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STORMWATER MANAGEMENT IN URBAN AREAS – ADAPTATION STRATEGIES BASED ON INTENSITY RANGES

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Abstract

Urban floods are becoming more frequent and extreme due to climate change, rapid urbanization, and aging infrastructure. The floods result mainly from intense rainfall events, terrain topography, soil impermeabilization, drainage network conditions, and sea-level rise. Damage from such events can vary and be harsh, that is why there is an urgent need of integrated and adaptive management solutions. This study applies the Stormwater 3-Step Approach (S3SA), which was originally developed in Norway, and adapts it for Portugal's reality. Nature-based Solutions (NbS) such as green roofs, pervious pavements, infiltration trenches, and rain gardens were integrated in each step to maximize soil infiltration, delay runoff and peak runoff, and reduce negative flood impacts. Storm Water Management Model (SWMM) simulation analyzed the performance of these measures for different return periods (2, 50 and 100 years, one for each step) in a real case study, and considered future variations. Results showed that for frequent, low-intensity events (RP=2y), increasing soil permeability significantly improved infiltration, from 0.61 mm to 1.05 mm, and eliminated flooding from 37 manholes. Under moderate events (RP=50y), retention basins reduced peak runoff by up to 631 $L \cdot s^{-1}$. In extreme events (RP=100y), bio-retention cells were strategically located in green areas to manage greater amounts of water while protecting urban infrastructure. The S3SA offers a feasible methodology for urban stormwater management in Portugal. Step one was optimized by 72% under infiltration, step two was best at reducing peak runoff, and step three had potential to control extreme events, although more advanced modeling tools are needed. Cumulatively, this approach enables a transition towards a more sustainable urban planning with the use of green infrastructure and correct hydrologic modeling, alongside ongoing research in floodway mapping and NbS optimization.

Keywords: urban water management, nature-based solutions, stormwater infrastructure

Declaração

Declara, sob compromisso de honra, que este trabalho é original e que todas as contribuições não originais foram devidamente referenciadas com identificação da fonte.

Porto, 23 de junho de 2025

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List of Abbreviations

3PA	Three Point Approach
APA	Agência Portuguesa do Ambiente
BMP	Best Management Practices
GHG	Greenhouse Gases
GI	Green Infrastructure
IPMA	Instituto Português do Mar e da Atmosfera
LID	Low Impact Development
NAO	North Atlantic Oscillation
NbS	Nature-Based Solutions
RCP	Representative Concentration Pathways
RP	Return Period
S3SA	Stormwater 3-Step Approach
SCM	Stormwater Control Measures
SDG	Sustainable Development Goals
SUDS	Sustainable Urban Drainage Systems
SWMM	Storm Water Management Model
WMO	World Meteorological Organization
WSUD	Water Sensitive Urban Design
WWTP	Wastewater Treatment Plant

1 Introduction

Flood can be defined as “the temporary covering by water of land not normally covered by water” and can be classified as river flood, coastal flood, storm surge, inland flooding, and flash floods. The European Council states that pluvial urban flooding occurs when the capacity of the urban sewerage systems is exceeded, and this definition focuses on deficient infrastructure as being the cause of urban floods. Flood risk is the combination of potential damage – to human health, environment, heritage, and economy – and the probability of that event to happen [1] [2].

Meanwhile, it is believed that a more holistic approach is important to enlarge the possible root causes of floods. Five causes for urban flooding have been mapped, the first being precipitation and this variable might be expressed in several forms, such as rainfall intensity, storm duration and total rainfall amounts, and these forms are considered alone in some studies and as a combination in others. The second cause is topography, in which the factors that affect urban floods are slope and elevation. Third cause is the land features, mainly the soil permeability. The fourth cause is infrastructure - aligned with the definition of the European Council - and here the performance of the drainage systems has a significant role. Finally, sea level rise is the last urban flood cause, and it represents a strong one since it was observed that in some cases there was at least an 80% reduction in the return period associated to sea flood levels [3, 4].

The damages caused by urban floods can be classified as direct tangible impacts, business interruption and indirect tangible impacts, impacts on infrastructure and intangible impacts. This exemplifies that there is a wide range of damages that can occur after a flood and in different sectors, such as commercial activities, community services, education and research, government services, manufacturing and processing, recreational facilities, residential buildings, transport services, among others. While data of the four categories might be hard to obtain in some cases due to simply inexistence or being highly sensitive, it is already clear that floods have a high potential of altering the well-being of a city [5].

Some recent examples of extreme flood events were observed in several regions around the world in 2024, namely Rio Grande do Sul state, in Brazil, where almost 500.000 people were directly impacted by the floods [6]. Also, Dubai, UAE, where the city experienced in one day more rain than the annual average [7]. Valencia, in Spain, is another example, where in eight hours rained more than the annual average for the city [8]. This highlights the relevance of studying and applying well-designed urban water management approaches because unprepared cities will suffer more every time with floods.

1.1 Objectives

Applying integrated approaches to manage stormwater drainage systems is important to ease decision-making among stakeholders, so the aim of this study is to present methodologies for urban stormwater management based on the three intensity ranges. It is intended to include these management strategies in the climate changing scenarios of the next decades and how they should be interspersed in Portugal authorities' mindset when making decisions concerning urban water and potential floods.

In this context, the specific objectives are described in the form of topics as follows:

i) State of art analysis to understand where studies are focusing on and how this study can help to expand the current knowledge.
ii) Build a model of a current drainage network, inputting elevation, diameter, and material to estimate the efficiency of damage reduction after applying Nature-based Solutions (NbS) in a case study.
iii) Run simulations for different intensity ranges at the drawn network, to understand how the current drainage network will respond to more extreme future scenarios.
iv) Check how the new set up reacts to the inclusion of NbS in the drainage network in each step.

1.2 Dissertation structure

This study approaches the subject by contextualizing the problem at the topic Stormwater management methodologies, by giving current examples of what is being studied in other countries, comparing the two mainly studied methodologies and selecting one that is more applicable to Portugal's reality, presenting NbS and their functioning systems, and finally indicating the most recent innovations developed.

Stormwater 3-Step Approach (S3SA) in Portugal is a topic that adapts the chosen methodology to Portugal's reality, presents the national hydrological characterization and the expected future climate changing scenarios until the year of 2100. Then the case study is presented, which is Rio Leça's basin with the study area, current pluvial drainage network and how SWMM software was designed to run the simulations. Finally, the results obtained for each step analysis and the conclusion are presented, indicating challenges and most relevant topics that should undergo further investigation.

1.3 Contribution to the Sustainable Development Goals

The Sustainable Development Goals (SDG) are a set of 17 global objectives established by the United Nations to guide countries, communities, and individuals toward a more just, resilient, and environmentally responsible future by 2030. They cover a wide range of challenges, including poverty, education, health, climate change, and sustainable cities. This dissertation aligns with several of these goals by focusing on solutions to urban flooding—an issue made worse by climate change and rapid urban growth. Using green infrastructure and nature-based strategies to manage stormwater, the research contributes to goals related to building safer and more sustainable cities, protecting water resources, preparing for climate impacts, and promoting innovation in infrastructure. In doing so, it illustrates how local scientific research and planning practices can play an important role in supporting global efforts toward a more sustainable and resilient world.

Specifically, this work supports SDG 11 (Sustainable Cities and Communities) by promoting resilient infrastructure and integrated urban planning to reduce the impacts of water-related disasters. It also aligns with SDG 6 (Clean Water and Sanitation) through the enhancement of stormwater infiltration and water quality via NbS. By modeling future climate scenarios and improving flood resilience, the work contributes to SDG 13 (Climate Action), while the development of innovative green infrastructure strategies supports SDG 9 (Industry, Innovation and Infrastructure). Additionally, the ecological benefits of NbS, such as improved soil permeability and green space integration, indirectly support SDG 15 (Life on Land) by fostering more sustainable interactions between urban environments and natural ecosystems. Table 1 below summarizes the SDGs and their specific targets which this work contributes.

Table 1. SDGs, their targets and how this work contributes to each

SDG	Target	Contribution
6	6.3	The use of NbS such as rain gardens, pervious pavements, and infiltration trenches improves stormwater quality by enabling natural filtration and infiltration processes, reducing surface runoff that can carry pollutants.
	6.6	Promoting soil infiltration and runoff control, indirectly supporting the health of local hydrological systems and water-related ecosystems. NbS also foster biodiversity and groundwater recharge, especially when integrated into urban areas.
9	9.1	Development of resilient and sustainable urban drainage infrastructure. Integrating bio-retention cells and retention basins, helping modernize stormwater systems to better withstand future flood events.
11	11.3	Locally adapted a method that promotes integrated urban water management, supporting the transition toward sustainable urban planning by incorporating green infrastructure and NbS.
	11.5	Providing adaptive flood management solutions that help mitigate urban flooding risks, reducing potential economic losses and improving urban resilience. Demonstrating practical strategies to lessen the frequency and impact of rainwater-related disasters.
13	13.1	Developing and testing a climate-resilient urban water management approach that incorporates future climate scenarios and proposes effective adaptation strategies using simulations and modeling.
	13.3	Building institutional and academic capacity by adapting an international best practice (S3SA) for Portugal and by highlighting the role of green infrastructure in urban adaptation planning, serving as a case study that can inform practitioners, policymakers, and future researchers.
15	15.1	Use of NbS contributing to the restoration of ecosystem functions in urban contexts, improving biodiversity, supporting soil health, and enhancing green urban spaces.

