provided by GeoPortale [36].

These lasts base files serve as an extra control to perform in order to be sure that the used digital elevation models have the corresponding reference system projection. In order to do so, we can use for instance a specialized software like Q-GIS in order to visualize and analyze the downloaded data, as well as to control the mentioned reference system.

Once opened Q-GIS, it is necessary to add a raster layer in order to visualize the downloaded DTM5 from GeoPortale Piemonte, while for projecting the base maps files, for instance the first one the “Mosaico_campiture” which could be translated as the “Urban backgrounds mosaic”, it is required to add a vector layer within the software available tools. After doing so, the visual result could be appreciated in the Figure 4.20:

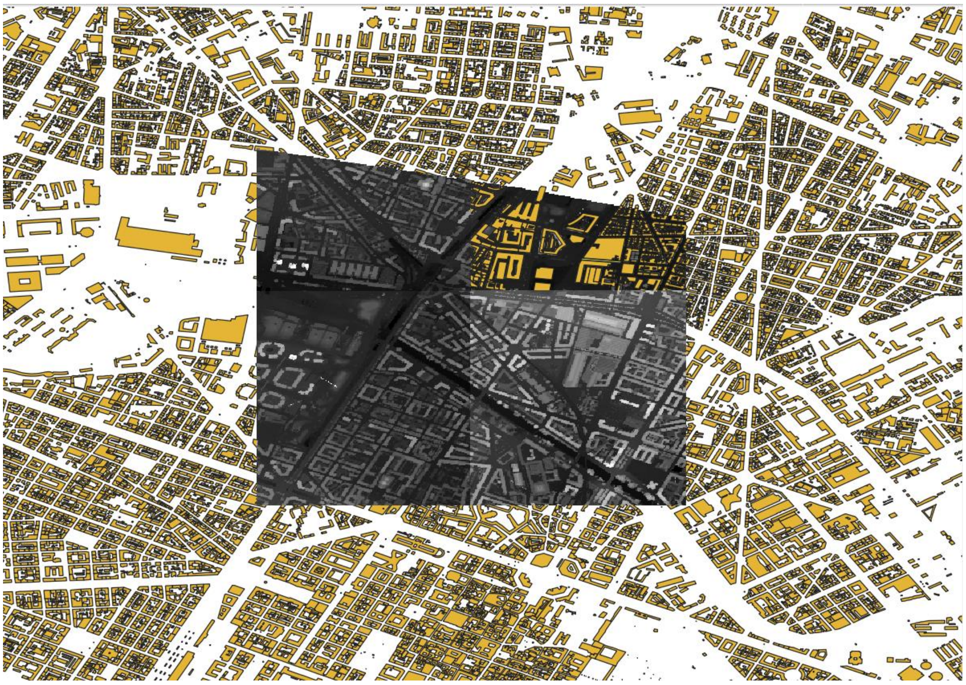


Figure 4.20: Visualization of the downloaded DTM5 and Base Maps within QGIS.

In the shown above figure, it is possible to observe both introduced layers: in “orange” tone the urban backgrounds representation, while in “black” shade refers to the DTM5 obtained. Moreover, visualizing more in detail into the specific Via Cervino location street, it is confirmed that the used downloaded data is precisely positioned within the desired study area as shown in Figure 4.21. On this last picture, besides showing again the two previously mentioned added layers, it is added a polygon layer (green rectangle on the image) encompassing Via Cervino in the block of interest for the present work. Therefore, it is verified that both Digital Terrain Model and Base Maps downloaded from Geoportale Piemonte are according to the appropriate reference system projection.

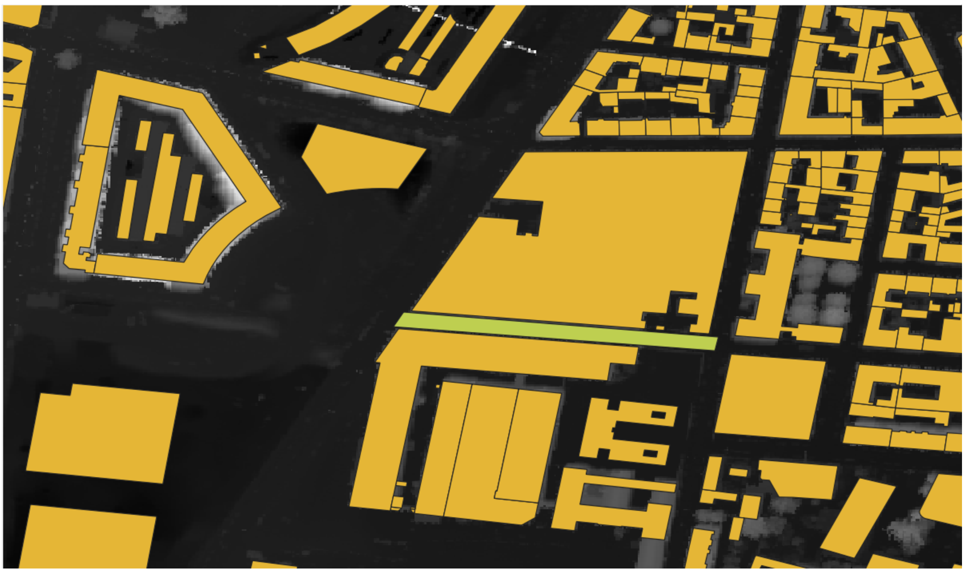


Figure 4.21: Via Cervino location presence within the used layers.

Recalling what was previously explained about DEMs resolution, in order to improve precision on the model construction, besides downloading a DTM with a mentioned resolution of 5m x 5m (which will be later analysed), it was of study interest also the obtention of a DEMs of 1m x 1m. Therefore, another data source had to be introduced, which is the so called “Geoportale Nazionale”.

The mentioned national geoportal is a cartographic database that spans from the years 1989/90 to the present day. GN users can access the data free of charge, representing the cornerstone of the National Data infrastructure (IDN), a network of peripheral nodes that enables central and local Public Administrations to exchange meta-information about the environment and territory quickly, allowing the use of database distributed among different entities [37].

The Environmental Remote Sensing Plan (both aerial and satellite) enables GN users, through a representative data repository of the national territory, to visualize essential information for the creation of high-value-added documents to intervene preventively in areas at high hydrogeological risk [37].

Figure 4.22: Geoportale Nazionale used DSM source [38].

Within the available dataset in the quoted website, the one of interest is represented by a Digital Surface Model (DSM) obtained by LiDAR methodology with a specific resolution of 1m x 1m which, as previously said, was the desired improved precision DEM, as shown in Figure 4.22. Nevertheless, in comparison with the elevation model of 5m x 5m which was available for the whole Turin city, in the case of the DSM 1x1 is only present for riparian areas [39].

A riparian zone can be defined as a transitional semi-terrestrial region, consistently affected by freshwater, typically spanning from the edges of water bodies to the boundaries of upland communities. These areas, play a pivotal role as key landscape elements, providing various functions and services such as stabilizing stream banks, minimizing sediment and nutrient pollution, enhancing both aquatic and terrestrial habitats, and offering recreational and educational possibilities. Lidar data with high-density point clouds (>10 points/m2) can offer a three-dimensional representation of floodplain features, particularly highlighting the characteristics and ecological attributes of riparian zones. This is achieved through the examination of a very high-resolution (<1 m GSD- Ground Sample Distance). Despite their effectiveness, conducting high-density Lidar surveys still incurs relatively high costs and is limited to specific, isolated surveys or local regions [40].

After discussing about the main attributes that characterize this alternative DSM raster matrix, in the particular case of Turin city area, the required elevation model pointed in Figure 4.23 could also be visualized through QGIS software:

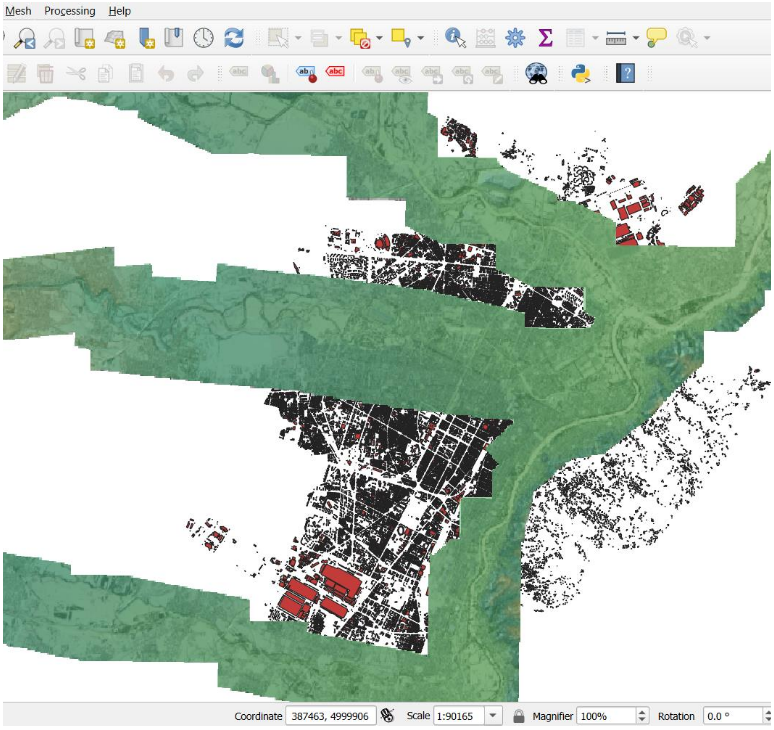


Figure 4.23: Piedmont Region DSM raster with Turin urban background on QGIS.

As observed, according to previously explained attributes regarding DSM with 1m x 1m resolution, the available provided DSM raster only covers the riparian areas related to the two main rivers present in Turin: Fiume Po and Fiume Dora.

In the same way done for the DTM of 5x5 resolution, it is required to verify the georeferenced system projection from the downloaded DSM 1x1 resolution. Hence, using the previously mentioned base maps which describe the urban background of Turin, is possible to localize the study area of Via Cervino within the DSM applied, as reported in Figure 4.24 where a "yellow rectangle" is positioned in the place where is effectively located the area of interest.

Figure 4.24: Via Cervino street position within the used DSM

4.4. GIS tools outside and inside HEC-HMS

As mentioned before, elevation data is not directly viewable in a browser, instead is necessary to take advantage of a specialized software like Geographic Information System (GIS). In our case, the chosen program to visualize and modify the elevation data of interest was the Q-GIS software.

QGIS is a freely available cross-platform desktop application for geographic information systems (GIS). It enables users to view, edit, print, and analyze geospatial data, providing several types of layers such as raster, vector, and mesh. In addition, QGIS facilitates easy sharing and publication of geospatial data in different file formats, including shapefiles, GeoTIFFs, and KML files [41].

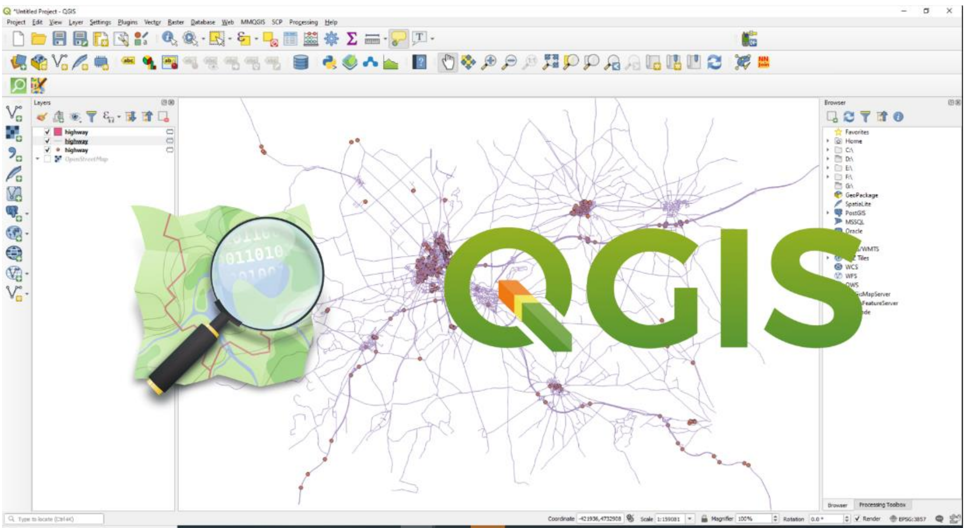


Figure 4.25: QGIS software interface [41].

Among the several utilities provided by QGIS software, the main one used in the present work was the clip instrument. The reason of this is because, digital elevation models downloaded as explained in the previous section have usually large dimensions in comparison with the mid-block street of interest for model construction. Consequently, in order to reduce memory requirement and time computation for the following steps, it was necessary to cut the original raster elevation model so as to arrive to the extension related to the area of study.

In particular, to cut a raster file (elevation models downloaded), the clip tool within QGIS was used. Specifically, the tool option named "Clip Raster by Mask Layer" was employed to perform the mentioned task, previously creating a polygon encompassing the mid-block street of interest in Via Cervino, as shown in Figure 4.26.

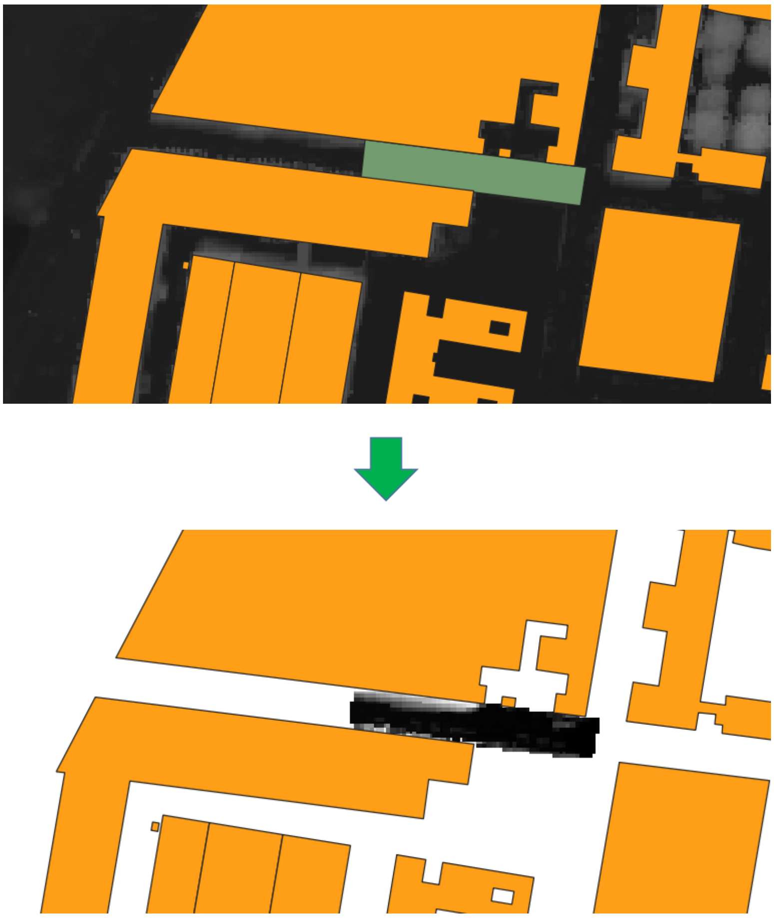


Figure 4.26: QGIS process of cutting original DEM to the required mid-block street dimension.

This last step was done for both the DTM with a resolution of 5m x 5m downloaded from Geoportale Piemonte, as well as for the DSM with a resolution of 1m x 1m downloaded from Geoportale Nazionale, in the following sections will be discussed which one of these was finally chosen to performing the hydrologic modeling.

Once obtained the required DEM dimensions for the model construction, it was time to start working with the previously selected software for our main hydrologic modeling purpose which was HEC-HMS. For doing so, QGIS allows the exportation of the previously clipped DEM, with the final appropriate dimensions, in a format that is compatible with those within HEC-HMS.

By opening HEC-HMS, the first task to perform is creating a new project and setting the desired program units: in our case the selected unit system was "Metrics". As a general overview, to analyze a hydrologic system, the following steps should be followed:

1. Create a new project.
2. Input shared component information.
3. Define the physical attributes of the watershed through the creation and modification of a basin model.
4. Outline the meteorological details through the generation of a meteorological model.
5. Specify simulation time widows by generating control specifications.
6. Create a simulation by combining the basin model, meteorological model, and control specifications.
7. View the results and, if desired, adjust data [32].