2 Stormwater management methodologies

Urban pluvial floods are becoming more frequent and extreme and climate change is one of the main characters responsible for that. Furthermore, growth of impermeable surfaces increases superficial runoff and tend to also increase the flood risk. That brings up the necessity of taking measures to prevent floods which should not be only technological but consider changes in lifestyle and expectations of local communities [9].

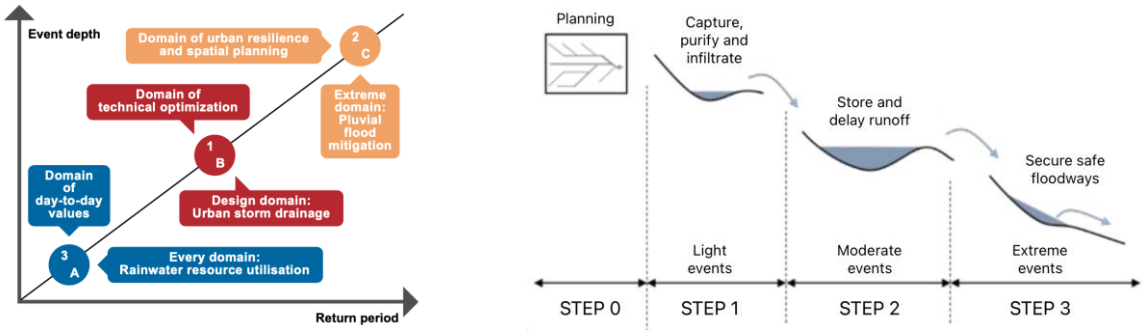
The main reason for the complexity of dealing with urban drainage systems is the conflicting needs and objectives. The traditional systems are getting outdated mainly because they disturb the natural water cycle and directly affect the watershed hydrology [10]. Old infrastructure, the wish for cyclical instead of linear networks and more frequent and extreme events of rainfall are rising the necessity of new forms of holistic approaches to urban floods [11]. The stormwater control measures (SCM) such as best management practices (BMP), green infrastructure (GI), low impact development (LID), sustainable urban drainage systems (SUDS) and water sensitive urban design (WSUD) are important tools that help water professionals provide the communities with the best alternatives [12].

A 3-Point Approach (3PA) was developed in Denmark and is a methodology of dealing with urban floods where three domains are evaluated to take actions that prevent all types of damage from floods. These domains are: 1) technical optimization, where standards are followed in the design of urban drainage systems; 2) urban resilience and spatial planning, making cities more resilient to future expected conditions; and 3) day-to-day values, where all stakeholders participate in the decision-making process. Consequently, the 3PA benefits the communication between water professionals and stakeholders about options for dealing with flood risk and so each part is more likely to get involved and support actions without feeling excluded [9].

In order to quantify the 3PA, Sørup *et al* [13] redefined the three original points as A, B and C with a more hydrological perspective, where the return periods are 0.2, 10 and 100 years, respectively. Some metrics were used to calculate the efficiency of a given SCM and, when combined with the 3PA, “can be used to describe how well a system designed for one rainfall domain functions when exposed to the rain events of the other domains”. This new point of view of the 3PA is important to complement the previous subjectiveness with numerical data that will serve as a facilitator in the decision-making process.

Another concept about urban water management was developed in Norway and is defined as S3SA, being a less theoretical – more technological – approach. Step one is about infiltration of all small rainfall events, step two is detention of medium rainfall events and step three is to ensure safe water paths in larger rainfall events [14]. The first two steps are more

focused in cities' infrastructure, given that around 40-50% of the impermeable surfaces of cities are the roofs [15], while step three involves considering urban surfaces as an integral component of the urban water infrastructure, being called floodways [16]. Figure 1-a presents the 3PA concept where A, B and C represent increasing return periods and -b the S3SA concept of the three steps approach to stormwater management.



-a -b

Figure 1. -a 3PA [13] and -b S3SA adapted from Paus [18] concepts

2.1 Ongoing examples

2.1.1 Denmark

In Copenhagen the 3PA proposed by Sørup *et al* [13] was tested and evaluated by Lerer *et al* [17] to assess its effectiveness. The case study was conducted on the Ydre Østerbro, which is a cloudbranch at the first climate resilient neighborhood in the city. The area covers 118 ha where around 62% is impermeable, with a highest point at 12.5 m and the lowest at 1 m above sea level – this highlights the vulnerability to flooding due to its coastal location. One of the strengths of the study is that it had access to a highly detailed already existent model of the cloudburst branch. It included almost three thousand catchments with an area of 436 m^2, 413 manholes and 24 km of pipes, which allows a better understanding of water movement and the responses of the system under the three domains of the 3PA.

After having the baseline, four scenarios (S1-S4) were simulated:

i) S1 by adding a cloudburst management system that directly discharge water from some low-traffic roads to a near harbor without treatment and, therefore, relieving the WWTP.
ii) S2 is similar to S1, but low-traffic roads that had inclination to main roads and roofs that drain water to these low-traffic roads were added to the rainwater collecting system.
iii) In S3 the cloudburst system was enlarged by adding high-traffic roads and more roofs in order to relieve the sewerage system.

iv) S4 contains the largest catchment area draining to the cloudburst pipes. All patios inside buildings and roofs facing these patios were also added to the catchment area, making S4 the worst scenario.

The results of the simulations provided important insights that might help urban water management. Under domain A, the WWTP could experience a significant reduction in the volume of water received, with up to 20% less inflow, since almost all of it would go to the harbor – the legislation allows direct discharge in specific cases. In domain B, it is expected a drastic reduction in surcharging manholes – from 46% to 1%, which exemplifies the improvements that can be achieved and minimizing the flood risk. Finally, domain C also showed an important reduction – from 43,100 m^3 to 7,400 m^3. Despite the improvements, there would still be some water causing floods, emphasizing the need of extending the study to a step-by-step simulation in order to find an optimum solution.

2.1.2 Norway

The Norwegian Water Association is also concerned about the aging of the infrastructure and the challenges of maintaining and upgrading the current system to ensure they are resilient under future climatic conditions. The S3SA is widely used, and its focus is to integrate stormwater management in cities prioritizing sustainable and efficient solutions. This approach relies on trying to establish a natural hydrological balance by putting more efforts in the everyday domain, making sure the cities are able to deal with low return period rains as well as ensuring that systems are robust enough to handle extreme events.

In that context, Paus [18] proposed design criteria for step one using data of annual precipitation and minute-by-minute-resolution data from six different stations, allowing a detailed comprehension of rain intensity. By comparing 1-minute and 10-minute resolutions data, the author found out that a 10-minute resolution is sufficient for hydraulic calculations and design inputs, significantly reducing computational load and time while maintaining accurate results.

A key finding of the referred article is that capturing 95% of annual precipitation can be achieved by managing only one third of a 2-year event. This exemplifies that being able to manage small rainfall events under the everyday domain makes it possible to significantly reduce the total occupation area of the network system, being relevant under the urban context where space is limited and expensive.

The author emphasizes the importance of a strategic and layered approach by separating measures based on precipitation levels. Step one aims to use green infrastructure, permeable surfaces, and local infiltration to small and more frequent events. Steps two and three are addressed to more extreme and less frequent events, by considering the usage of detention

basins, underground storage of water and safe floodways, aligned that to infrastructure changes in the current network. This perspective guarantees that resources are well allocated for each domain and that cities are well designed while being able to handle rain events of all intensities and frequencies.

2.1.3 Netherlands

Since the country is in a coastal area and some parts are below sea level, the Netherlands has long been used to dealing with flood risks. That geographical reality has led to a proactive mindset in water management and authorities are more open to new and non-trivial solutions. The Dutch have innovative strategies that incorporate NbS in the current traditional cities to mitigate flood risk while making peoples' life better.

Fratini *et al* [9] made interviews in two Dutch cities to understand different realities and management actions. These cities, Egmond aan Zee and Dordretch, provided insights about the effectiveness of strategies to mitigate damage from floods.

Egmond aan Zee demonstrated integration of solutions to reduce flood risk through aesthetic and functional solutions implemented across the city. Such solutions include permeable pavements with underground storage, which increase infiltration and reduce superficial runoff while retaining large volumes of water and releasing it slowly to the drainage system. Another aspect was the urban planner's cooperation to find the best cost-effective solutions that maximize flood resilience. However, even though the technical aspects were well developed, the study found a gap at public engagement since the population was not well inserted in actions. Thus, their needs and expectations were not fully met, what highlights the importance of public integration to ensure long-term success of measures.

Dordretch, in the other hand, gave extra attention to its citizens and invested in environmental education by showing the benefits of having more gardens and what measures could be taken to make them more permeable. Also, some little constructions like rain barriers were made to retain rainwater in those gardens instead of going directly to the collection network. Another effective measure was to build a retention garden in a residential area, able to store rainwater under extreme rain events, while being a pleasant area for inhabitants to walk their dogs and enjoy the green area in regular days. The design and construction of the area was collaborative between citizens and technicians. The initiative demonstrates the benefits of involving the community and public awareness about sustainable solutions. By including its citizens in the decision-making process and provide them tools and knowledge to manage urban water, the Dutch city could transform itself in a more resilient and sustainable city.

2.2 Strengths and weaknesses of S3SA and 3PA

Urban water use and management, aligned with spatial planning, require strong approaches that balance scientific research, stakeholders' involvement, and decision-making. Despite being broadly used in the countries presented in last section, both 3PA and S3SA have strengths and weaknesses when it comes to implementation and, mainly, to their outcomes.

Strengths

The 3PA is, by default, an inclusive approach to urban water management through always trying to integrate at most water professionals, urban spatial planners, government authorities and the citizens, which end up being ensured that multiple perspectives and interests are considered throughout the process of deciding. This reality allows a more holistic planning process that makes sure all three pillars – social, economic, and environmental – of sustainability are pondered, resulting in strategies that are more sustainable and well accepted by society.

In addition, this method promotes governance structures that motivate collaboration between stakeholders, therefore enhancing the accountability and legitimacy of decisions. By involving a wide range of actors, the chances of implementing a new or different policy and the feeling of ownership of the community are increased, while leading to adaptive and contextual solutions that meet local needs and priorities.

On the other hand, S3SA is a more science-driven approach where several software and predictive analysis are used to achieve results from modelling future scenarios and how well the study areas will react. The main strength is providing objective, data-driven insights that elevate accuracy and reliability of urban water management decisions. The S3SA combines hydrology, environmental and urban contexts and simulate scenarios based on future predictions of a climate changing world.

Another advantage is the speed of processing data and simulating conditions, since the S3SA is more computer-based. The absence of subjective and biased information, by delivering reliable results in short times, allows authorities and planners to make decisions based on scientific evidence. Overall, this method lies over a scientific background and therefore removes the personal, political, and institutional opinions.

Weaknesses

3PA can be time-consuming and complex since it involves a large number of people. Processes may get slow due to discussions and bureaucracies between people who usually are diverse and have conflicting ideas and interests. Reaching a consensus might be difficult in some cases. Additionally, even though this method increases participation of groups, the final decision is commonly taken by few people, and this reality could affect the objectivity of

decisions if political influences become strong. Since politicians change over time, short-term decisions that prioritize economic gain or popularity are a threat to this approach, which aims to a long-term sustainable future.

Due to the fact of being a more scientific approach, the S3SA is eventually disconnected from the real-world dynamics, in the social and political spheres. It provides valuable technical results and since that does not consider peoples' perspectives, the outcome might be less effective when it comes to governance and community-related concerns. Also, it depends on the availability of data with high quality, precision, and resolution. And that can become a problem if the study area has limited access or is remotely located in a way that there are no weather stations nearby. Such conditions may reduce the effectiveness of the computational models. Since models are a representation of the real world, they always come with an associated error, so people must be careful with results and double-check them. Finally, human behavior is not considered at all, such as social and political changes that affect urban development.

The two approaches are different although both provide valuable results and insights into urban water management and spatial planning. While the 3PA focuses on inclusivity, stakeholders' engagement, and governance, the S3SA is more objective, modelling future scenarios and results are more scientific and technological. It could be stated that the S3SA is part of the 3PA, since it carries the answers found by water professionals through scientific research that will be relevant to substantiate the authorities' decisions. Table 2 sums up the main strengths and weaknesses of the two methods. However, since this study focuses on developing a numerical analysis and not to make decisions government-wise, the S3SA was chosen to be used and applied to achieve the expected results.

Table 2. Strengths and weaknesses of each approach – 3PA and S3SA

	3PA	S3SA
Strengths	i) Stakeholders' involvement ii) Sustainability iii) Ensure community's needs and expectations are met	i) Objective, data-driven analysis ii) Predictive future scenarios iii) Scientific results
Weaknesses	i) Time-consuming in some cases ii) Consensual decisions iii) Political influences	i) Absence of human dynamics and behavior ii) Availability of data iii) Error of models

2.3 Nature-based Solutions (NbS) to stormwater control

Since rainfall events will become each time more frequent and extreme, it is important to expand the approach to non-trivial solutions. About 40-50% of the paved surfaces in cities are the rooftops and dealing with them might have a significant impact on the city's resilience to extreme events [15]. NbS are important SCM as they aim to restore the natural water cycle and reduce superficial runoff through retention (infiltration and evapotranspiration), detention and efficient urban space management while its main objective is to reduce damage in all its forms. These measures intend to mimic natural processes to manage pluvial water through the most sustainable and integrated way.

The hydrological processes affected by dense urbanization are infiltration and evapotranspiration, so the NbS tend to increase those, favoring the recharge of aquifers and reducing superficial runoff. To increase evapotranspiration the strategy is often seen as trivial by planting trees. However, there are many other important factors to increase the release of water to the atmosphere through plants. Some examples of NbS to rainwater control in an urban context are presented below.

i) Green roofs (Figure 2) should collect, store, and retain water through evapotranspiration and detention in the substrate, all this with focus on delaying and reducing the peak runoff. Some humid and very cold places do not provide the perfect conditions for plants' evapotranspiration and a non-vegetated approach may be valid in some cases, where only the water detention is achieved using extruded clay [14].

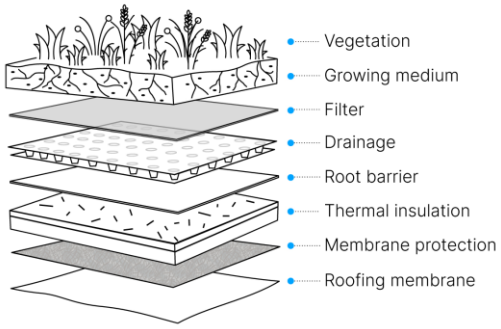


Figure 2. Typical layers of a green roof [19]

ii) Infiltration trenches (Figure 3) or swales present effects on slowing down the water flows but might not be effective under extreme conditions. These structures are constructed between roads and sidewalks and are below both their levels in a V-shape so that water flows in that direction. A small pipe shall be installed and covered with small vegetation or grass [20].

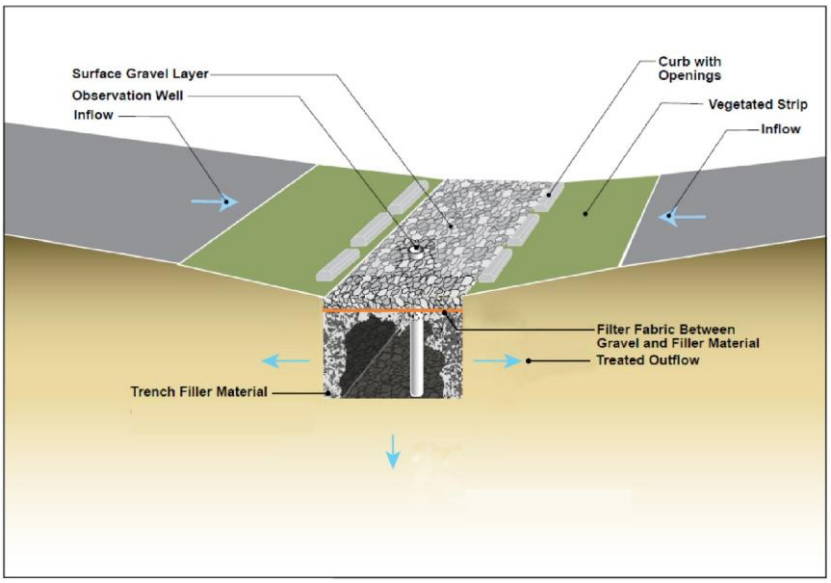


Figure 3. Infiltration trench setup [21]

iii) Detention basins (Figure 4) are structures usually integrated in parks or green areas to temporarily store rainwater and slowly discharge them to the collecting system. They are commonly used in cities because of the high engineering performance, less environmental impact, and low costs [22]. One feature is that detention basins can reduce local temperature through releasing moisture to the air via evaporation or evapotranspiration from the surface or surrounding vegetation [23].

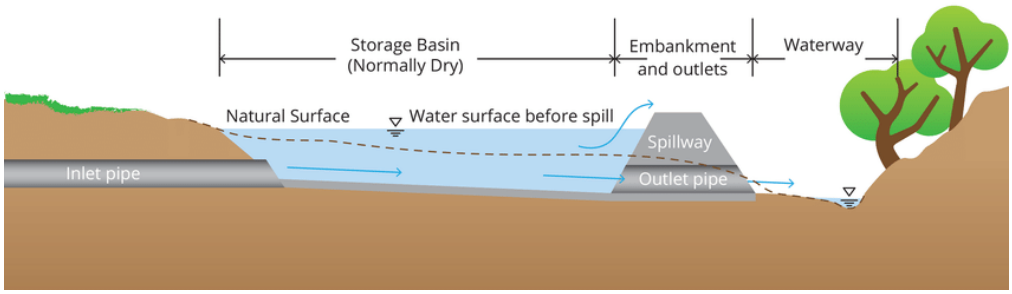
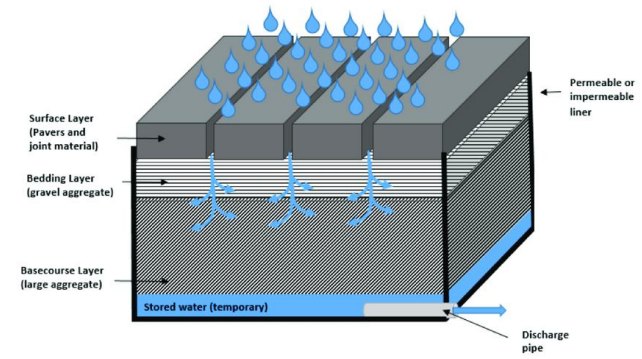
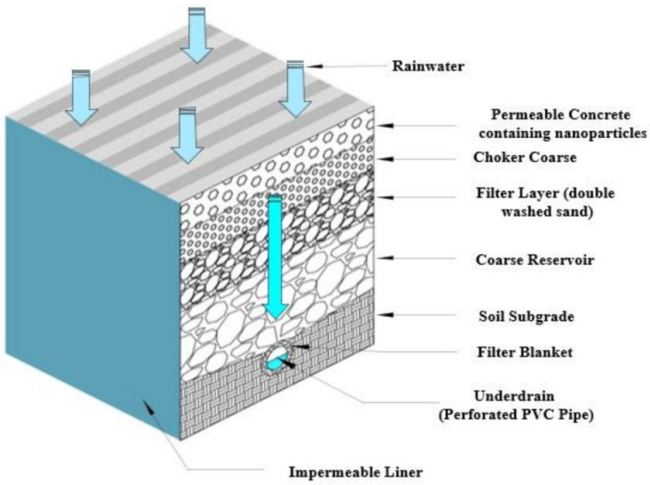