In order to represent the physical watershed, is required to create the basin model. So, by clicking on the "Components" tool and "Basin Model Manager", the needed component is generated. Then, hydrologic elements can be added and connected to one another to simulate the actual flow of water in a natural basin [32]. Moreover, to visualize the previously treated DEM inside HEC-HMS, again going on "Components" tool and "Terrain Data Manager" the mentioned elevation model is imported, as shown in Figure 4.27.

Once having the desired DEM inside HEC-HMS, is time to analyze and use the GIS tools available within the program for dealing with models that have spatial information. That is to say, including spatial references for hydrologic elements and tools for delineating a watershed from a digital elevation model. In particular, majority of these tools are found in the GIS menu, but they could also be placed in other program settings. Analyzing Figure 4.27, it is possible to distinguish the mentioned menu on the left-top corner of the shown program interface [32].

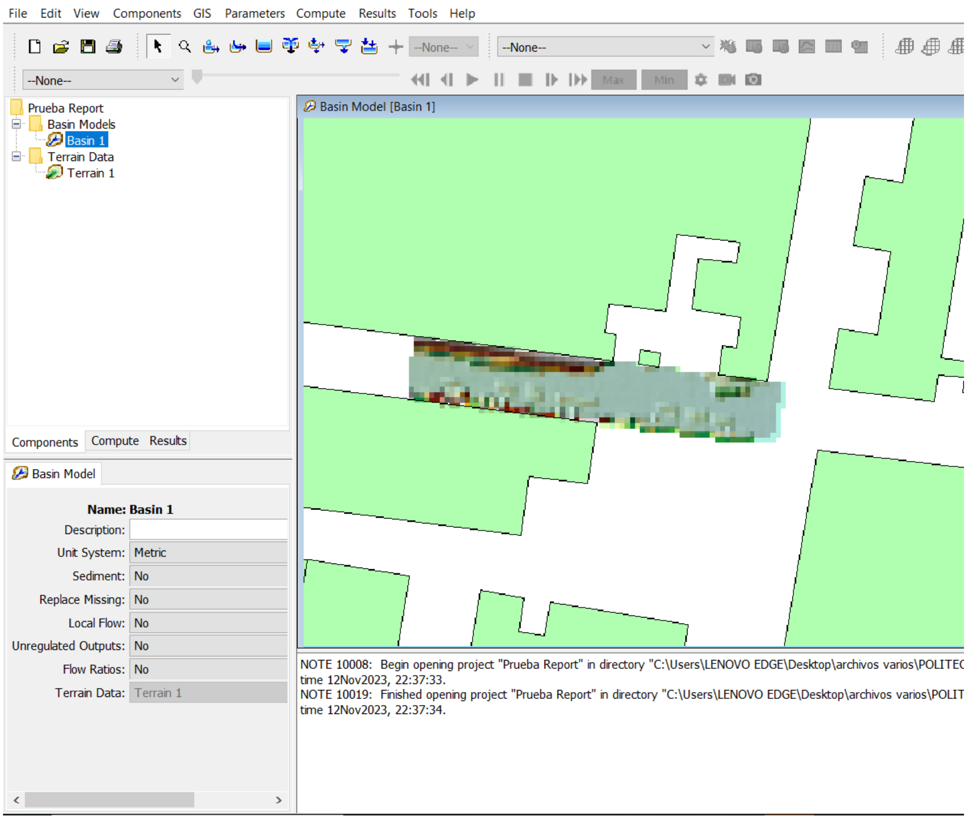


Figure 4.27: DEM of interest inside HEC-HMS.

Inside the GIS menu available in the program, there are several relevant tools to consider when processing a model. In addition, for a watershed delineation functions, this menu represents a sort of roadmap: the workflow proceeds from top to bottom in order.

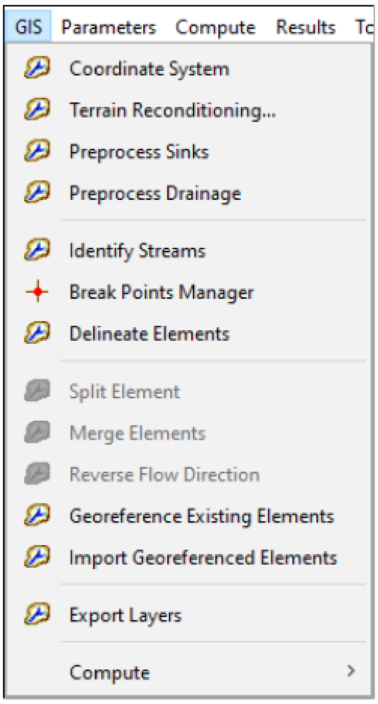


Figure 4.28: GIS menu tools within HEC-HMS [21].

In the following section, some of the available GIS tools applied for the model construction will be explained:

- <u>Coordinate System.</u>

If the basin model under consideration has no coordinate system assigned, then selecting the GIS Coordinate System tool will prompt the user to select a coordinate system for the spatial referencing of the basin model. Here, it is possible to choose a predefined coordinate system, or browse to GIS data with a coordinate system and selecting it [21].

In the model construction case, the basin model did not have a defined coordinate system. Then, once skipping the first option of selection a specific one among the possible previously explained options, the coordinate system was automatically set based on the GIS source data that we introduced. That is to say, the same one as the digital elevation model used, which is the shown in the Figure 4.29.

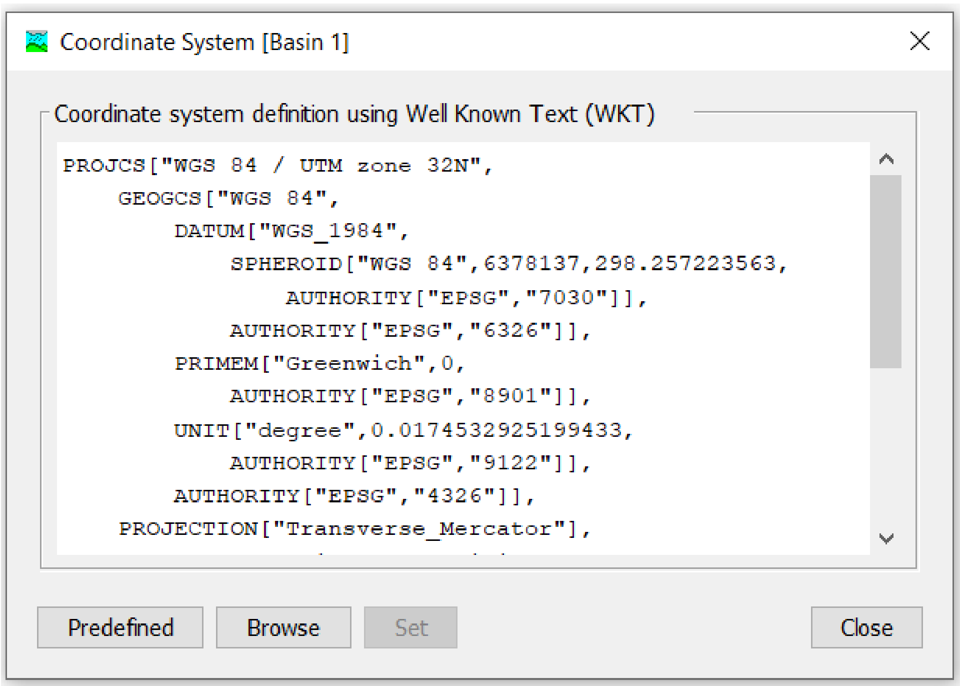


Figure 4.29: DEM coordinate system.

- <u>Preprocess Sinks.</u>

A sink could be defined as an area surrounded by higher elevation points, so it can also be referred to as a depression or a pit. These particular elements may be natural, or imperfections in the present DEM. Instead, a peak is an area surrounded by cells of lower value [21].

It is important to remove or fill them because they may lead to an erroneous flow-direction raster. Therefore, by selecting in the GIS menu the tool Preprocess Sinks it will run a pit removal algorithm on the terrain data assigned to the selected basin model. Then, it produces a new hydrologically corrected DEM and a raster which indicates the sinks position and the filled depth. In addition, these two new rasters are then introduced to the Map Layer list as Sink Fill and Sink Locations [21].

- Preprocess Drainage.

Another relevant GIS tool option is the one represented by Preprocess Drainage tool. By selecting the mentioned command, the software runs an algorithm to determine the flow direction and flow accumulation for each grid cell in the terrain data raster. Indeed, if previously used the Preprocess Sink tool, then the hydrologically corrected DEM will be the base model for defining the drainage pattern. Again, both resulting rasters are introduced to the Map layers list as Flor Direction and Flow Accumulation [21].

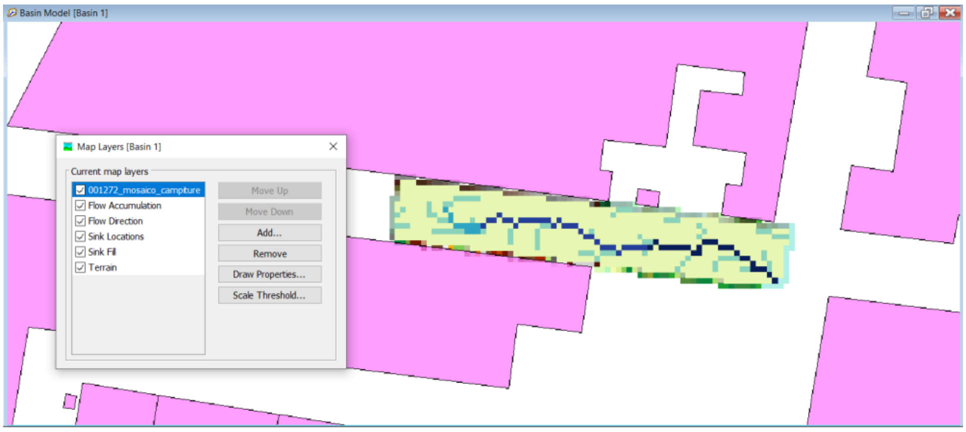


Figure 4.30: Map Layers applied elements activated.

4.5. Subbasins definition and precision criterion

With the aim of particularly defining the subbasins that will compose the hydrologic model, the following GIS tools are required:

- Identify Streams.

Before using the mentioned tool, it is necessary to have already created and selected a basin model, possessing a terrain data component, and executed the previously explained Preprocess Drainage command [21].

Then, selecting Identify Streams, it produces a prompt that requires to introduce the drainage accumulation threshold that will define where a stream starts. It could be used the default value based on the raster resolution, but it may produce undesired too fine (or too coarse) of a threshold for the intended delineation. In other words, the value introduced will be the approximate drainage area for the subbasin elements that result [21].

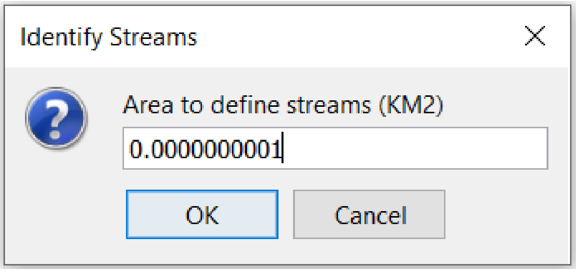


Figure 4.31: Value area to define streams.

As a rule, the smaller the value area, denser stream network. So, to obtain the densest stream network, it was introduced the smallest acceptable value in the software, as shown in Figure 4.31.

- Break Points Manager.

In order to perform the watershed delineation, at least one break point must be introduced, which will define the watershed outlet. We must pay attention that the introduced Break point should be within the previously defined stream flow, in particular inside the cell which possesses the mentioned flow [21].

Figure 4.32: HEC-HMS model outlet (left) and Via Cervino street outlet (right).

Once applied the explained GIS tools, it is possible to visualize the resulting flows on the software. Indeed, the positioned Break Point 1 (Figure 4.32) is in correspondence with the end flowing in the mid-block modelled basin, which verifies the position of the real street outlet as shown in the previous mentioned figure as well as in the Figure 4.33.

Figure 4.33: Real outlet (storm drain) of the mid-block street modelled.

- <u>Delineate Elements.</u>

Upon completion of the preceding steps, it was time for subbasins creation. That is to say, the total mid-block street area representing the basin model will be subdivided, for the hydrologic analysis, into subbasins with their corresponding extra elements and connections [21].

Once selected GIS Delineate Elements tools, a prompt that requires entering the information reported in Figure 4.34 will be produced. Subbasins Prefix, Reach Prefix, and Junction Prefix options are text strings needed for the automatic numbering scheme in the element's creation during delineation process [21].

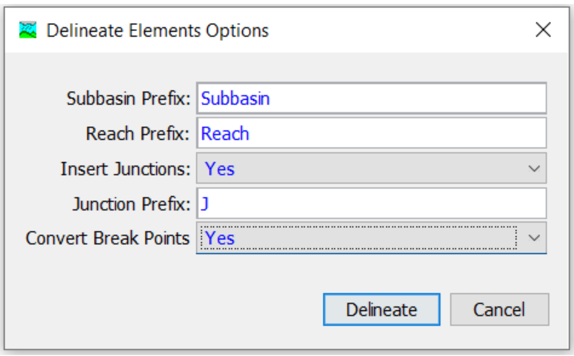


Figure 4.34: Inputs reference for Delineate Elements process.

In particular, the Convert Break points option will produce that in any place where break points are present, to transform into computation points in the basin model. Moreover, the most downstream break point, that represents the watershed outlet, will produce the generation of a sink element at that point. It is important to remark that

Delineate Elements can be re-run any time there is a change in the threshold for the Identify Streams tool, so it can be re-delineated [21].

Once finished the process of delineating elements, subbasins composing the total basin are created, with their corresponding hydrologic elements, which can be described as reported in Figure 4.35.

Hydrologic Element	Description
Subbasin	The subbasin is used to represent the physical watershed. Given precipitation, outflow from the subbasin element is calculated by subtracting precipitation losses, calculating surface runoff, and adding baseflow.
Reach	The reach is used to convey streamflow in the basin model. Inflow to the reach can come from one or many upstream elements. Outflow from the reach is calculated by accounting for translation and attenuation. Channel losses can optionally be included in the routing.
Junction	The junction is used to combine streamflow from elements located upstream of the junction. Inflow to the junction can come from one or many upstream elements. Outflow is calculated by summing all inflows.
Source	The source element is used to introduce flow into the basin model. The source element has no inflow. Outflow from the source element is defined by the user.
Sink	The sink is used to represent the outlet of the physical watershed. Inflow to the sink can come from one or many upstream elements. There is no outflow from the sink.

Figure 4.35: Hydrologic elements within HEC-HMS [32].

Recalling what was explained in section 4.3 Elevation Data download, it was appropriately indicated that two types of DEMs were acquired with different attributes:

- Digital Terrain Model (DTMs) with resolution 5m x 5m from Geoportale Piemonte.
- Digital Surface Model (DSMs) with resolution 1m x 1m from Geoportale Nazionale.

Therefore, the recent procedure involving GIS Menu Tools implemented to define and create the possible subbasins responsible for representing the total basin area, can be applied to both DEMs so as to compare their results and precision, with the final goal of choosing the most appropriate elevation model for the ongoing steps in the hydrologic modelling. Hence, in the following pictures both results can be appreciated:

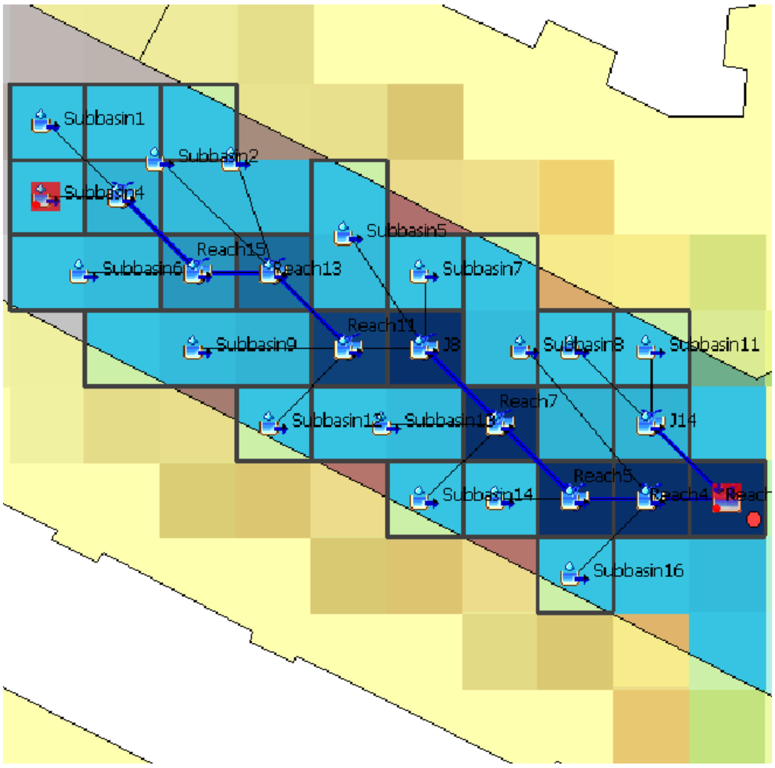


Figure 4.36: DTM 5x5 subbasins configuration density.