Figure 4. Detention basin typical section [24]

iv) Pervious pavements can be divided in two categories according to [25]. First is permeable pavement (Figure 5-a) which is a composition of an impermeable surface where water infiltrates through the voids between elements, bringing benefits as runoff reduction, groundwater recharge, water recycle and pollution prevention. This type of pavement is applicable in cases where the water might be contaminated and there is the necessity of a gross filtering. The second type is porous pavements (Figure 5-b) which are permeable along their entire surface, and that is achieved mainly by omitting fine aggregates. This system is susceptible to clogging and replacements usually occur every three years.



-a



-b

Figure 5-a permeable pavement [26] and -b porous pavement [27]

v) Rain gardens (Figure 6) enable a delay and reduction of the peak runoff by storing water once they are built below the surface of the ground. The volume of water that would go to drainage systems is reduced and, consequently, also are ponding and flooding risk. These structures provide benefits in water quality since they can retain pollutants, in biodiversity by creating a small habitat, and in public recreation by making it possible for people to use the garden for themselves [28].

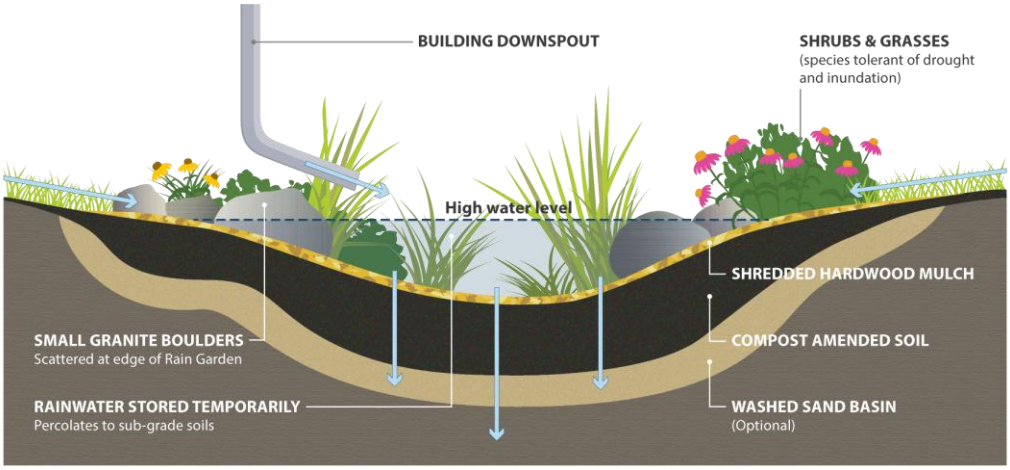


Figure 6. Rain garden diagram [29]

By applying the presented above as a combination or alone, it is possible to make urban areas more resilient and sustainable. Once cities present highly impermeable surfaces, there is now an uprising need of increasing permeability of water to the ground so that flood risk is minimized. It is crucial to consider a fair distribution of cities through a holistic and multidisciplinary approach to achieve a sustainable development and ensure a flood risk free environment in the future.

In conclusion, it offers a sustainable and efficient way to manage stormwater in urban areas by restoring natural hydrological processes and minimizing the negative effects of dense urbanization. They promote a reduction in flood risk and improve water quality and urban resilience through rainwater retention, detention, and filtering. Integration of and management strategies is crucial to cities' transition toward a more adaptive and environmentally responsible approach, guaranteeing a safer environment for citizens and their future generations.

2.4 Innovative tools

Two of the main recent revolutionary developments that tend to be the future's reality to reduce response time under extreme conditions and flooding are Real-Time Control (RTC) and digital twins (Figure 7). These technologies integrate sensors, data analytics, and machine learning to create intelligent networks capable of pointing critical sites. Therefore, helping to

achieve the needed shift from reactive to proactive management in flood mitigation and civil defense actions.

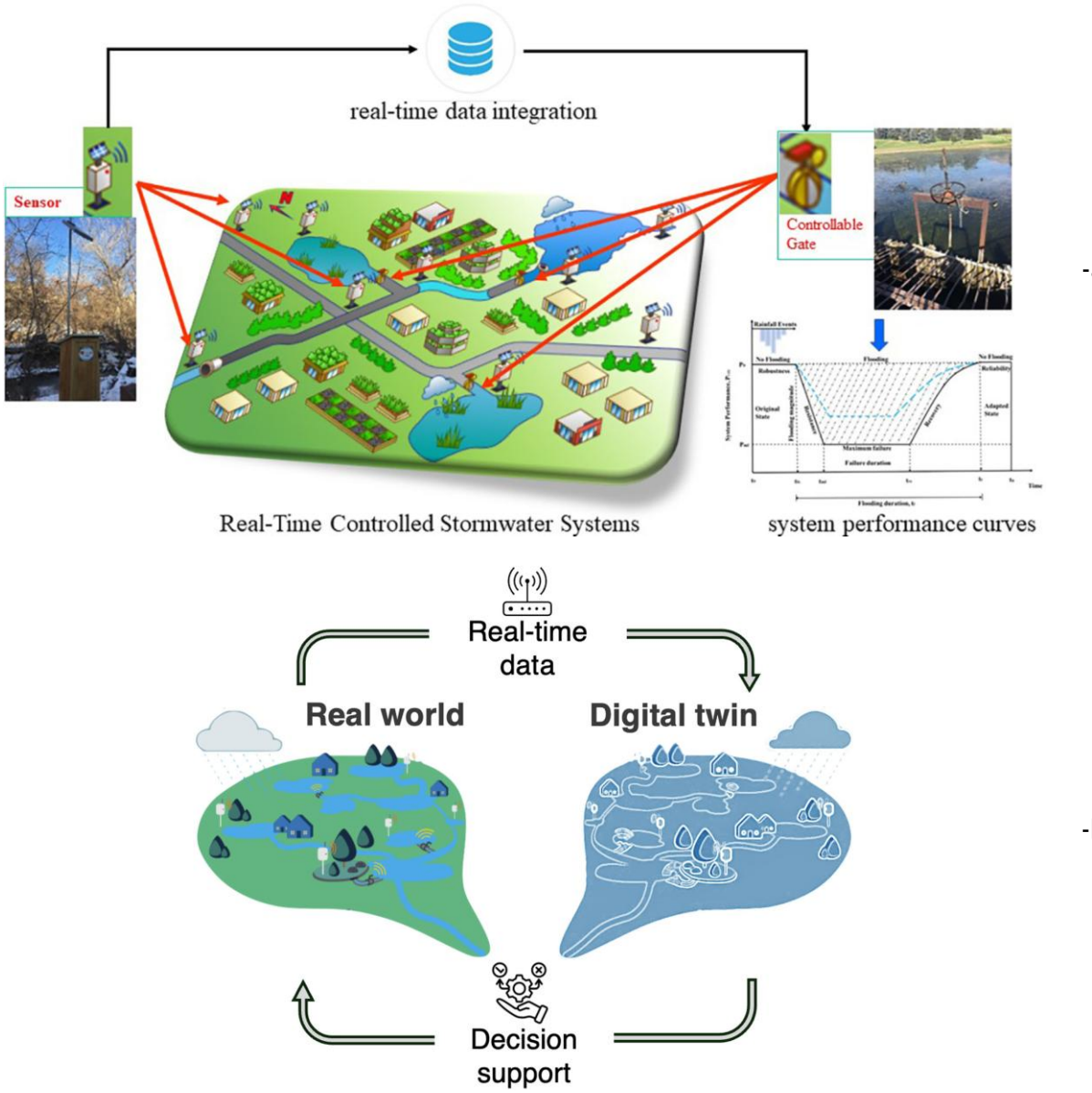


Figure 7-a RTC example of integration between gates and sensors [30] and -b digital twin representation of the real world to help decisions [31]

Networks with RTC are an adaptive solution that improve the performance of infrastructures by mitigating urban flooding. Implementing this system contributes to the reduction of peak flow and flooding volume, control sewer overflows, keep streams healthy and improve water quality. It enables stormwater infrastructure to respond almost instantaneously to environmental changes by applying concepts such as Internet of Things (IoT), cloud computing and automation to dynamically adjust flow rates, storage capacities and flow routes based on meteorology and water levels read by sensors that send information to a central every second. A case study in Salt Lake City, UT, USA showed that RTC strategies can perform better

than GI when comparing them in long-term stormwater management, since actions are taken through analyzing momentaneous data [30].