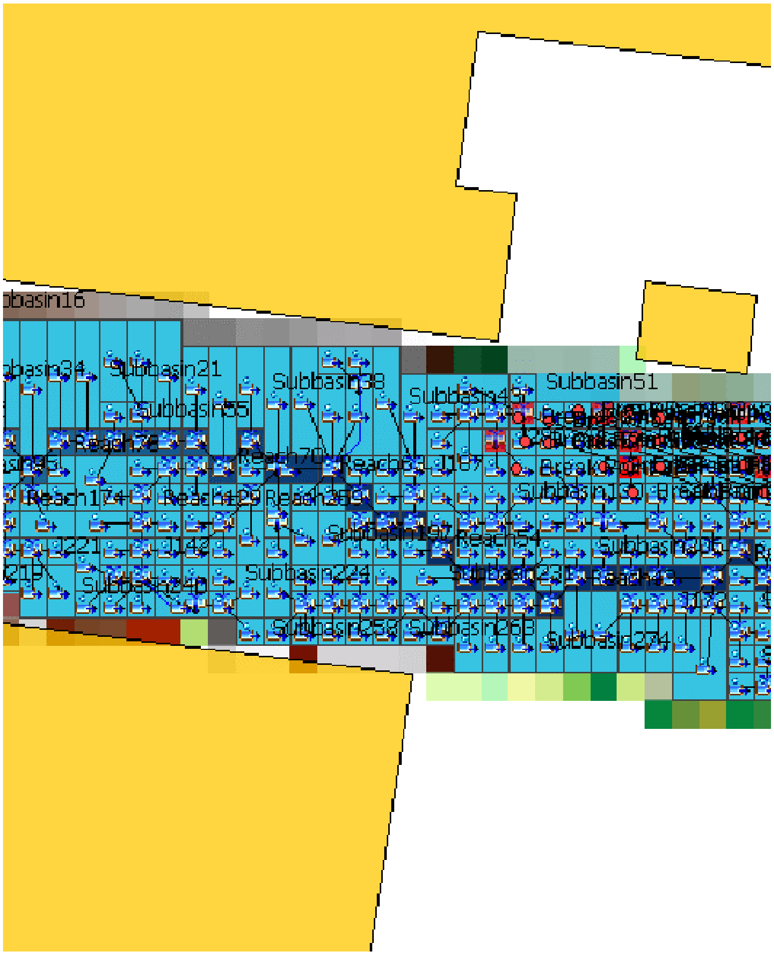


Figure 4.37: DSM 1x1 subbasins configuration density.

By comparing both configurations' results, it is remarkable the precision and density quality between the two different elevation models. On one side, for the DTM with 5m x 5m resolution there are wasted and unconsidered spaces between the street and the path, as well as much less amount of subbasins elements generated as observed in Figure 4.36. On the other hand, for the DSM with 1m x 1m resolution there are much less neglected regions in the street boundaries, while the subbasin quantity is much bigger. Consequently, in order to have the maximum possible precision and a respectful representation with the reality, DTM5 was discarded for the hydrologic modeling, moving forward with the resulting subbasins from the DSM 1x1.

4.6. Defined subbasins and its connections

If different subbasins are hydrologically connected, HEC-HMS also allows the utilization of another GIS Tools such as Merge and Split. So, to have a more manageable subbasins quantity, it was decided to merge the total obtained quantity in the delineation process presented in 4.37 into a set of subbasins which can be integrated into 3 main groups:

- Subbasins representing the SuDS area.
- Subbasins representing areas surrounding each SuDS element which collaborate in collecting water into the mentioned drainage systems.
- Subbasins representing areas to cover the rest of the mid-block street total basin.

A panoramic view of the final configuration is reported in Figure 4.38:

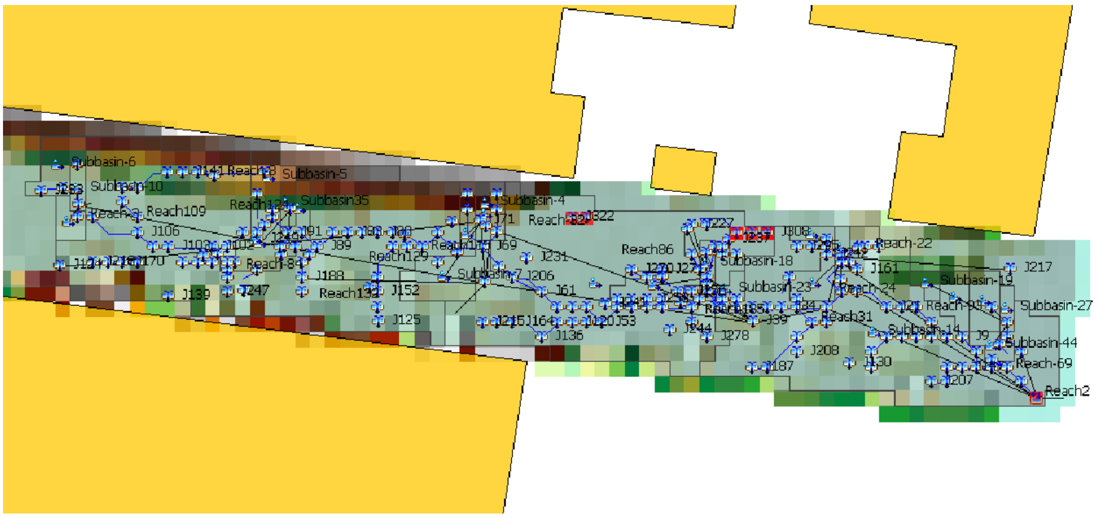


Figure 4.38: Basin Model configuration of Via Cervino.

For a better understanding of the obtained Basin Model configuration, the different final elements composing the hydrologic model will be identified in the following section:

Subbasin	Area (KM2)
Subbasin-5	0.000008
Subbasin-4	0.000007
Subbasin-10	0.000003
Subbasin35	0.000003
Subbasin48	0.000003
Subbasin-18	0.000003
Subbasin-27	0.000003
Subbasin-6	0.000011
Subbasin-9	0.000008
Subbasin-1	0.000013
Subbasin-11	0.000006
Subbasin-7	0.000016
Subbasin-22	0.000003
Subbasin-13	0.000005
Subbasin-12	0.000215
Subbasin-20	0.000010
Subbasin-23	0.000004
Subbasin-32	0.000145
Subbasin-53	0.000003
Subbasin-25	0.000008
Subbasin-8	0.000007
Subbasin-44	0.000004
Subbasin-19	0.000003
Subbasin-14	0.000154
Subbasin-3	0.000007
Subbasin-2	0.000003

Figure 4.39: List of subbasins modelled areas.

Figure 4.40: Basin Model subbasins identification scheme.

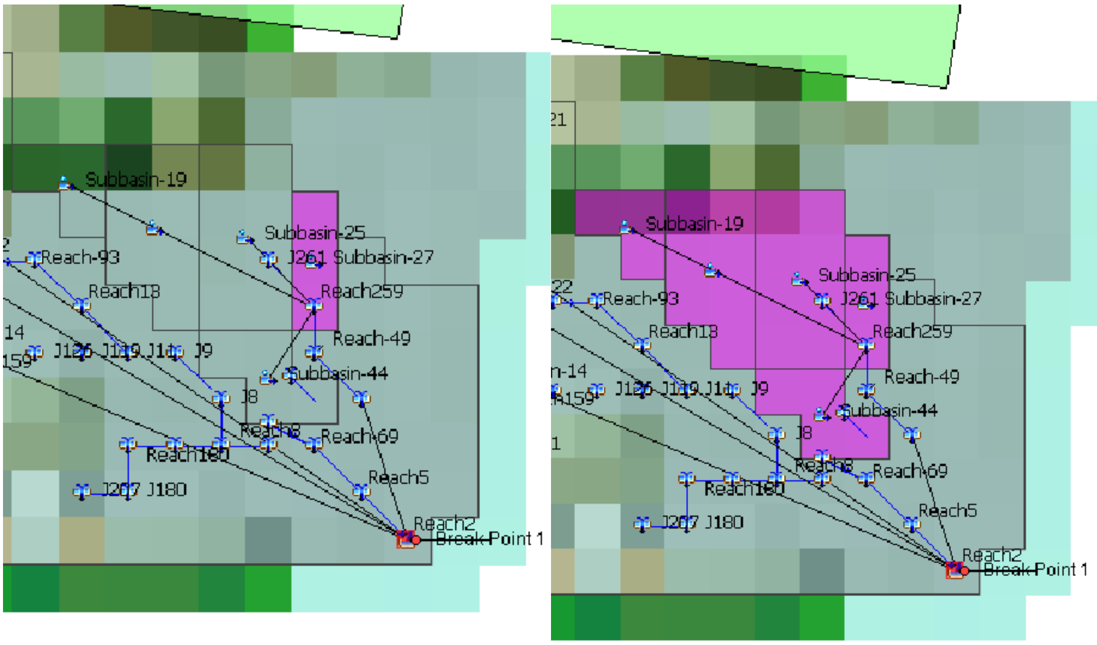


Figure 4.41: SuDS N°1 (left) and its collaborating areas (right).

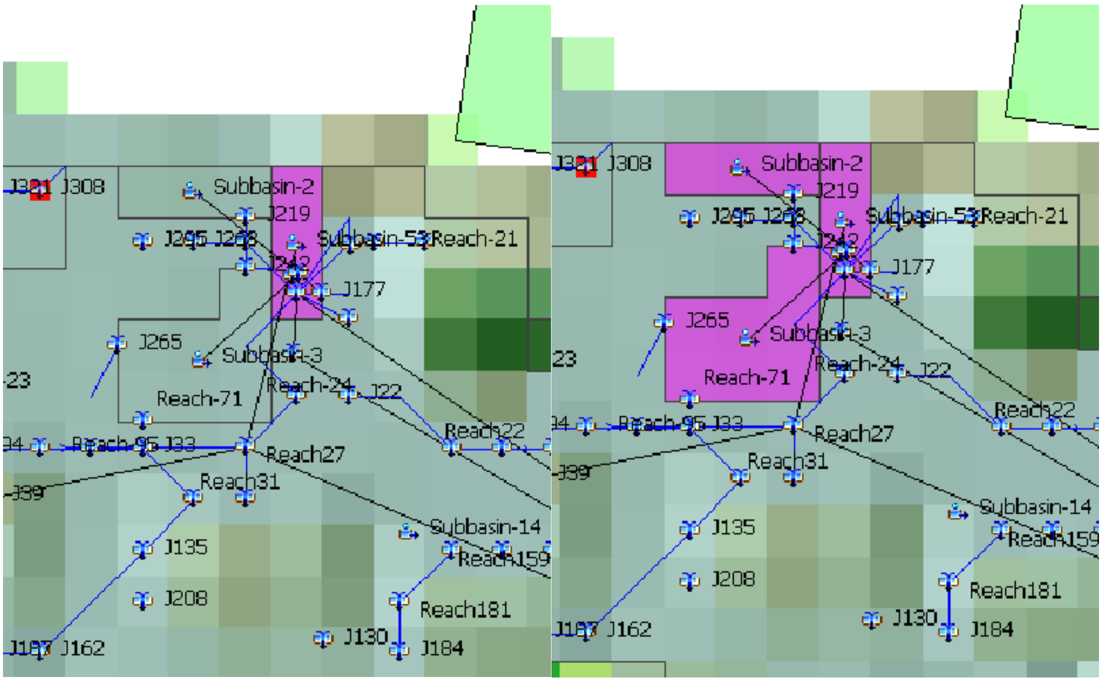


Figure 4.42: SuDS N°2 (left) and its collaborating areas (right).

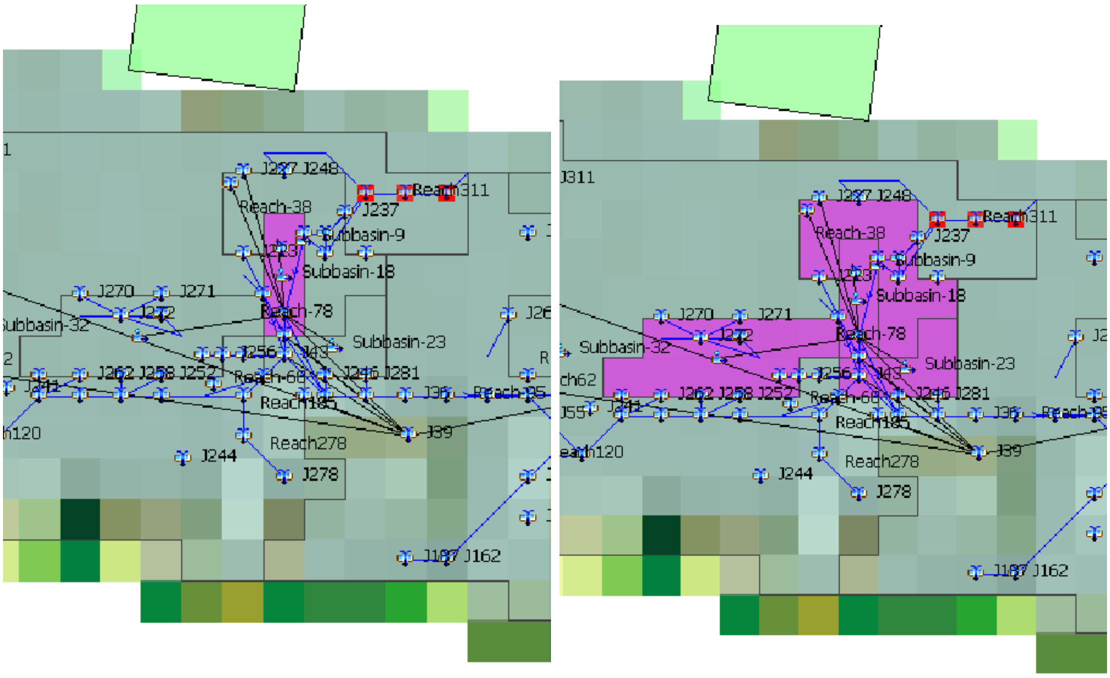


Figure 4.43: SuDS N°3 (left) and its collaborating areas (right).