Digital twins are a virtual replica of an actual stormwater network to provide real-time monitoring, decision support and control, which are achieved through the strategic use of sensors that are wirelessly connected and send data to the authorities or professionals. They combine sensor data with hydraulic models to generate a real-time picture of stormwater dynamics, aiming to warn flood risk at a street-scale, pre-detect sewer clogging, and actively control valves and gates. These systems are under a continuous improvement regime, in a way that they learn with new data and experience thus enhancing their predictive accuracy over time [31].

3 S3SA in Portugal

3.1 National hydrological characterization

Temperature and precipitation are closely related to water availability since higher temperatures result in more evaporation, which then precipitates and become superficial runoff. Portugal will witness a general increase of temperature in the future, although changes in precipitation are still uncertain. Water availability will decrease because of more precipitation during winter but much less during spring and summer, so climate change should always be considered when predicting future conditions to implement mitigation strategies [32].

Portugal is a country with 92,226 km^2 [33] located at the west side of the Iberian Peninsula, area that is influenced by the oceanic and atmospheric conditions from the North Atlantic, Mediterranean, arid and semi-arid from the Sahara and Spain. The North Atlantic Oscillation (NAO) is an index calculated by subtracting the surface sea-level pressure at the Subtropical (Azores) High by the Subpolar Low [34]. It impacts the rain availability in the Iberian Peninsula in a way that under a negative NAO, winter tends to be wetter with more precipitation and that behavior was proven by measuring the flow of the Tejo river [35, 36].

Two oceanic currents also impact on Portugal's climate, namely the North Atlantic Current, which is an extension of the Gulf Stream, and transports warm water from the tropics to higher latitudes of the North Atlantic. This contributes to warmer temperatures during winter when compared to other regions of the same latitude, which ends up favoring water evaporation and forming humid air masses [37]. Contrarily, the Canary Current is cold and saline [38], lowering the water temperature throughout Portugal's coast and culminating in less evaporation and, later, less precipitation. [39] proven that sea surface temperature is a relevant parameter that directly influence rainfall at the north-west of the Iberian Peninsula, even temperatures at the Pacific Ocean.

The National Institute of Sea and Atmosphere (IPMA) has access to meteorological data since 1865 and, according to the World Meteorological Organization (WMO), 30-year series should be considered when defining a place's climate. IPMA defined three climates in Portugal using Köppen's climate classification (Figure 8): i) Csa which is temperate climate with hot and dry summer, that can be found in the interior regions of the Douro valley (part of the Bragança district), as well as in the southern regions of the Montejunto-Estrela mountainous system (except on the west coast of Alentejo and Algarve); ii) Csb represents a temperate climate with dry and mild summer and is found in almost all regions north of the Montejunto-Estrela mountainous system and in the west coastal regions of Alentejo and Algarve; finally, iii) Bsk is

a cold steppe climate of the middle latitude, found in a small region of the Lower Alentejo, in the district of Beja [40].

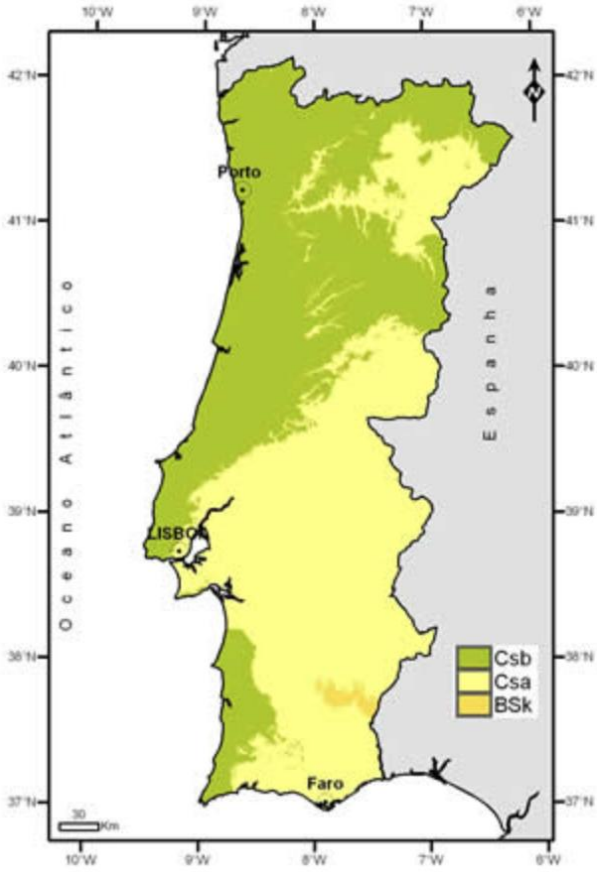


Figure 8. Köppen's climate classification of Portugal [40]

Temperatures in Portugal are spatially distributed and do not have extremes, with annual averages that range from 9 to 18ºC in the ocontinental region, as shown in Figure 9, and there is a clear relation between the Köppen's climate classification and the annual average temperatures. The clear distinguish between Portugal's north and south temperatures can be seen in Figure 9. The south part is undergoing a process of desertification [41] and the increasing temperature tendency can be observed at Figure 10-a, while Figure 10-b is at Coimbra (center of the country) and the temperatures are stabilized.

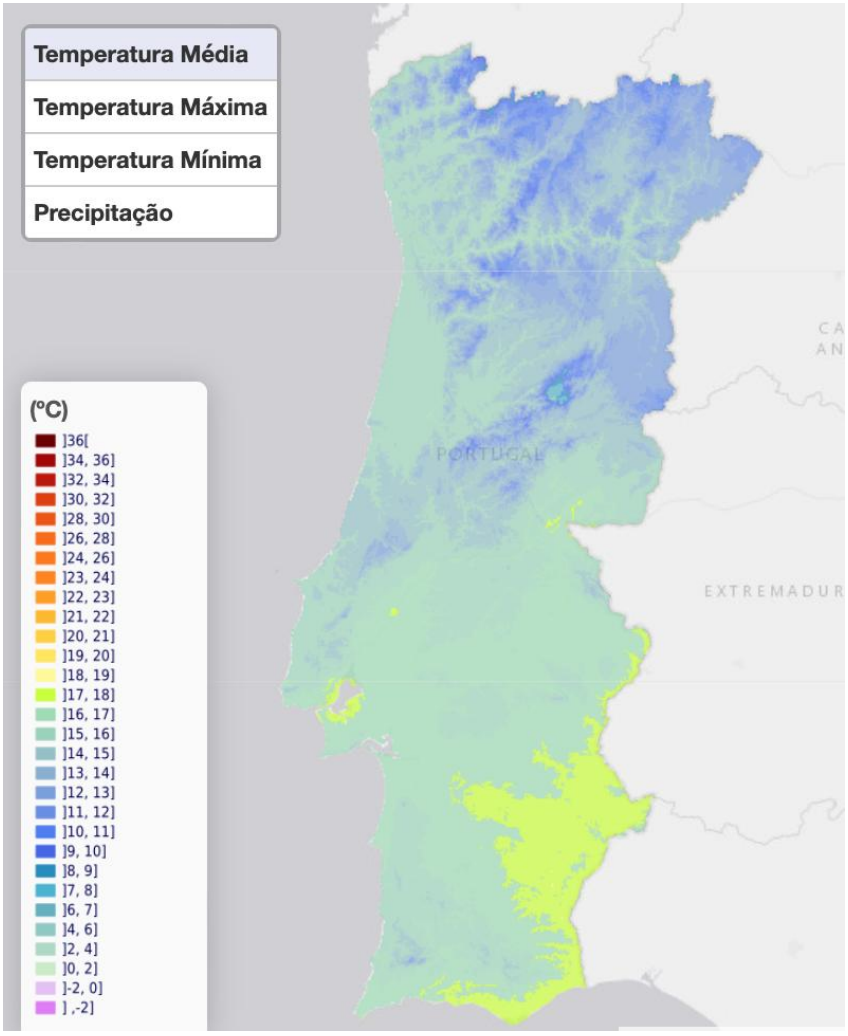
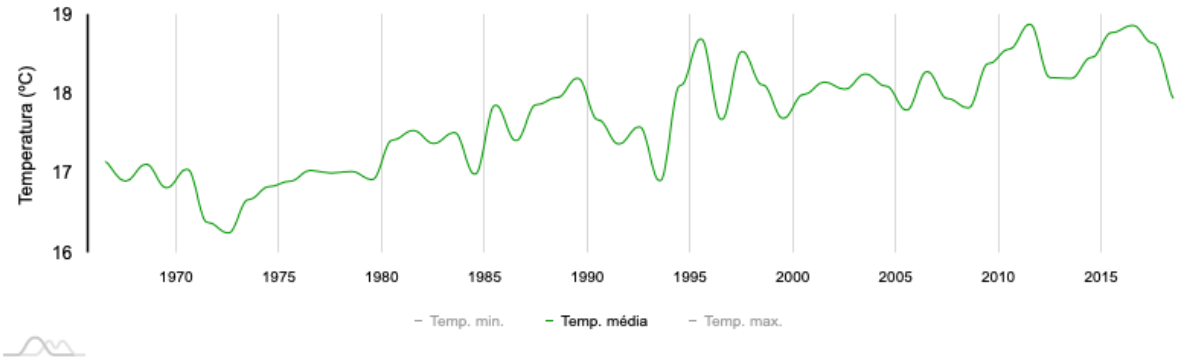
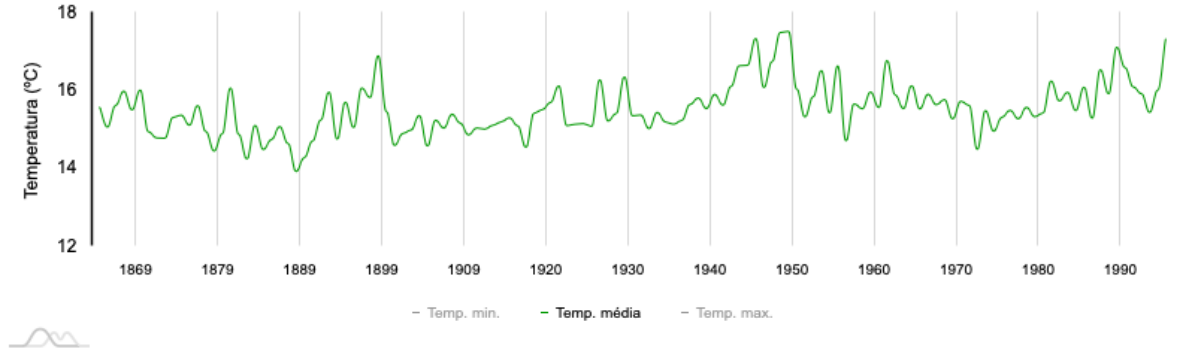