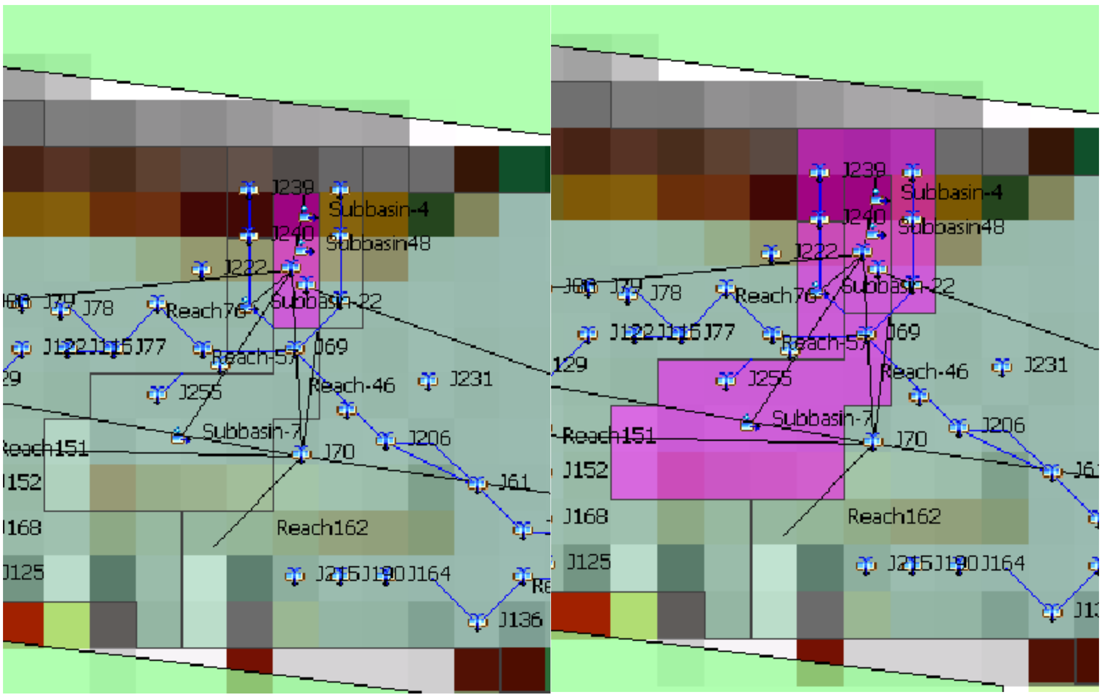


Figure 4.44: SuDS N°4 (left) and its collaborating areas (right).

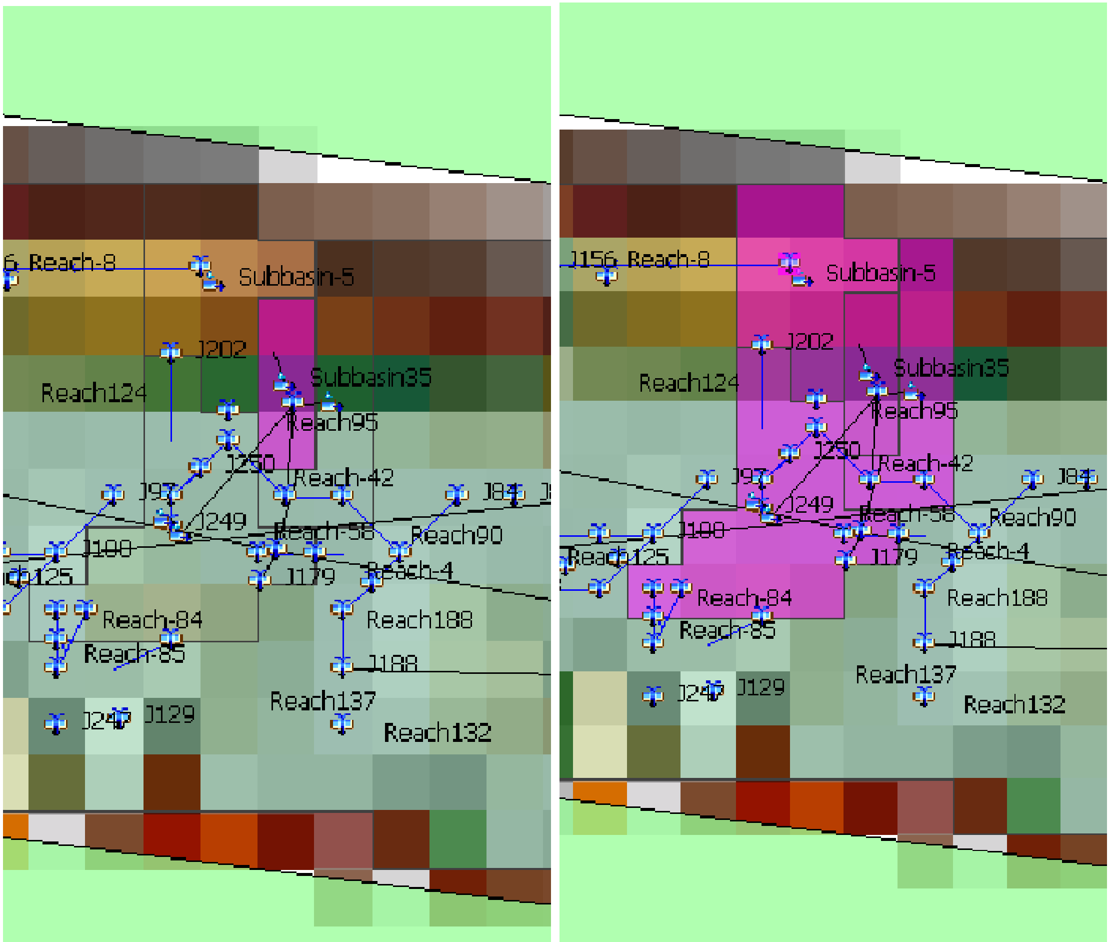


Figure 4.45: SuDS N°5 (left) and its collaborating areas (right).

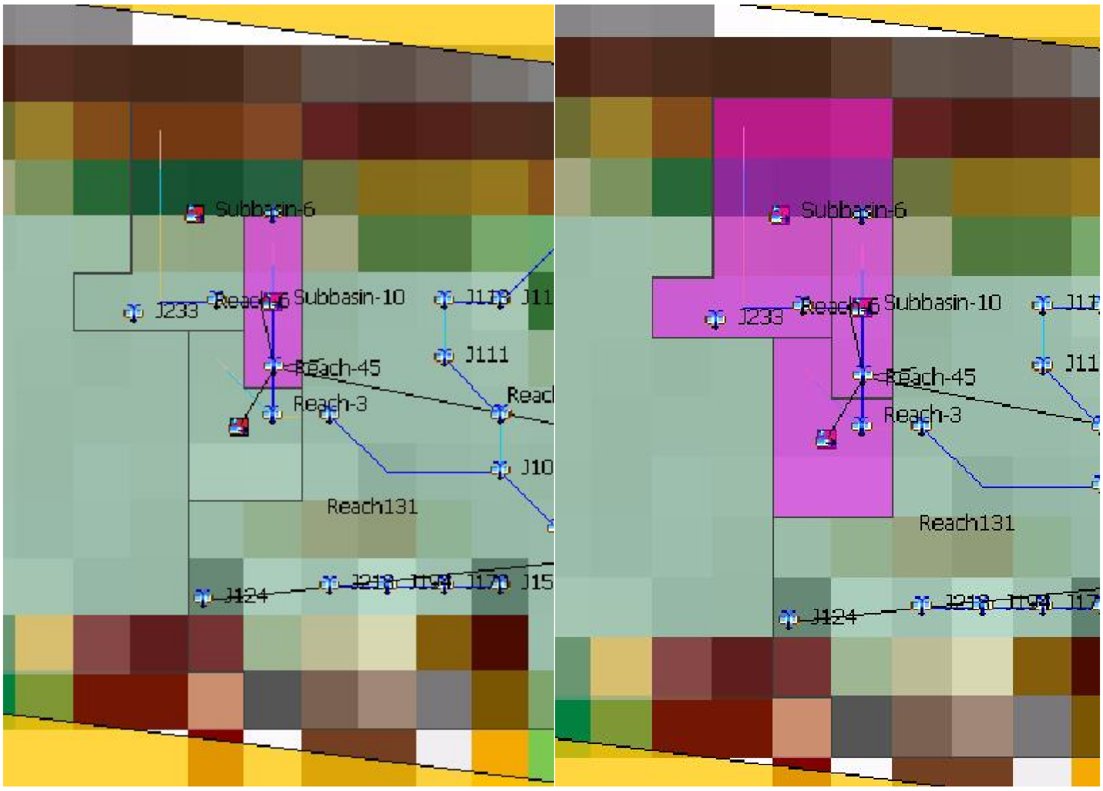


Figure 4.46: SuDS N°6 (left) and its collaborating areas (right).

Chapter 5

Hydrologic methods

Once built the basin which represents the hydrologic system of interest within the mid-block street area, with its required elements and attributes which characterize the mentioned system, it is necessary to define the main hydrologic methods to apply in the simulations.

As previously mentioned, HEC-HMS program uses several methods to represent each component of the runoff process, including those who process precipitation, compute infiltration and resulting runoff, describe baseflow and computing channel flow. The importance of these presented techniques is relevant because they address significant questions such as how much water infiltrates on pervious surfaces? how much runs off of the impervious ones? When does it runoff? In addition, some of them describe what happens as water that has not infiltrated or been stored, moves over or just beneath watershed surface, moreover, simulating slow subsurface drainage water from the system into channel [32].

In other words, under these methodologies rely the physics and hydraulics processes involved in every part of the precipitation-runoff transformation on a watershed. Therefore, if the goal is to model a representative hydraulic response of the area of interest, appropriate methods should be selected as well as adequate parameters values on each of them must be defined so as to replicate with the highest precision and fidelity possible the phenomena under study.

5.1. Loss method

Regarding the different types of possible loss methods available inside HEC-HMS, for all of them precipitation loss is found for each computation time interval, being then subtracted from the precipitation depth for the same considered period. Consequently, remaining depth is called precipitation excess, which is considered to be uniformly distributed over the watershed area, representing volume of runoff [32].

Program includes various loss methods, some of which are gridded. These particular methods assume that a subbasin consists or regularly spaced cells with equal dimensions. It allows users to set specific initial conditions and parameters for each grid cell independently from its neighboring cells. Conversely, all other loss methods model the entire subbasin using a single set of initial conditions and parameters [32].

In the present thesis, the deficit and constant loss method will be used, which in particular when paired with a canopy technique (is the rainfall intercepted by tree canopy and successively evaporated from leaves), enables ongoing simulation. In particular, this combination operates by extracting water from the soil in response to potential evapotranspiration (ET) calculated in the meteorological model. During periods between precipitation events, the soil layer gradually loses moisture due to the canopy extracting water that has infiltrated the soil. Unless a canopy method is selected, no soil water extraction occur. This approach can also be combined with a surface method designed to retain water on the land surface, water held in surface storage has the ability to seep into the soil later and/or be removed through evapotranspiration. The rate at which infiltration occurs depends then on soil layer's capacity to absorb water [32].

<u>Infiltration</u>

Regarding infiltration, the soil layer utilized within the deficit and constant loss model possesses a maximum capacity to retain water. Saturation of the soil occurs when it reaches the maximum storage capacity, and it remains unsaturated when the layer contains less than this capacity. Then, deficit is the water quantity needed at any given time to saturate the soil layer. So, if deficit equals zero, layer is saturated. Conversely, when the layer is not saturated, the deficit is the amount of water that must be added to bring it to saturation. Moreover, difference between maximum capacity and deficit indicates the volume of water currently stored, which is assumed to be uniformly spread across soil layer, whose properties are presumed to be uniform [32].

At the onset of a storm event, the soil layer typically has a specific moisture deficit. This value might be zero, suggesting complete saturation of the soil. However, it is more typical for the layer to exhibit a deficit exceeding zero, indicating it is unsaturated state. Under circumstances where there has been an extended absence of rain and evapotranspiration has drawn out all moisture from the soil layer, the moisture deficit might align precisely with the maximum capacity possible [32].

When the deficit in the soil layer exceeds zero, it is presumed to have an unlimited capacity of infiltration. This implies that when the layer is below its saturation point, all precipitation will seep into the soil until it reaches saturation. This assumption simplifies the model, as in reality, rainfall rates can surpass the soil's infiltration rate, leading to direct runoff when soil is not saturated. However, within this model, all precipitation is assumed to infiltrate until the soil reaches saturation. Moreover, once water infiltrates, it remains within the soil layer and does not percolate out [32].

Percolation and Excess Precipitation

Water exits the bottom of the soil layer when precipitation occurs, and the deficit reaches zero. This process involves precipitation seeping from the soil surface into the soil layer, and then percolating through the soil layer, eventually passing out from the layer's base. This water is lost from the system unless the linear reservoir baseflow method is employed, in which case, percolation water transforms into baseflow. Percolation will persist as long as the soil layer retains its maximum storage capacity and precipitation continues. If the rate of precipitation exceeds the percolation rate, only precipitation equivalent to the percolation rate will infiltrate the soil layer and percolate out. Any precipitation surpassing this rate becomes excess precipitation and contributes to direct runoff. Conversely, if the precipitation rate falls below percolation rate, all of the precipitation will infiltrate into the soil layer and percolate out, so no excess precipitation occurs. Therefore, percolation can occur only while the soil layer remains saturated [32].

Evapotranspiration

This process removes the water present in the soil between different storm events. . The potential evapotranspiration rate, derived from the meteorological model, employs various methods to represent this process. Without alteration, this evapotranspiration rate is directly utilized as specified by the meteorological model. During precipitation-free time intervals, water is extracted from the soil layer at this potential rate. However, once the water in the soil layer diminishes to zero, evapotranspiration ceases. As soon as water reappears in the soil layer in the absence of precipitation, evapotranspiration resumes its process [32].

Required Parameters

Initial Deficit: is the volume of water that is required to fill the soil layer at the beginning of the simulation.

Maximum Deficit: represents the total amount of water that the soil can hold. In particular, initial deficit must be less than or equal to maximum deficit, both parameters are specified as effective depths (inches, millimeters).

Constant Rate: specifies the rate at which precipitation will be infiltrated into the soil layer after the initial deficit has been satisfied in addition to the rate at which percolation occurs once soil is saturated. Commonly, this parameter is equated with saturated hydraulic soil conductivity.

Percentage of Impervious Area: directly connected impervious areas are surfaces where runoff is conveyed directly to a waterway or collection system. These areas are different than disconnected impervious areas where runoff find permeable areas which may infiltrate some of the water excess before reaching waterway or collection system. Moreover, no loss calculations are carried out on the specified percentage of the subbasin. Then, all precipitation that falls on this portion of the subbasin becomes excess precipitation and subject to direct runoff.

Once explained the basics under which the applied loss method works, in the following pictures will be presented the different subbasins cases with their corresponding parameters for the used loss method:

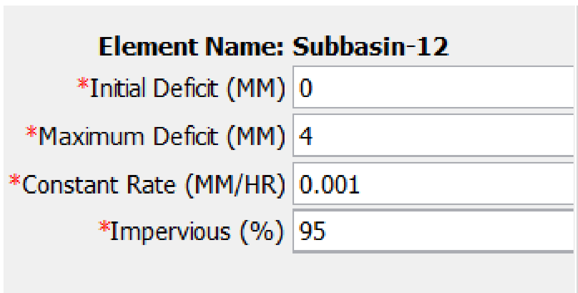


Figure 5.1: Subbasin representing impermeable existing surface without SuDS.

A common subbasin representing any part of the impermeable surface, where there are pavement and curb elements, can be modelled considering values reported in Figure 5.1, with an impervious area of 95% and an almost null constant rate of infiltration of about 0.001 mm/h.

On the other hand, to represent the specific SuDS system, the methodology implemented was based on the modification of the last two explained parameters. Specifically, for each one of the 6 SuDS system under analysis, was considered an impervious area of 0%, while for the constant rate parameter the criteria selected was to compare three different materials with their associated constant rate capacity:

- Material 1: with a Constant Rate capacity of 5 mm/h.
- Material 2: with a Constant Rate capacity of 20 mm/h.
- Material 3: with a Constant Rate capacity of 160 mm/h.

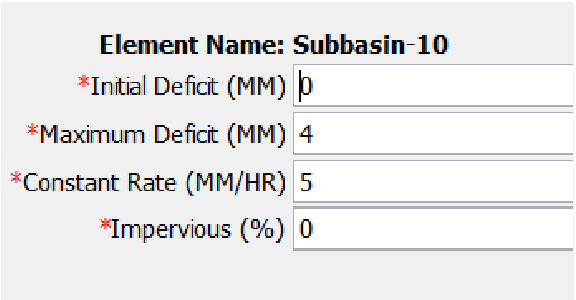


Figure 5.2 Subbasins representing a SuDS system with Material 1.