Figure 9. Average temperatures in Portugal from 1981-2010 [42]



-a



-

b

Figure 10-a Average annual temperatures at Faro meteorological station, from 1966 to 2018 and -b average annual temperatures at Coimbra/Geofísico meteorological station, from 1864 to 1995 [43].

Figure 11 below presents the monthly evolution of average temperatures in continental Portugal from 1990 to 2020. During summer, Portugal's average temperature is between 20 and 25ºC, while during winter the minimum recorded average is 7.5ºC.

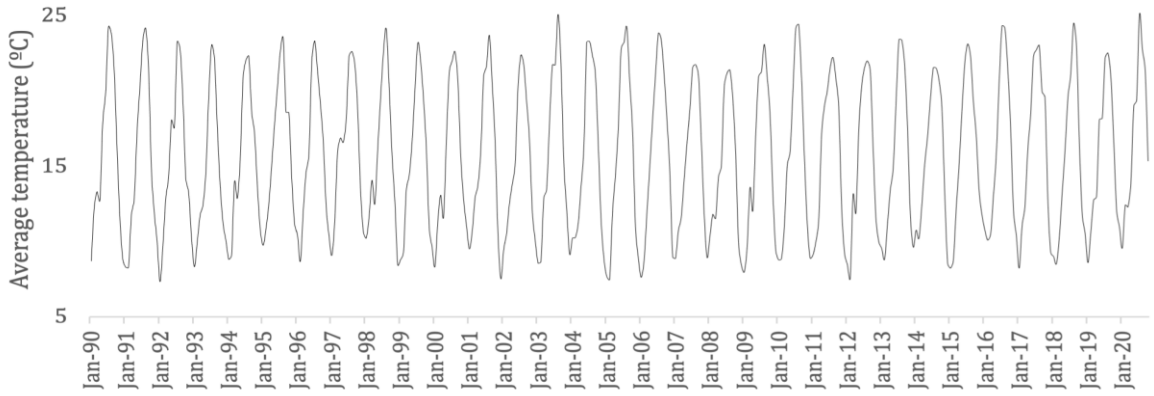


Figure 11. Average temperatures in continental Portugal, 1990-2020 [43]

When it comes to precipitation, there is also a clear distinguish between northern and southern Portugal, with more precipitation concentrated at the north, as presented in Figure 12, which divides Portugal into regions and highlights the two main rivers that flow through the two largest cities of the country, Lisboa and Porto.

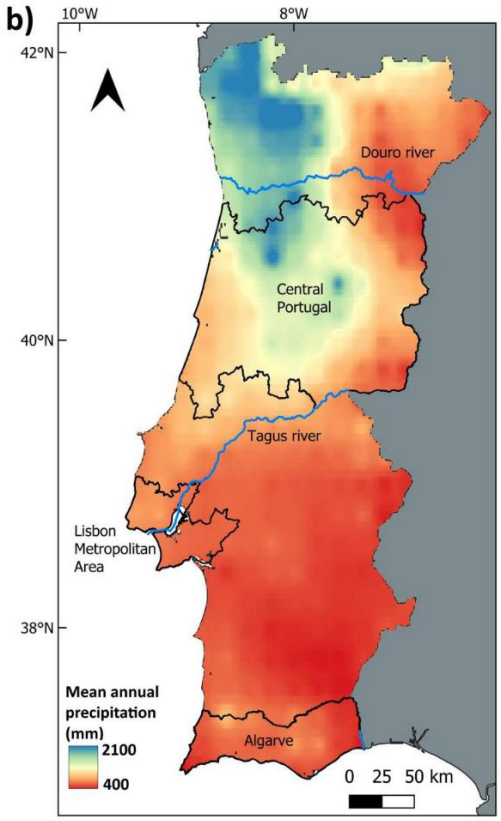


Figure 12. Mean annual precipitation for continental Portugal, 1950-2003 [44].

Figure 13 below shows the yearly evolution of total precipitation in continental Portugal, from 1931 to 2020. The average is around 800.0 mm/year while values tend to be below 1550.0 mm/year with a maximum value of 1509.8 and a minimum value of 503.1 mm/year. The discrepancy between north and south is clear, even with average values at 800 mm/year, the south holds a 505.2 mm/year average, with a 212.2 mm/year minimum and a maximum of 1177.0 mm/year. The north, however, has an average of 1239.0 mm/year, a maximum recorded value of 2255.3 mm/year and a minimum of 603.5 mm/year.

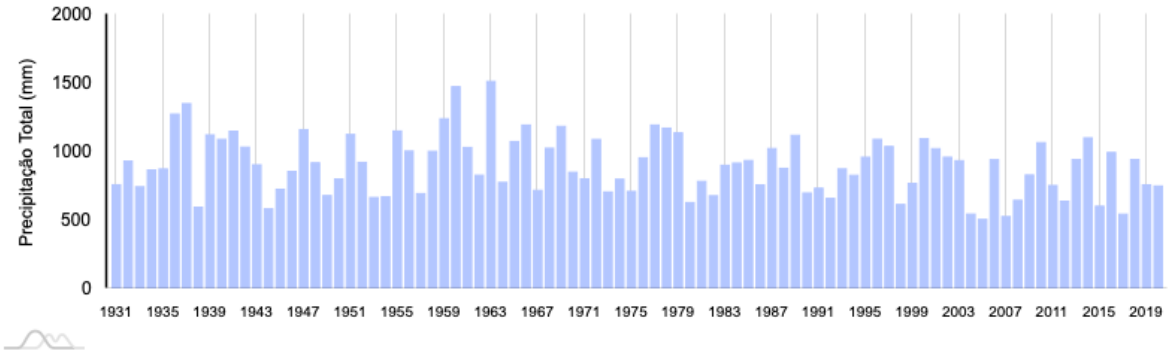


Figure 13. Accumulated annual precipitation for continental Portugal, 1931-2020 [43].

It is also important to consider the annual time distribution of precipitation, as seen in Figure 14, which is concentrated between October and March/April while from April/May to September the values of precipitation are the lowest. This highlights the need of a good management of water resources in order to ensure the public supply of water throughout the year. All areas of Portugal have a dry summer, meaning that even though the graph below is for the whole country, graphs for different meteorological stations would look like the one below.

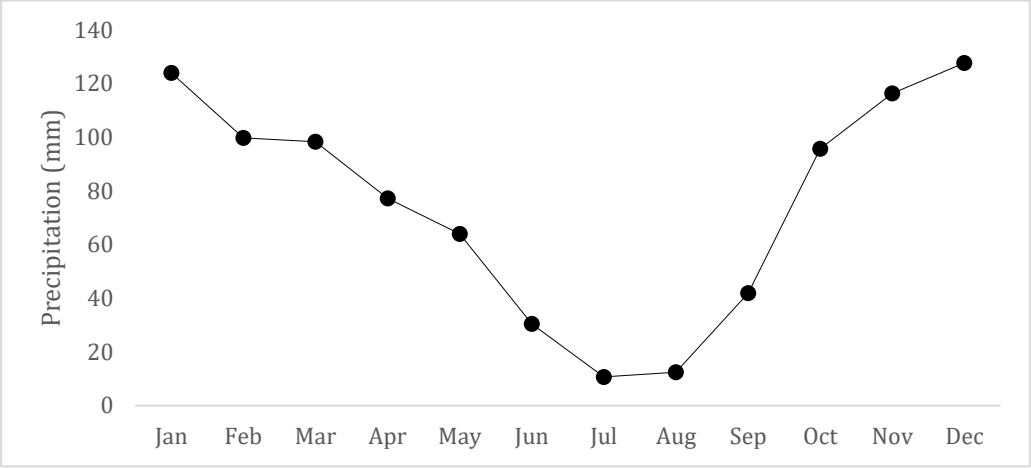


Figure 14. Average monthly values of precipitation for continental Portugal, from 1931 to 2020 [43].