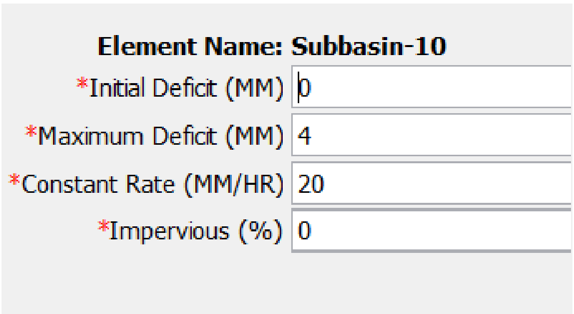


Figure 5.3: Subbasin representing SuDS system with Material 2.

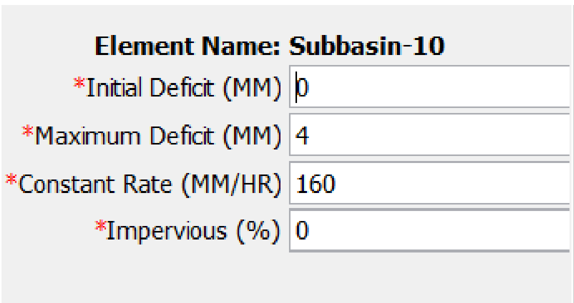


Figure 5.4: Subbasin representing SuDS system with Material 3.

5.2. Baseflow method

As water permeates into the subsurface, a portion of it may be lost to deep aquifer storage, while another part is momentarily stored and will swiftly return to the surface. The combination of this baseflow and immediate runoff leads to the formation of a comprehensive runoff hydrograph. Among the different available options for representing the baseflow, the method selected for the present modelling is the so-called Linear Reservoir Model. Referring to its name, this technique uses one to three linear reservoirs (layers) to simulate the recession of baseflow after a storm event [32].

Particularly, unlike other baseflow methodologies of HEC-HMS, this method is guaranteed to conserve mass, so baseflow volume cannot exceed precipitation losses. So, volume of infiltrated water is used as inflow to the Linear Reservoir method. The input can be distributed among individual layers, apart from recharging the deep aquifer. Consequently, higher infiltration periods result in increased generation of baseflow. Conversely, periods with minimal or no infiltration lead to reduced baseflow generation [32].

A significant attribute to highlight is that this baseflow method can be used with any loss method, with the following parameters requirements in order to utilize it:

- Number of reservoirs/layers.
- Initial baseflow type and value.
- Partition fraction.
- Routing coefficient (hours)
- Number of routing steps for each layer.

The initial discharge can be defined in two ways: as a discharge rate (measured in ft^3/sec or m^3/sec) or as a discharge rate per area (expressed in $ft^3/sec/mi^2$ or $m^3/sec/km^2$). Opting for the discharge rate method is suitable when observed streamflow data at the subbasin outlet helps determine the initial channel flow. Alternatively, the discharge rate per area method is preferable when regional data is accessible. However, it's important to use the same method consistently to specify the initial condition across all layers [32].

The partition fraction determines the inflow allocation to each layer. Each fraction must exceed 0.0, and their sum should be less than or equal to 1.0. If the sum falls short of 1.0, the remaining volume will be removed from the system (i.e., as deep aquifer recharge). When the sum equals exactly 1.0, all percolation converts to baseflow, eliminating deep aquifer recharge. The routing coefficient stands as the time constant for each layer, this coefficient can be evaluated using measurable characteristics of the watershed. The number of routing steps subdivides the routing through each layer and is linked to the level of attenuation during routing. Opting for a single routing step achieves minimal attenuation, while increased routing steps intensify baseflow attenuation [32].

Subbasin	Number of Layers	Initial Type	GW 1 Flow Type	GW 1 Initial (M3/S)	GW 1 Initial (M3/S /KM2)	GW 1 Fraction	GW 1 Coefficient (HR)	GW 1 Reservoirs
Subbasin-1	2	Discharge	Baseflow	0		0.5	0.162	1
Subbasin-11	2	Discharge	Baseflow	0		0.5	0.162	1
Subbasin-7	2	Discharge	Baseflow	0		0.5	0.162	1
Subbasin-22	2	Discharge	Baseflow	0		0.5	0.162	1
Subbasin-13	2	Discharge	Baseflow	0		0.5	0.162	1
Subbasin-20	2	Discharge	Baseflow	0		0.5	0.162	1
Subbasin-23	2	Discharge	Baseflow	0		0.5	0.162	1
Subbasin-53	2	Discharge	Baseflow	0		0.5	0.162	1
Subbasin-25	2	Discharge	Baseflow	0		0.5	0.162	1
Subbasin-8	2	Discharge	Baseflow	0		0.5	0.162	1
Subbasin-44	2	Discharge	Baseflow	0		0.5	0.162	1
Subbasin-19	2	Discharge	Baseflow	0		0.5	0.162	1
Subbasin-3	2	Discharge	Baseflow	0		0.5	0.162	1
Subbasin-2	2	Discharge	Baseflow	0		0.5	0.162	1

GW 2 Flow Type	GW 2 Initial (M3/S)	GW 2 Initial (M3/S /KM2)	GW 2 Fraction	GW 2 Coefficient (HR)	GW 2 Reservoirs
Baseflow	0.0000		0.5	0.54	1
Baseflow	0.0000		0.5	0.54	1
Baseflow	0.00		0.5	0.54	1
Baseflow	0.0000		0.5	0.54	1
Baseflow	0.0000		0.5	0.54	1
Baseflow	0.00		0.5	0.54	1
Baseflow	0.0000		0.5	0.54	1
Baseflow	0.0000		0.5	0.54	1
Baseflow	0.0000		0.5	0.54	1
Baseflow	0.0000		0.5	0.54	1
Baseflow	0.0000		0.5	0.54	1
Baseflow	0.0000		0.5	0.54	1
Baseflow	0.0000		0.5	0.54	1
Baseflow	0.0000		0.5	0.54	1

Figure 5.5: Base Flow Parameters used values.

5.3. Channel flow

In the moment when total runoff reaches the defined channels, there water depth increases and so the predominant flow regime starts a transition to open channel flow. When this happens, open channel flow approximations are considered in order to represent translation and attenuation effects as flood waves move downgradient. HEC-HMS has several models for this phenomenon, which are referred to as routing models. These methodologies evaluate a downstream hydrograph, given an upstream hydrograph as a boundary condition. In particular, they do so by solving continuity and momentum equations [32].

Among the possible routing methods, the one applied in the hydrologic model is the so-called Muskingum routing method. In this technique a conservation of mass is used to route flow through the stream reach, accounting for "looped" storage vs outflow relationships present in rivers. This allows to replicate the observed pattern of increased channel storage during rising side and decreased channel storage during falling side of a passing flood wave. For doing so, the overall storage within a specific area is conceptualized as the combined accumulation of prism (a rectangle-shaped component) and wedge (a triangular-shaped component) storage, illustrated in Figure 5.6. Then, during rising phases on the leading edge of a flood wave, wedge storage is positive and added to prism storage. On the contrary, during falling stages on the receding side of a flood wave, wedge storage is negative and subtracted from the prism storage. As a consequence, using the inclusion of a travel time for the reach and a weighting between the influence of inflow and outflow is feasible to approximate the reduction in intensity [32].

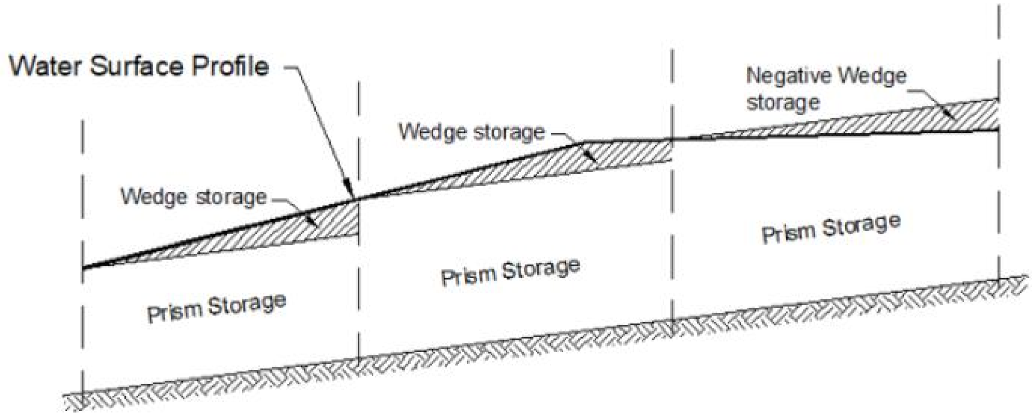


Figure 5.6: Muskingum route method scheme [32].

This method requires certain parameters to be used, among which we can mention the initial condition, K (hours), X, and the number of subreaches. Two options are provided for defining the starting state: equating outflow to inflow and specifying discharge. The initial outflow matching the initial inflow from the upstream elements is presumed in the first option, which is the same as assuming a steady-state initial condition. Second option instead is better suited when actual streamflow information is observed at the downstream end of the area. In both cases, initial storage is calculated considering initial inflow entering the area and its relationship between storage and discharge [32].

X is a dimensionless coefficient that lacks a strong physical meaning, ranging between 0 for maximum attenuation and 0.5 without attenuation. For majority of stream reaches, an intermediate value can be considered [32].

K is equivalent to the travel time through the reach. For an idealized channel, this parameter through a subreach should be approximately equal to the simulation time step. As a first estimation also, it can be obtained by dividing actual reach length by the product of the wave celerity and simulation time step [32].

Initial Discharge (M3/S)	Muskingum K (HR)	Muskingum X	Number of Subreaches
	0.016	0.2	1

Figure 5.7: Values used for Muskingum route method.

5.4. Transform method

These methodologies simulate the process of direct runoff of excess precipitation on a watershed. So, involves conversion of precipitation excess into point runoff. Program offers two alternatives for doing so: from one side there are empirical models. These are system-theoretic models, encompassing traditional unit hydrograph ones. These aims to establish cause-and-effect relationship between runoff and excess precipitation without detailing considerations of internal processes. The equations and parameters have limited physical significance. On the other hand, there are the so-called conceptual models. Among the possible available in the software, it is possible to mention Kinematic Wave model and the two-dimensional diffusion wave one. These last models strive to incorporate all feasible physical mechanisms governing the movement of excess precipitation across watershed [32].

On the present thesis, 2D Diffusion Wave transform method was applied. This one, routes excess precipitation throughout a subbasin element by employing a combination of the continuity and momentum equations. In contrast to unit hydrograph transformation techniques, this method enables simulation of non-linear flow of water across a subbasin when subjected to large quantities of excess precipitation [32].

The approach 2D Diffusion Wave Method is employing a representation of the subbasin through a 2D grid, consisting of grid cells and cell faces. Each of them are characterized by hydraulic properties tables derived from details of the underlying terrains, so represents a high-resolution subgrid model. For doing so, users are required to create a 2D mesh (along with connections) within HEC-RAS, and then import it into HEC-HMS. In particular, 2D mesh preprocessor in HEC-RAS generates two crucial components: 1) an elevation-volume relationship for each grid cell and 2) cross-sectional data such as elevation-wetted perimeter area, roughness, etc. for each cell. Moreover, the overall advantage of employing a subgrid model like this include reducing computational requirements, faster processing times, enhanced stability, and improved accuracy [32].

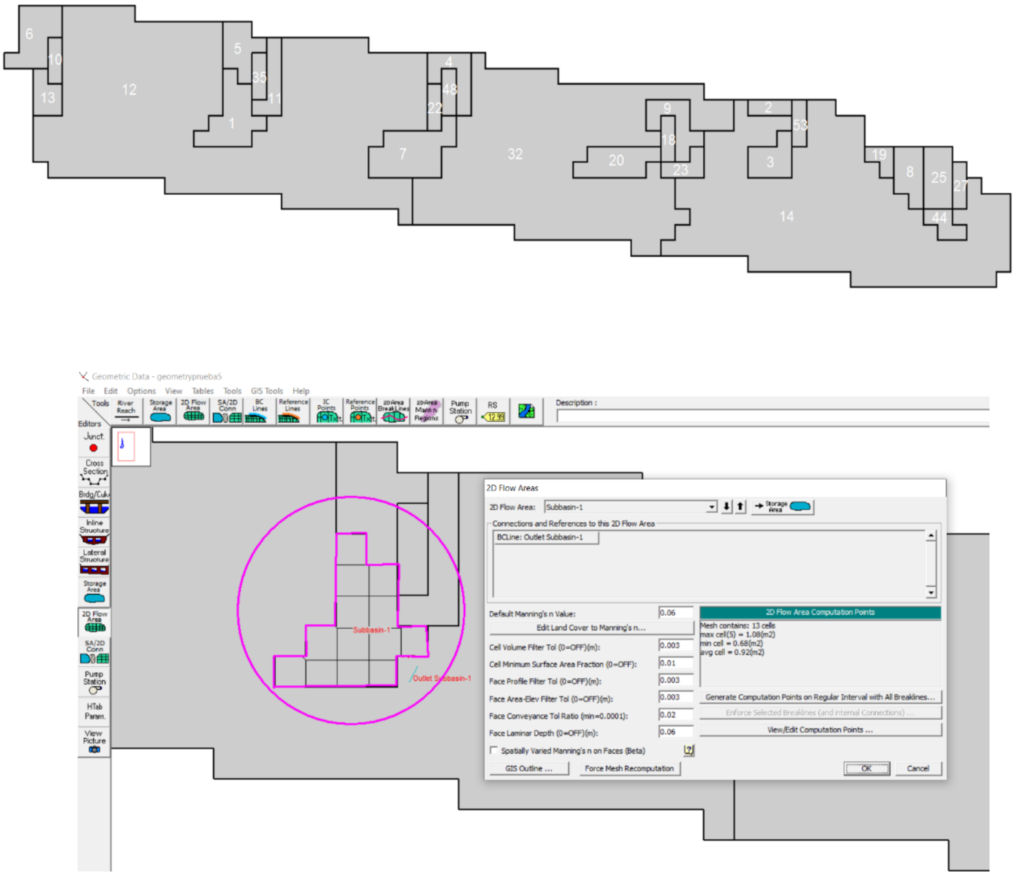


Figure 5.8: 2D Mesh generation on HEC-RAS for 2D Flow Method.

This methodology is compatible exclusively with unstructured or file-specified discretizations. An Unstructured one can be established by importing a 2D mesh from an HEC-RAS Unsteady Plan HDF file, which brings along any associated boundary conditions for the chosen 2D mesh (excluding precipitation time series), generating new 2D connections with identical parametrization. As observed in Figure 5.8, first of all we have the subbasins configuration map exported from HEC-HMS, therefore the procedure was to create for each subbasin its corresponding 2D mesh with a grid cell dimension of 1m x 1m, as shown for Subbasin-1 example, with their corresponding outlet. These last both elements are then imported again into HEC-HMS, requiring the connection of the imported outlet to the original downstream element in the hydrologic whole basin. [32].

Regarding the equations under this process, HEC-HMS 2D engine employs St. Venant Equations, utilizing physically measurable attributes to direct water flow across the overland surface. This technique, relies on an implicit finite volume algorithm, offering several advantages such as:

- Enables larger computational time steps compared to explicit methods.
- Enhances stability and robustness in contrast to traditional finite difference and finite element techniques.
- Facilitates efficient wetting and drying of 2D cells.
- Accommodates subcritical, supercritical, and mixed flow regimes.

Computational cells and cell faces undergo preprocessing to incorporate detailed hydraulic property tables, encompassing relationships like elevation-volume, and elevation-conveyance, among others. Among it advantages, it can be mentioned that the predicted values are in accordance with open channel flow theory, is much more accurate than unit hydrograph theory. However, requires much more computationally intense when compared to other transform methods [32].