DISASTER is a database with information regarding natural disasters that happened in Portugal from 1865 to 2010, created by Zêzere *et al* [45]. It points that between those years, 3804 cases were reported, divided in 1621 of disastrous floods, 281 of disastrous landslides and 1902 hydro-geomorphologic disasters, causing altogether more than 2500 deaths. The worst ever recorded floods in Portugal took place in 1967 near Lisbon and 1997 at Algarve region. The first flash flood occurred in the first hours of November 26th in small subcatchments near Lisbon, where Monte Estoril weather station recorded 159 mm in 24h that day, which is about 20% of the annual average. The second one at Serra de Monchique, Algarve, happened on October 26th

and the flood carried several tons of rock boulders, sand, mud, and tree trunks, destroying bridges, roads, and villages. Monchique station recorded 274 mm of rain between midnight and 06:00, which was twice the monthly average, corresponding to a 1000-year return period. Garganta stream is a very steep (~18%) small river at the referred area, which contributed to worsening the disaster [46].

Those two examples show that floods are a relevant problem, and, under a climate changing scenario, things tend to get worse. The Intergovernmental Panel on Climate Change (IPCC) developed four scenarios considering Earth's average temperature to increase by 1.5, 2, 3 and 4ºC (Figure 15).

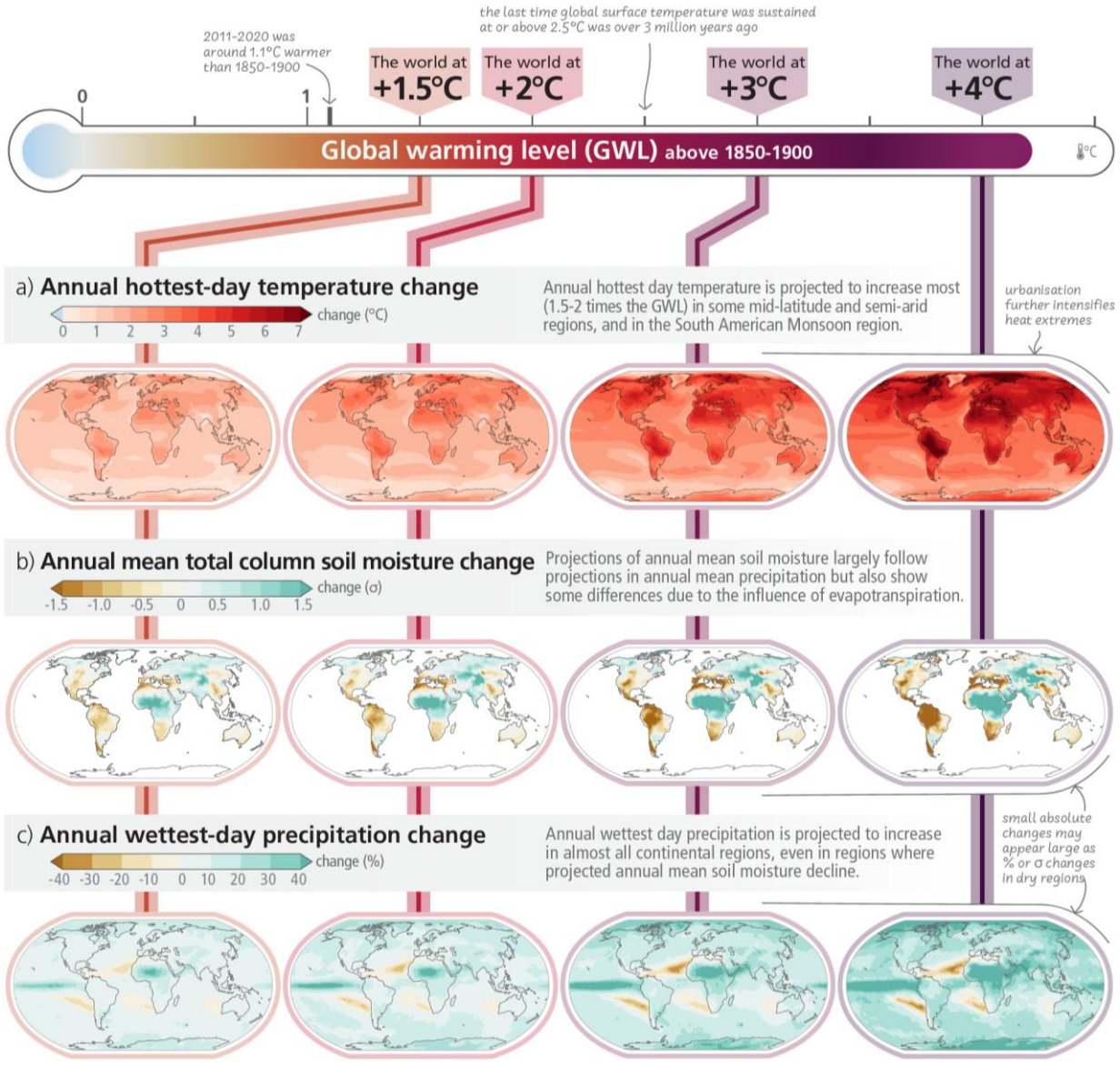


Figure 15. Potential effects of global warming by four different perspectives [47].

By looking at the part c) of Figure 15, it becomes evident that in all four scenarios it is expected more rainfall across all continents, while only oceans will witness less precipitation.

This reality acts as a warning to decision-makers to invest and prevent damage from floods, since more frequent and extreme rainfall events are already a reality.

These scenarios defined by IPCC are Representative Concentration Pathways (RCP) that "include time series of emissions and concentrations of the full suite of greenhouse gases (GHG), aerosols and chemically active gases, as well as land use / land cover". They are used by Agência Portuguesa do Ambiente (APA) in a way that the first one is more optimistic, the second is considering average values of the prementioned and RCP8.5 considers the worst-case scenario, with the highest GHG emissions. Considering these three scenarios, projections related to precipitation in continental Portugal until 2100 were made as shown in Figure 16.

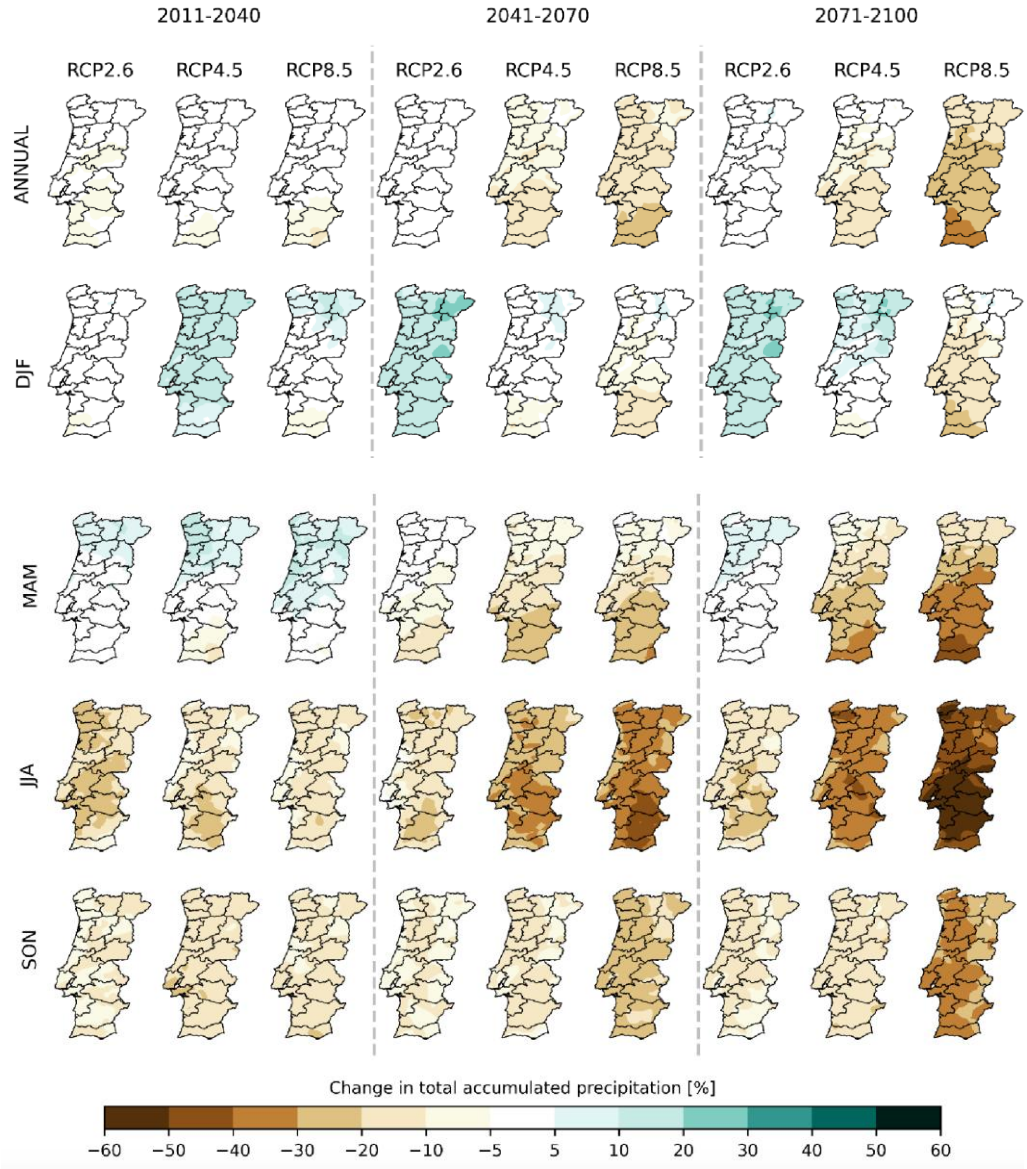


Figure 16. Percentual variation of the accumulated precipitation for the projections made by APA until the year 2100 considering three scenarios: RCP2.6 is optimistic, RCP4.5 is conservative and RCP8.5 is the most pessimistic [48].