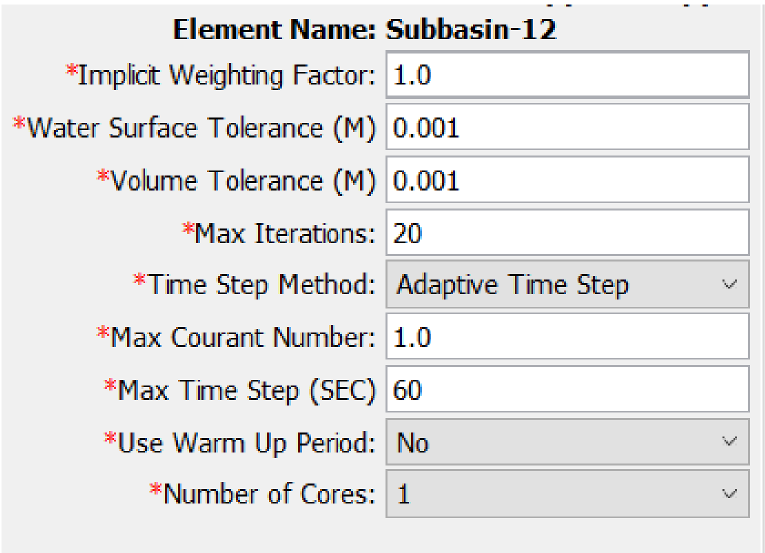


Figure 5.9: 2D Flow method parameters for the specific case of Subbasin-12 after exporting mesh.

Once imported the generated mesh into HEC-HMS, on each subbasin composing the model, for the transform method properties there are a set of parameters automatically generated which define the characteristics of the applied transform method, as shown in Figure 5.9.

5.5. Precipitation data

Intensity-Duration-Frequency (IDF) curves delineate the correlation among rainfall intensity, duration of rainfall, and the return period. These curves are applicated in designing, planning, and managing hydrologic, hydraulic, and water resource systems. The design based on the IDF relationship is based on the assessment of maximum rainfall events concerning their duration and developed for a certain recurrence return period. The precision of this relies on various characteristics of the rainfall, including magnitude, frequency, and duration. The data under analysis is the precipitation time series, projected for future estimations on a regional scale [44]. In order to apply, inside the time-series data offered by HEC-HMS, the so-called precipitation gauge, it was required to look for IDF curves of the area of interest as shown in Figure 5.10.

Figure 5.10: Precipitation data source of the area of interest [43].

Once identified Via Cervino inside the available map, the obtained IDF curves reported the following precipitation data:

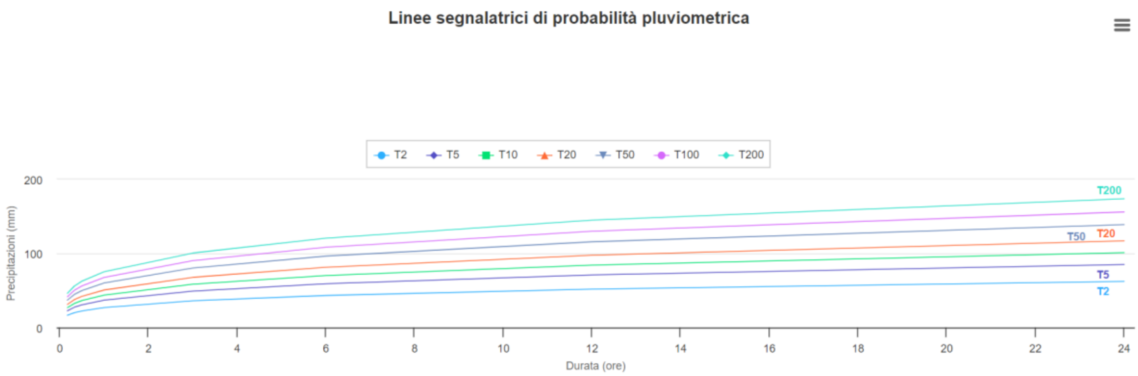


Figure 5.11:Via Cervino area IDF curves: probability lines [43]

Comune di **TORINO** (lat: 4988959.95 , lon: 392905.45)

Parametri della curva di probabilità pluviometrica. **a: 29.21 n: 0.26**

CSV Excel

Fattore di crescita KT

K2	K5	K10	K20	K50	K100	K200
0.924	1.263	1.5	1.737	2.061	2.315	2.579

Piogge di assegnato tempo di ritorno per durate da 10 minuti a 24 ore (mm)

CSV Excel

Durata	Tempo di ritorno in anni						
	2	5	10	20	50	100	200
10 minuti	16.6	22.6	26.9	31.1	36.9	41.5	46.2
20 minuti	20.1	27.5	32.7	37.8	44.9	50.4	56.2
30 minuti	22.5	30.7	36.4	42.2	50.1	56.3	62.7
1 ora	27	36.9	43.8	50.8	60.2	67.6	75.3
3 ore	36	49.2	58.5	67.8	80.4	90.3	100.6
6 ore	43.3	59.1	70.2	81.3	96.5	108.4	120.7
12 ore	51.9	70.9	84.3	97.6	115.8	130.1	144.9
24 ore	62.3	85.1	101.1	117.2	139	156.1	173.9

Figure 5.12: Via Cervino area IDF curves: table values [43].

5.6. Rational Method comparison criteria

One of the widely employed techniques for computing peak flow from small drainage areas under 200 acres is the rational method. This approach is particularly precise when estimating runoff from small drainage areas characterized by substantial impervious surfaces, such as housing developments, industrial zones, parking lots, and similar settings [11].

The formula related to the method is:

$$Q = Cf * C * i * A$$

Where:

Q = Peak flow

Cf = Runoff coefficient adjustment factor to account for reduction of infiltration and other losses during high intensity storms.

C = Runoff coefficient to reflect the ratio of rainfall to surface runoff.

i = Rainfall intensity.

A= Drainage area.

However, some limitations and assumptions must be considered when using this technique:

- Drainage area should be smaller than 200 acres.
- Peak flow is assumed to take place when the whole basin is contributing to water excess.

- Rainfall intensity is considered to be uniform over a time duration equal or greater than concentration time.
- Peak flow recurrence interval is supposed to be equal to the rainfall intensity one [11].

Once presented the main characteristics of this method, since it is commonly used for urban areas, the purpose of the application of the rational formula is to calculate a first estimation of peak flow generated by the mid-block street basin in the reality. Later, this value will be used as a reference point to test if the values resulting from the hydrologic model built inside HEC-HMS are in accordance with the one expected.

To calculate the reference value, besides considering the actual modelled area A and the appropriate runoff coefficient C according to the type of surface, it is selected the first intensity I mm/h considered in the simulation S1, D10, TR2 which will be explained in Chapter 6:

$$Area = 653\ m^2$$

$$C = 0.8$$

$$I = 16.6mm/10min$$

This last intensity can also be expressed as:

$$I = 1.66mm/min$$

$$I = 99.6mm/h$$

Therefore, peak flow according to rational formula results:

$$Qmax = 0{,}001 * \frac{99{,}6mm}{h} * 653\ m^2 * 0{,}8$$

$$Qmax = 0{,}01\frac{m^3}{s} = 10\frac{L}{s}$$

Chapter 6

Simulations results

In this final chapter, after presenting the whole procedure performed for building the desired hydrologic model, as well as introducing the main processes selected for computing the precipitation-runoff methods, the several simulation results will be reported. First of all, an explanation regarding the assessment criterion adopted for identifying specific precipitation events from IDF curves is given, as well as the different selected scenarios with their corresponding material characteristics.

Once presented the main input parameters for the different kind of simulations, the corresponding results are reported. The values concerning maximum flow rate and volume of runoff collected at the outlet of the system will be analyzed, with an illustration of the obtained hydrograph and appropriate tables summarizing the several duration events. Moreover, graphs regarding the behaviors evaluating different durations, return periods and scenarios will be presented to compare and analyze the performance of the hydraulic response under different influences, in order to assess the thesis objective which is the hydraulic efficiency of the existing SuDS.

6.1. Selection of different return periods and durations

According to what has been previously explained, in the following picture there is a table reporting the different intensity values for several durations and return periods regarding the area of interest from Turin city:

Comune di **TORINO** (lat: 4988959.95 , lon: 392905.45)

Parametri della curva di probabilità pluviometrica. **a: 29.21 n: 0.26**

CSV Excel

Fattore di crescita KT

K2	K5	K10	K20	K50	K100	K200
0.924	1.263	1.5	1.737	2.061	2.315	2.579

Piogge di assegnato tempo di ritorno per durate da 10 minuti a 24 ore (mm)

CSV Excel

Durata	Tempo di ritorno in anni						
	2	5	10	20	50	100	200
10 minuti	16.6	22.6	26.9	31.1	36.9	41.5	46.2
20 minuti	20.1	27.5	32.7	37.8	44.9	50.4	56.2
30 minuti	22.5	30.7	36.4	42.2	50.1	56.3	62.7
1 ora	27	36.9	43.8	50.8	60.2	67.6	75.3
3 ore	36	49.2	58.5	67.8	80.4	90.3	100.6
6 ore	43.3	59.1	70.2	81.3	96.5	108.4	120.7
12 ore	51.9	70.9	84.3	97.6	115.8	130.1	144.9
24 ore	62.3	85.1	101.1	117.2	139	156.1	173.9

Figure 6.1: IDF curves from area of interest in Turin [43].

In order to evaluate the hydraulic response of the built model, the following return periods, durations and intensities were selected from the values reported in Figure 6.1 according to the typical size of SuDS:

1. Two years return period (TR 2).
    - Duration of precipitation event of ten minutes with a corresponding intensity of 16.6 mm/10min = 99.60 mm/h (D10)
    - Duration of precipitation event of twenty minutes with a corresponding intensity of 20.1 mm/20min = 60.30 mm/h (D20).
    - Duration of precipitation event of sixty minutes with a corresponding intensity of 27.0 mm/60min =27.00 mm/h (D60).
2. Five years return period (TR 5)
    - Duration of precipitation event of ten minutes with a corresponding intensity of 22.6 mm/10min = 135.60 mm/h (D10).
    - Duration of precipitation event of twenty minutes with a corresponding intensity of 27.5 mm/20min = 82.50 mm/h (D20).

   - Duration of precipitation event of sixty minutes with a corresponding intensity of 36.9 mm/60min =36.90 mm/h (D60).

3. Ten years return period (TR 10).
   - Duration of precipitation event of ten minutes with a corresponding intensity of 26.9 mm/10min =161.40 mm/h (D10).
   - Duration of precipitation event of twenty minutes with a corresponding intensity of 32.7 mm/20min = 98.10 mm/h (D20).
   - Duration of precipitation event of sixty minutes with a corresponding intensity of 43.8 mm/60min = 43.80 mm/h (D60).

For each of these last durations, intensities and return periods, 4 different types of scenarios will be simulated:

Scenario N°1 (S1): basin model without presence of sustainable urban drainage systems. This constitutes the so called "base scenario".

Scenario N°2 (S2): basin model with presence of the previously 6 explained sustainable urban drainage systems, where each of them has an infiltration capacity of C= 5mm/h.

Scenario N°3 (S3): basin model with presence of the previously 6 explained sustainable urban drainage systems, where each of them has an infiltration capacity of C= 20mm/h.

Scenario N°3 (S4): basin model with presence of the previously 6 explained sustainable urban drainage systems, where each of them has an infiltration capacity of C= 160mm/h.

Once presented the selected values and appropriate scenarios to use in each of the simulations to perform, in the following sections each of the obtained results will be reported:

6.2. Two years return period simulations.

1. Two years return period (TR 2).
   - Duration of precipitation event of ten minutes with a corresponding intensity of 16.6 mm/10min.
   - Precipitation gauge input value of 1.66mm/min:

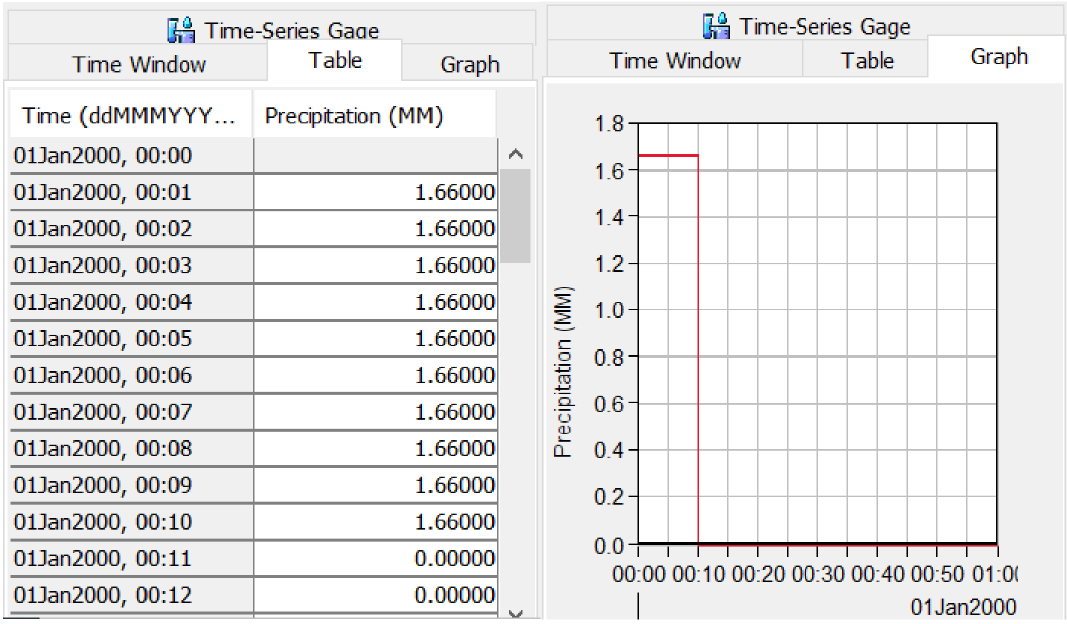


Figure 6.2: Precipitation data input for TR2, D10.

As a general criterion for evaluating hydraulic response, in the following picture there is the Global Summary for this particular simulation where 2 main values are reported: maximum flow rate and volume of runoff collected at the outlet of the system. This last element stands for the mid-block street built model, which outlet is represented by the hydrologic element called Sink-1 inside HEC-HMS:

Scenario N°1: basin model without presence of sustainable urban drainage systems. This constitutes the so called "base scenario".

Hydrologic Element	Drainage Area (KM2)	Peak Discharge (M3/S)	Time of Peak	Volume (MM)
Sink-1	.0006535471205	0.00749	01Jan2000, 00:10	9.21285

Figure 6.3: Global Summary for S1, TR2, D10.

Moreover, the hydrograph reporting the flow performance is presented in next figure:

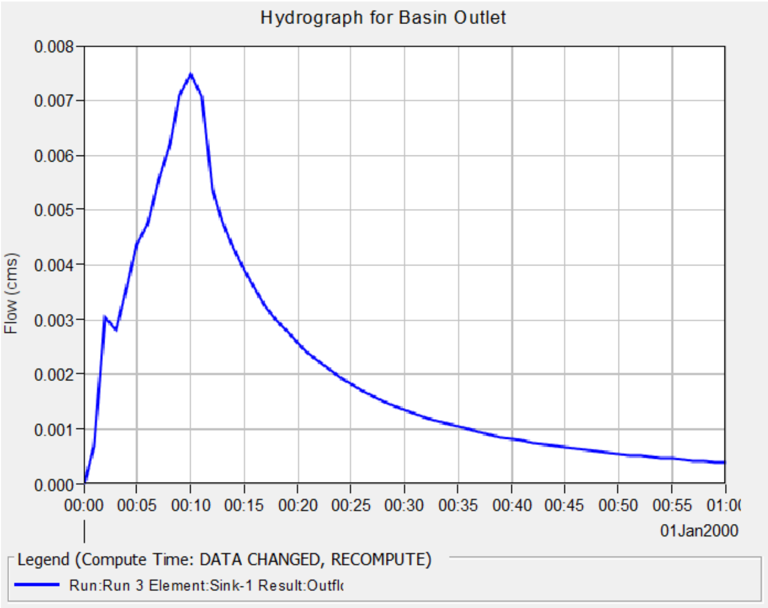


Figure 6.4: Hydrograph for basin outlet for S1, TR2, D10.

<u>Scenario N°2 (S2):</u> basin model with presence of the previously 6 explained sustainable urban drainage systems, where each of them has an infiltration capacity of C= 5mm/h.

Hydrologic Element	Drainage Area (KM2)	Peak Discharge (M3/S)	Time of Peak	Volume (MM)
Sink-1	.0006535471205	0.00702	01Jan2000, 00:09	8.55324

Figure 6.5: Global Summary for S2, TR2, D10

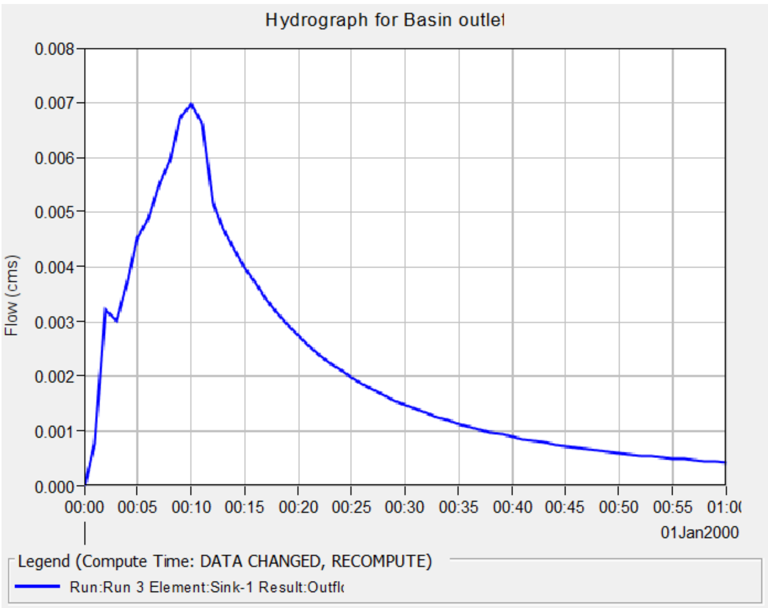


Figure 6.6: Hydrograph for basin outlet for S2, TR2, D10

<u>Scenario N°3 (S3):</u> basin model with presence of the previously 6 explained sustainable urban drainage systems, where each of them has an infiltration capacity of C= 20mm/h.

Hydrologic Element	Drainage Area (KM2)	Peak Discharge (M3/S)	Time of Peak	Volume (MM)
Sink-1	.0006535471205	0.00680	01Jan2000, 00:10	8.34350

Figure 6.7:Global Summary for S3, TR2, D10

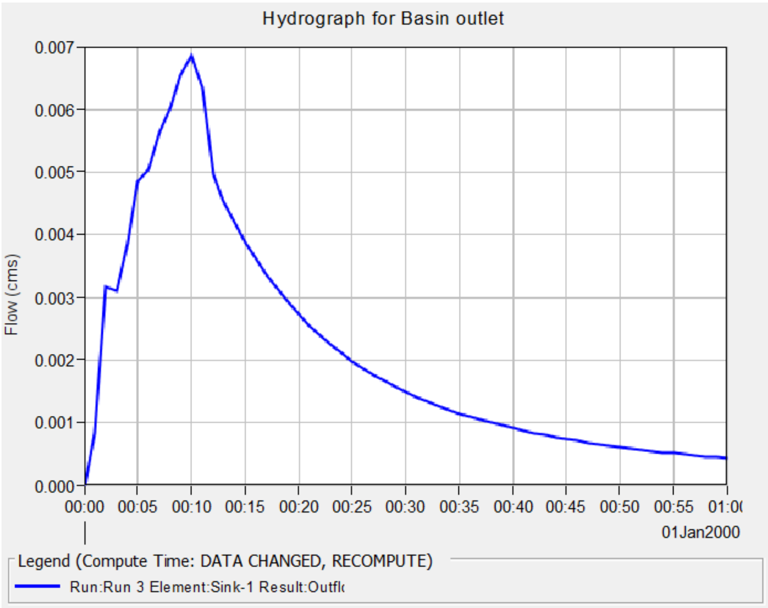


Figure 6.8: Hydrograph for basin outlet for S3, TR2, D10.

<u>Scenario N°4 (S4):</u> basin model with presence of the previously 6 explained sustainable urban drainage systems, where each of them has an infiltration capacity of 160mm/h.

Hydrologic Element	Drainage Area (KM2)	Peak Discharge (M3/S)	Time of Peak	Volume (MM)
Sink-1	.0006535471205	0.00593	01Jan2000, 00:10	7.56774

Figure 6.9: Global Summary for S4, TR2, D10

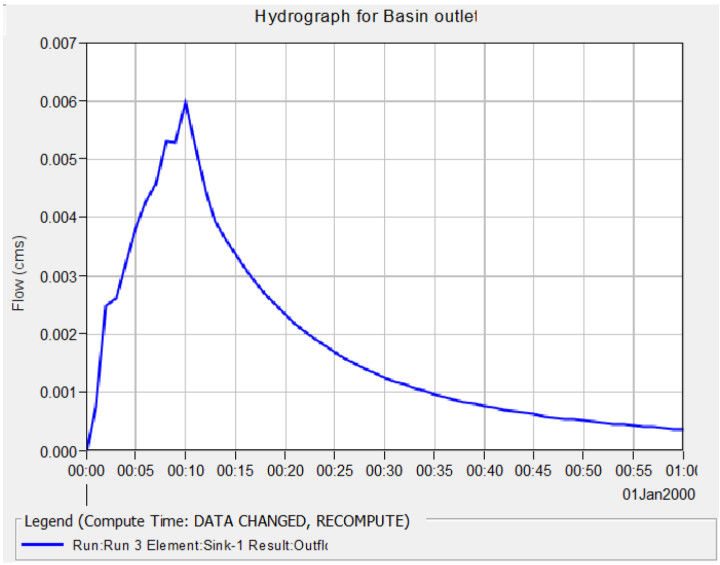


Figure 6.10: Hydrograph for basin outlet for S4, TR2, D10.

For a better understanding of this simulation, ahead there is a summary table presenting the main facts of the mentioned scenarios:

Scenario	Qmax (L/s)	Volume (mm)	Intensity / 10min	Q max Reduction %	Volume Reduction %
Without SUDS	7.49	9.23	16.60		
With SUDS C=5mm/h	7.02	8.55	16.60	6.28	7.29
With SUDS C=20mm/h	6.80	8.34	16.60	9.21	9.56
With SUDS C=160mm/h	5.93	7.57	16.60	20.83	17.97

Table 6-1: Summary Table for D10, TR2.

The same procedure can be applied, within the same return period and considering always the previously explained 4 scenarios, varying the corresponding selected durations with their intensities. Therefore, the appropriate summary tables are reported in the following section:

For TR 2, D20:

Scenario	Qmax (L/s)	Volume (mm)	Intensity / 20min	Q max Reduction %	Volume Reduction %
Without SUDS	5.84	11.03	20.10		
With SUDS C=5mm/h	5.58	10.55	20.10	4.45	4.29
With SUDS C=20mm/h	5.32	10.42	20.10	8.90	5.49
With SUDS C=160mm/h	5.03	10.05	20.10	13.87	8.85

Table 6-2: Summary Table for D20, TR2

For TR 2, D60:

Scenario	Qmax (L/s)	Volume (mm)	Intensity / 60min	Q max Reduction %	Volume Reduction %
Without SUDS	2.92	14.85	27.00		
With SUDS C=5mm/h	2.89	14.62	27.00	1.03	1.50
With SUDS C=20mm/h	2.81	14.44	27.00	3.77	2.72
With SUDS C=160mm/h	2.74	13.92	27.00	6.16	6.25

Table 6-3: Summary Table for D60, TR2

To facilitate the comprehension, a significant graph highlighting the different reduction percentages about maximum flow Qmax vs the several infiltration capacities applied in S2, S3 and S4, always regarding TR2 for the selected durations, is reported below:

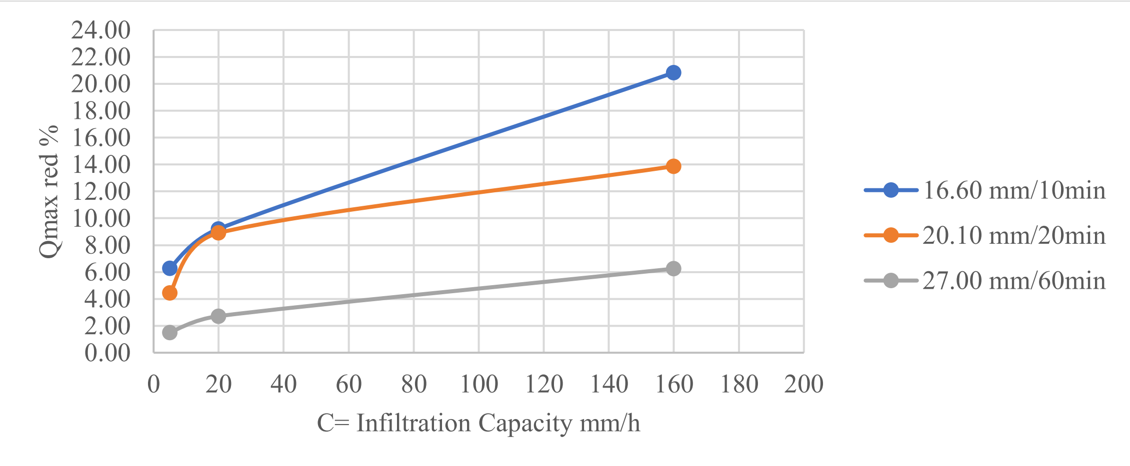


Figure 6.11: Graph comparing different durations for TR2.

After presenting the main results regarding the simulations from the return period of two years, the following conclusions can be exposed:

1. Increasing the infiltration capacity of SuDS enhances the percentages of reduction of maximum flow and volume for the same duration of the precipitation event.
2. As the duration of the precipitation event increases, for the same infiltration capacity, the percentages of maximum flow reduction and volume decrease.
3. As the duration of the precipitation event increases, the slope of the curves encompassing different infiltration capacities becomes lower, causing a decrease in the efficiency of flow and volume reduction.
4. For a low infiltration capacity of SuDS, the percentages of maximum flow reduction obtained are similar even when the duration varies. On the other hand, for high infiltration capacities of SuDS, the percentages of maximum flow reduction differ more.
5. For the highest duration of the precipitation event used, with SuDS having the most significant infiltration capacity, a similar reduction percentage is obtained as that achieved for the lowest duration and infiltration capacity. In other words, the hydraulic efficiency of SuDS decreases as the duration of the precipitation event increases.

6.3. Five years return period simulations

The same procedure can be applied, for the return period of five years and considering always the previously explained 4 scenarios, varying the corresponding selected durations with their intensities. Therefore, the appropriate summary tables are reported in the following section:

Scenario	Qmax (L/s)	Volume (mm)	Intensity / 10min	Q max Reduction %	Volume Reduction %
Without SUDS	11.29	14.78	22.60		
With SUDS C=5mm/h	10.82	14.16	22.60	4.16	4.19
With SUDS C=20mm/h	10.57	13.82	22.60	6.38	6.50
With SUDS C=160mm/h	9.67	13.13	22.60	14.35	11.15

Table 6-4: Summary Table for D10, TR5.

Scenario	Qmax (L/s)	Volume (mm)	Intensity / 20min	Q max Reduction %	Volume Reduction %
Without SUDS	8.00	15.64	27.50		
With SUDS C=5mm/h	7.80	15.32	27.50	2.50	2.07
With SUDS C=20mm/h	7.69	15.24	27.50	3.88	2.56
With SUDS C=160mm/h	7.34	14.83	27.50	8.25	5.20

Table 6-5: Summary Table for D20, TR5.

Scenario	Qmax (L/s)	Volume (mm)	Intensity / 60min	Q max Reduction %	Volume Reduction %
Without SUDS	4.06	21.27	36.90		
With SUDS C=5mm/h	4.02	21.06	36.90	0.99	1.01
With SUDS C=20mm/h	4.00	20.99	36.90	1.48	1.32
With SUDS C=160mm/h	3.90	20.51	36.90	3.94	3.57

Table 6-6: Summary Table for D60, TR5.

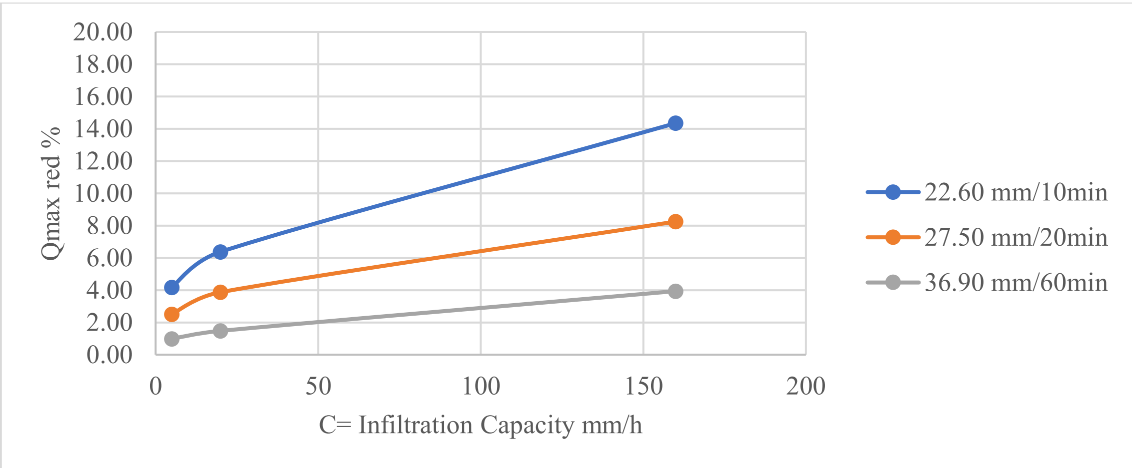


Figure 6.12: Graph comparing different durations for TR5.

6.4. Ten years return period simulations

The same procedure can be applied, for the return period of ten years and considering always the previously explained 4 scenarios, varying the corresponding selected durations with their intensities. Therefore, the appropriate summary tables are reported in the following section:

Scenario	Qmax (L/s)	Volume (mm)	Intensity / 10min	Q max Reduction %	Volume Reduction %
Without SUDS	23.22	23.19			
With SUDS C=5mm/h	22.33	22.72	26.90	3.83	2.06
With SUDS C=20mm/h	22.03	22.09	26.90	5.12	4.77
With SUDS C=160mm/h	21.26	21.55	26.90	8.44	7.10

Table 6-7; Summary Table for D10, TR10.

Scenario	Qmax (L/s)	Volume (mm)	Intensity / 20min	Q max Reduction %	Volume Reduction %
Without SUDS	14.02	27.41	32.70		
With SUDS C=5mm/h	13.84	26.92	32.70	1.28	1.80
With SUDS C=20mm/h	13.69	26.85	32.70	2.35	2.05
With SUDS C=160mm/h	13.24	26.31	32.70	5.56	4.01

Table 6-8: Summary Table for D20, TR10.

Scenario	Qmax (L/s)	Volume (mm)	Intensity / 60min	Q max Reduction %	Volume Reduction %
Without SUDS	7.04	31.89	43.80		
With SUDS C=5mm/h	7.00	31.60	43.80	0.57	0.91
With SUDS C=20mm/h	6.98	31.56	43.80	0.85	1.05
With SUDS C=160mm/h	6.95	31.30	43.80	1.28	1.84

Table 6-9: Summary Table for D60, TR10.

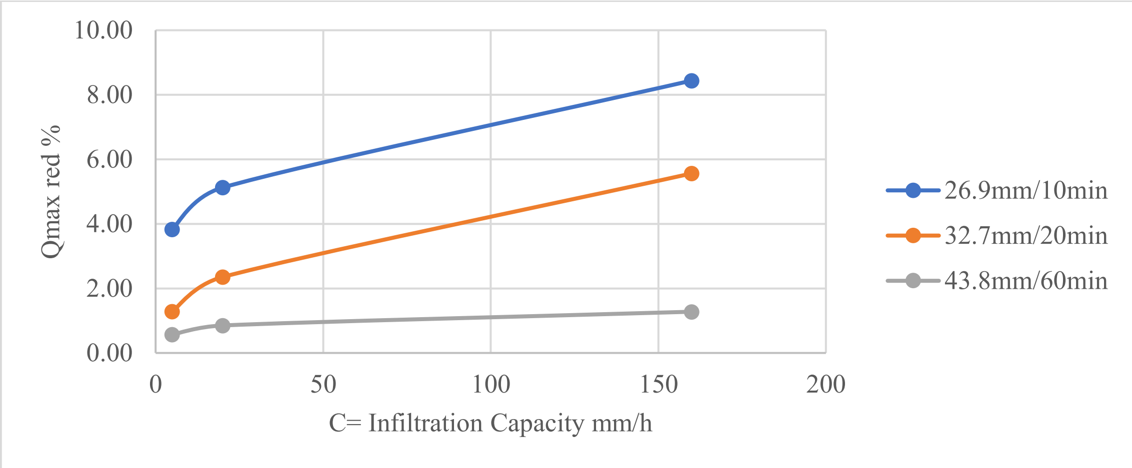


Figure 6.13: Graph comparing different durations for TR10.

6.5. Comparison between different return periods

A further comparison can be performed regarding the results obtained among different return periods:

1. For the same duration and infiltration capacity, as the return period increases, the intensity and consequently the maximum flow also increase. As a result, the percentage of maximum flow reduction decreases.
2. For the same duration and an increased return period, if similar percentages of reduction in maximum flow are desired, it is logically necessary to increase the infiltration capacity of the system.
3. For the same duration of the precipitation event, as the return period increases, the curve encompassing the behaviour of different infiltration capacities logically tends to become horizontal. In other words, the hydraulic efficiency of the SuDS decreases.

Chapter 7

Conclusions

The objective of the present thesis was to model the hydraulic response of an urban basin, represented by a mid-block street located in Turin (Italy) in order to determine the efficiency of an existing SuDS. For doing so, a 2D hydrodynamic software called HEC-HMS, with the required capacities for representing the main factors influencing the mentioned processes, has been tested. Therefore, in order to build the necessary hydrologic model, appropriate data regarding elevation model and precipitation event from the region of interest was downloaded.

After generating the desired model configuration, taking into account cell dimension resolution, model precision and specific criteria of street representation, it was obtained a particular configuration for the subbasins. Then, where possible, hydrologically connected elements were merged so as to reduce memory requirement and time computation, as well as for practicality in terms of data entry. Furthermore, appropriate hydrologic methods were identified for representing main process involved in precipitation-runoff process such as loss methods, baseflow and transform one.

Once finished the hydrologic model construction, three different return periods from Intensity Duration and Frequency (IDF) curves, from Turin city, with their corresponding durations and intensity, were selected as meteorological input. In addition, a base scenario without the presence of the SuDS system was defined for each simulation as a reference point, to be compared with other three scenarios represented by different materials characteristics in terms of infiltration rate capacity of the SuDS. Therefore, a set of simulations results was obtained by combining and changing these last-mentioned inputs.

A number of reflections can be pointed out after analysing the several results, first of all it can be explained that using the three different kind of infiltration rates, which were 5mm/h, 20mm/h and 160 mm/h according to commonly used range of values regarding clogged soil, ordinary soil, and engineered high-drainage soil, for the several durations and intensities tested, in general the studied SuDS system contribute to a reduction in terms of maximum flow and volumes which ranges from 0% to 20%. In particular, for any duration and return period, the higher the infiltration capacity of the SuDS system, the higher the reduction percentage of maximum flow and volume involved in the particular event. Therefore, a first thing to reflect about is the importance of the material attributes used in these low impact development systems, which should not be a thing left to chance.

Another point to remark is the importance of considering the appropriate return period and precipitation duration concerning the type of studied structure. This last thing is because, as results demonstrate, for a single return period, as the duration of precipitation event increases, for a single infiltration rate capacity, the percentages of maximum flow and volume reduction decrease, so hydraulic efficiency is reduced. In the same way, for the same duration and infiltration capacity, as the return period increases there is a decrease in the percentage of maximum flow reduction. Consequently, independently of the type of material used for infiltrating water excess, the mentioned behaviour is observed for all the simulations performed. Hence, it should be carefully evaluated the appropriate return period and duration to be used when evaluating these SuDS to avoid wrong conclusions. Moreover, there are also areas where flooding occurs with a low return period but with an intensity sufficient to stress the drainage system, particularly increased by the effects of climate change in recent periods.

Last but not least, slopes and contributing areas when positioning a SuDS and analysing its effects are remarkable aspects to take into account. That is to say, the quantity of water excess which arrive to the SuDS to be infiltrated, to be considered as a part of the runoff reduction, depends strongly on the street slope characteristics, and how this last is connected to the low impact development system. Hence, with a particular street slope, a part of water excess can be considered or not as a fraction of the collected water. Consequently, the network defined by these last flows surrounding each SuDS element are the so-called contributing areas. Then, under or overestimation of the mentioned contributions, in both designing and modelling, could strongly affect the final value regarding the two main parameters evaluated throughout the process: peak discharge and volume quantity.

References

[1] Scott J. McGrane. “Impacts of urbanisation on hydrological and water quality dynamics, and urban water management: a review” Department of Civil and Environmental Engineering, University of Surrey, Guildford, UK. https://www.tandfonline.com/doi/full/10.1080/02626667.2015.1128084

[2] Ruby, Emily. “How urbanization affects the water cycle” OEHHA, California Water and Land Use Partnership. https://oehha.ca.gov/media/downloads/ecotoxicology/fact-sheet/watercyclefacts_0.pdf

[3] Cea, Luís and Costabile, Pierfranco. “Flood Risk in urban Areas: Modelling, Management and Adaptation to Climate Change. A Review”. Water and Environmental Engineering Group, Departmeng of Civil Engineering, Universidade da Coruña, Spain. Department of Environmental Engineering, Univeristy of Calabria, Cosenza, Italy. https://www.mdpi.com/2306-5338/9/3/50

[4] Cosner, Charles; Reed, Jacob. “Precipitation Education- Water Cycle- Hydologic Cycle”. https://gpm.nasa.gov/education/water-cycle/hydrologic-cycle

[5] “Natural and Urban Water Cycle”. Melbourne Water. *https://www.melbournewater.com.au/education/activities-all-ages/natural-and-urban-water-cycle*

[6] Rafferty, John P. Britannica, The Editors of Encyclopaedia. "water cycle". Encyclopedia Britannica, 3 Jul. 2023, https://www.britannica.com/science/water-cycle. Accessed 15 October 2023.

[7] Gibelli G., Gelmini A., Pagnoni E., Natalucci F., 2015, GESTIONE SOSTENIBILE DELLE ACQUE URBANE. MANUALE DI DRENAGGIO ‘URBANO’. Perché, Cosa, Come Regione Lombardia, Ersaf, Milano. https://www.contrattidifiume.it/.galleries/Pubblicazioni-team-CdF/Manuale_DrenaGGio_v092015.pdf

[8] Yang, Dawen. “Hydrological cycle and water resources in a changing world: a review”. State Key Laboratory of Hydro Science and Engineering, Beijing, China *https://www.sciencedirect.com/science/article/pii/S2666683921000213*

[9] Critchley, Will - Conservation Agronomist Centre for Development Cooperation Services Free University, Amsterdam- and Siegert, Klaus - Water Resources Engineer Land and Water Development Division FAO, Rome-. “A Manual for the Design and Construction of Water Harvesting Schemes for Plant Production”. FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS - Rome, 1991. https://www.fao.org/3/u3160e/u3160e00.htm#Contents

[10] ODOT Hydraulics Manual. Appendix F- Rational Method. *April 2014 https://www.oregon.gov/ODOT/GeoEnvironmental/Docs_Hydraulics_Manual/Hydraulics-07-F.pdf*

[11] Ligtenberg, Jora. “Runoff changes due to urbanization: a review” 20 January 2017. UMEA UNIVERSITET. https://www.diva-portal.org/smash/get/diva2:1067287/FULLTEXT01.pdf

[12] Telvio, H.S. Francisco; Menezes, V.C. Osvaldo; Guedes, L.A. André; Maquera, Gladys; Neto, C.V Dácio; Longo, C. Orlando; Chinelli, K. Christine, and Soares, A.P. Carlos. “The Main Challenges for Improving Urban Drainage Systems from the Perspective of Brazilian Professionals”. 1 Programa de Pós-Graduação em Engenharia Civil, Universidade Federal Fluminense, Niterói 24210-240, RJ, Brazil 2 Programa de Pós-Graduação em Desenvolvimento Local, Centro Universitário Augusto Motta, Rio de Janeiro 21041-010, RJ, Brazil 3 Grupo de Investigación INARI, Universidad Peruana Unión, Juliaca 21100, Peru. https://www.mdpi.com/2412-3811/8/1/5

[13] Water Science School. “Runoff: Surface and Overland Water Runoff”. USGS science for changing world. https://www.usgs.gov/special-topics/water-science-school/science/runoff-surface-and-overland-water-runoff#overview

[14] Flood Defenders. “Why Your Community Needs Better Stormwater Draiange”. https://www.flooddefenders.org/why-your-community-needs-better-stormwater-drainage

[15] "Framing the Challenge of Urban Flooding in the United States". National Academies of Sciences, Engineering, and Medicine; Division on Earth and Life Studies; Water Science and Technology Board; Policy and Global Affairs; Program on Risk, Resilience, and Extreme Events; Committee on Urban Flooding in the United States. https://www.ncbi.nlm.nih.gov/books/NBK541185/

[16] Redazione Alpa Uno. 23 Agosto 2022. Nubifragio a Selinunte. Saltati tombini e acqua di fogna riversata in mare | Alpauno

[17] Sambeto Bibi, Takele; Reddythta, Daniel; Kebebew, Abdisa Sime. "Assessment of the drainage systems performance in response to scenarios and flood mitigation measrures using stormwater management model". Department of Water Supply and Environmental Engineering, College of Engineering, Madda Walabu University, Robe, P.O.Box 247, Ethiopia. Faculty of Water Supply and Environmental Engineering, AWTI, Arba Minch Univeristy, Arba Minch, P.O.Box 21, Ethiopia. Department of Hydrologi, College of Engienering, Madda Walabu Univeristy, Robe, P.O.Box 247, Ethipia. https://www.sciencedirect.com/science/article/pii/S2590252023000132

[18] British Red Cross. " What you need to know about floods in the UK". https://www.redcross.org.uk/stories/disasters-and-emergencies/uk/what-are-floods

[19] M. Tucci, Carlos E. "Urban Flood Management". World Meterological organization. https://www.floodmanagement.info/floodmanagement/wp-content/uploads/2020/06/Cap-Net-WMO-Urban-Flood-Management.pdf

[20] Woods-Ballard, B., Kellagher, R., Martin, P., Jefferies, C., Bray, R., Shaffer, P. (2007) The Sustainable Urban Drainage Systems (SUDS) Manual, CIRIA, London. https://www.semanticscholar.org/paper/The-SUDS-manual-Ballard/fb9b741ef407aceb3326eb165faf3a96620e5fdf

[21] HEC-HMS User's Manual. U.S. Army Corps of Engieneers. https://www.hec.usace.army.mil/confluence/display/HMSGUIDES

[22] HEC-HMS Symbol. https://www.hec.usace.army.mil/software/hec-hms/downloads.aspx

[23] Dr. Gautam, Dilip. K. RIMES, AIT Campus, Bangkok. "Hydrological Modeling for Upper Chao Phraya Basin Using HEC-HMS". https://www.slideserve.com/monifa/hydrological-modeling-for-upper-chao-phraya-basin-using-hec-hms

[24] Darsbandsari, Pedram. "inter-comparison of lumped hydrological models in data-scarce watershed using different precipitation forcing data sets: Case study of Norther Ontario, Canada". University of Toronto. https://www.researchgate.net/publication/343947053_Inter-comparison_of_lumped_hydrological_models_in_data-scarce_watersheds_using_different_precipitation_forcing_data_sets_Case_study_of_Northern_Ontario_Canada

[25] Lapointe, M., Rochman, C.M. & Tufenkji, N. Sustainable strategies to treat urban runoff needed. Nat Sustain 5, 366–369 (2022). https://doi.org/10.1038/s41893-022-00853-4

[26] DiPaolo, Michael. "Groundwater Recharge-Its importance and Scalability" AQUOSO. https://aquaoso.com/how-to-conserve-water-in-agriculture/groundwater-recharge/

[27] Luxem, Katja. "Managed Aquifer Recharge". AGI, September 2017. https://www.americangeosciences.org/geoscience-currents/managed-aquifer-recharge

[28] Wakode, Hemant Balwant; Baier, Klaus; Jha, Ramakar; and Azzam, Rafig. " Impact of urbanization on groundwater recharge and urban water balance for the city of Hyderabad, India" Department of Engineering Geology and Hydrogeology, RWTH Aachen University, Lochnerstr.4-20,52064 Aachen, Germany. Department of Civil Engineering, National Institute of Technology (NIT) Patna, Patna, Bihar 800005, India. https://www.sciencedirect.com/science/article/pii/S2095633916300818

[29] Overview of Hydrologic Modeling for Project Studies. US Army Corps of Engineers. https://www.usace.army.mil/

[30] Dunn, Christopher N. "Projects and Initiatives at the Hydrologic Engineering Center". Hydrologic Engienering Center Institue for Water resources. https://www.slideserve.com/valiant/projects-and-initiatives-at-the-hydrologic-engineering-center-hec

[31] HEC-HMS Application-Guide. June 2017. US Army Corps of Engineers https://www.hec.usace.army.mil/software/hec-hms/documentation/HEC-HMS_Applications_Guide_June2017.pdf

[32] HEC-HMS Technical Reference Manual. US Army Corps of Engineers. https://www.hec.usace.army.mil/confluence/display/HMSGUIDES

[33] Njambi, Rose. "How digital surface models and digital terrain models elevate your insights". May 04, 2022. https://up42.com/blog/ndsms-how-digital-surface-models-and-digital-terrain-models-elevate-your

[34] Duffy, Elizabeth; and Marwaha, Nikita " Everything you need to know about DEMs, DSMs, and DTMs. Mar 12, 2021. https://up42.com/blog/everything-you-need-to-know-about-digital-elevation-models-dem-digital

[35] Piras, Marco "GIS Data Format". Laboratory of GIS and Geospatial Services for Engineering Applications". 2021, Politecnico di Torino. https://file.didattica.polito.it/download/MATDID/33256172

[36] Geoportale Piemonte. Direzione Ambiente, Energia e Territorio. Settore Sistema Informativo Territoriale e Ambientale. Regione Piemonte. https://www.geoportale.piemonte.it/cms/il-geoportale/cos-e-il-geoportale

[37] Geoportale Nazionale, Ministero dell'Ambiente e della Sicurezza Energetica. Governo Italiano. https://www.mase.gov.it/pagina/geoportale-nazionale

[38] Dataset metadati. Geoportale Nazionale. http://www.pcn.minambiente.it/mattm/visualizzazione-metadati/?keyword=prodotti%20lidar&rid=local&paged_e=2

[39] Tamea, Stefania. "Lez1_area. Data preparation". Laboratory of GIS and Geospatial Services for Engineering Applications. Politecnico di Torino, 2021. https://file.didattica.polito.it/download/MATDID/33276655

[40] Michez, Adrien; Piégay, Hervé; Lejeune, Philippe; and Claessens, Hugues. "Characterization of riparian zones in Wallonia (Belgium) from local to regional scale using aerial lidar data and photogrammetric DSM". University of Liege and Ecole Nationale Supérieure de Lyon. https://www.researchgate.net/publication/272487096_CHARACTERIZATION_OF_RIPARIAN_ZONES_IN_WALLONIA_BELGIUM_FROM_LOCAL_TO_REGIONAL_SCALE_USING_AERIAL_LIDAR_DATA_AND_PHOTOGRAMMETRIC_DSM

[41] QGIS Documentation. https://qgis.org/en/docs/index.html

[42] Torino, Google Earth. https://earth.google.com/web/@45.08949303,7.67930247,238.23044254a,2817.97999788d,35y,7.54561771h,2.97522324t,0r/data=OgMKATA

[43] Atlante piogge intense in Piemonte (GEV). ARPA Piemonte. https://webgis.arpa.piemonte.it/atlante_pioggia_webapp/grafici_new/index_gev.php?NUMCODICE=191454

[44] Gámez-Balmaceda, E.; López-Ramos, A.; Martínez-Acosta, L.; Medrano-Barboza, J.P.; Remolina López, J.F.; Seingier, G.; Daesslé, L.W.; López-Lambraño, A.A. Rainfall Intensity-Duration-Frequency Relationship. Case Study: Depth-Duration Ratio in a Semi-Arid Zone in Mexico. *Hydrology* 2020, *7*, 78. https://doi.org/10.3390/hydrology7040078