By observing the annual predictions, overall, less rain is expected across the country at the 21st Century, especially during summer in south and central areas of Portugal. The already existing imbalance of rainy winters and dry summers will be even greater, which means that the flood risk increases as rainfall events will be concentrated in winters. Special attention shall be given to RCP8.5 since that scenario consists of the highest GHG emissions and results in a reduction of precipitation in all months of the year, with less rain even during winter.

These predictions are detailed at *Roteiro Nacional para a Adaptação 2100* that was developed by APA. They indicate a reduction in annual precipitation, a higher temporal irregularity and an increase in intensity and frequency of extreme events. When relating these future conditions to urban water drainage networks, with more frequent and extreme rainfall events, the systems are more likely to get overcharged resulting in flooding. Another important insight to bear in mind is that the reduction is regionalized, so while less water is expected at center and south, the northern areas will experience more stabilized values, increasing the territorial inequalities of rain distribution. That is why mitigation measures are needed, mainly the implementation of RTC, infrastructure maintenance and upgrading, and an adaptive urban planning to ensure more resilient cities and prepared drainage networks.

3.2 S3SA – methodology adaptation

The S3SA is the Norwegian methodology to urban water management, based on three steps: (1) infiltration for light rainfall; (2) detention and retention for moderate rainfall; and (3) conveyance of stormwater in safe floodways for heavy rainfall [16]. Although this methodology is applied in the present work, it needed some adjustments to Portugal's reality – temperature, precipitation, soil impermeability, urbanization, drainage network current status, pipe material, among others.

The main challenges regarding Portugal's reality are: (1) the Mediterranean climate, with the winter being the wet season and, therefore, rain is not well distributed throughout the year; (2) the elevated impermeabilization, mainly at large metropolis like Lisboa and Porto, limiting ground infiltration; (3) networks that often do not handle the intense rainfall events, considering the recent flood events seen at Lisboa on December 7th, 2022 [49], and at Porto on January 7th, 2023 [50].

The objectives of step one are ensuring the natural hydrological balance, increasing pluvial water quality, and reusing rainwater therefore contributing to groundwater recharge and relieving drainage networks. This involves the use of NbS to increase infiltration for light rainfall events – small return periods, such as pervious pavements, green roofs, infiltration trenches, and rain gardens that will reduce the percentage of impermeable surfaces across

urban areas. Also, designing and implementing projects of rainwater harvesting is always important to reduce the amount of water that flows to the drainage systems.

To apply step two the objective is to delay rainwater flow in case of greater events when comparing to step one. By having retention basins, detention basins and rain gardens, the peak runoff during moderate rain events is reduced, which is, in practical terms, storing water and releasing it gradually to ensure that the network can manage to drain all the water. Scattered green roofs can store water as well and help step two implementation. Besides that, network upgrading is also considered by increasing pipe diameters where manholes overflowing is expected after simulating a scenario in SWMM.

Finally, step three's objective is to establish floodways that are controlled and minimize damage to infrastructures. It consists in requalifying streams and urban rivers to their natural capacity so they can help relieving the drainage network, ensuring the existence of the safe floodways that were previously planned and can handle the total amount of rainwater under extreme rain events. Implementing rain gardens to temporarily store water while infiltrating and reducing the flow to the networks can also contribute to achieve step three's objective. Table 3 below sums up all three steps objectives and implementation methods.

Table 3. Objectives and implementation method of each step

Step	Objectives	Implementation methods
1 Light events	Ensure natural hydrological balance, increase pluvial water quality, reuse rainwater, increase groundwater recharge, and relieve drainage networks	Pervious pavements, green roofs, infiltration trenches, rain gardens, and rainwater harvesting
2 Moderate events	Delay rainwater flow and reduce peak runoff	Retention and detention basins, rain gardens, green roofs, and network upgrade
3 Extreme events	Establish floodways that do not allow infrastructure damage and relieve drainage networks	Requalify streams and urban rivers, define where the floodways will take place, and apply rain gardens

The implementation of the S3SA in Portugal should be integrated and hierarchical to guarantee that each step is complementing the previous one, and to achieve that step one must be applied in existing infrastructure and always considered when building new ones. Step two structures must be built in strategic areas such as parks in central areas and expansion zones. Mapping floodways and simulating scenarios that are as close as possible to reality is important

to ensure step three is the last level of managing urban water, complementing the two previous ones. After having the correct implementation of the S3SA, benefits are expected, such as reducing frequency and intensity of urban flood events, increasing population's well-being. Increased groundwater recharge and mitigating drought effects under a climate changing future scenario are especially important to southern Portugal. Implementing improvements in water quality and enhance public areas to create spaces that are useful and pleasant to citizens while complying to reduce damage of flood events.

4 Case study: Rio Leça's basin

The municipality of Matosinhos is part of the metropolitan area of Porto, Portugal, with a population of 172.557 which represents roughly 1,7% of the country's total and a high demographic density of 2.764 inhab/km^2 [51]. Porto de Leixões is a port located in the municipality and it was responsible for 57,5 million euros in movements through its 2.391 ships in 2023 [52]. This highlights the municipality within Portugal context and the potential external impacts of any disruptions or events.

Since it is located very close to the ocean, it is also under the influence of oceanic conditions. The average annual precipitation is 1240 mm [43]. The hydrology is highly disturbed since most of the water courses are not visible anymore. The areas near the ocean are highly urbanized with impervious surfaces in almost all its extent while the interior areas are greener, with a higher permeability and less densely populated.

It is important to highlight that this dissertation is focused on the drainage network that is currently connected to Rio Leça's and affluent waterlines (Figure 17). Also, that the river is not fully located inside Matosinhos' municipality, since its spring is inland Portugal, while Matosinhos is by the coast.

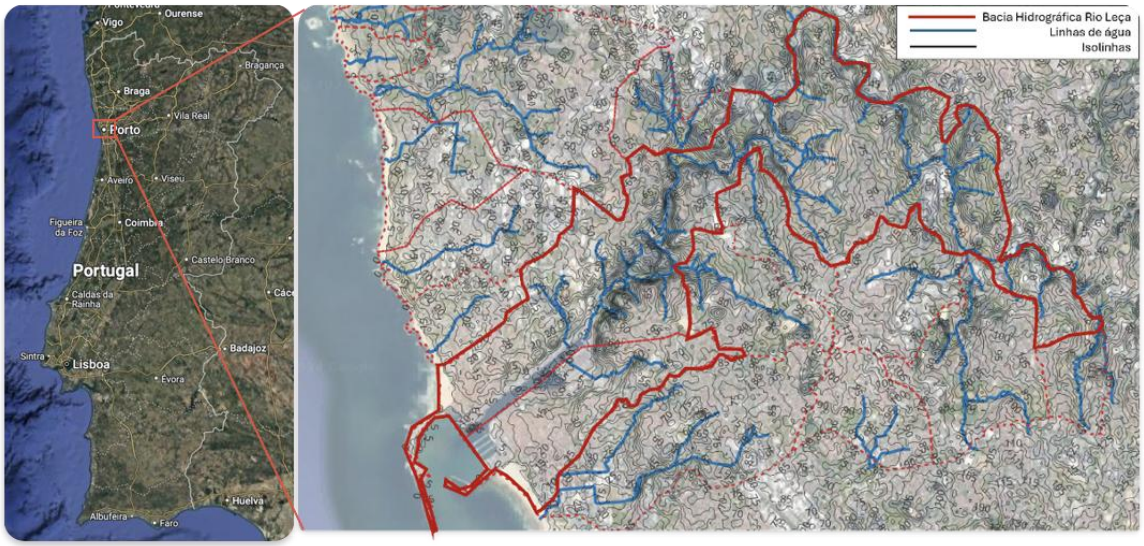


Figure 17. Limits of the watershed basin and waterlines

The current stormwater network was drawn based on two inputs of data, one being more recent and conducted by a third-party company through *in situ* data collection and the other being the former mapping done by the municipality management.

4.1 Storm Water Management Model (SWMM) design

The United States' Environmental Protection Agency (EPA) first developed a mathematical model for storm water management in 1971 that is widely used until today [53]. Nowadays, SWMM is a Windows-based software that, according to the user's manual [54]:

> *"is a dynamic rainfall-runoff simulation model used for single event or long-term (continuous) simulation of runoff quantity and quality from primarily urban areas. The runoff component of SWMM operates on a collection of subcatchment areas that receive precipitation and generate runoff and pollutant loads. The routing portion of SWMM transports this runoff through a system of pipes, channels, storage/treatment devices, pumps, and regulators. SWMM tracks the quantity and quality of runoff generated within each subcatchment, and the flow rate, flow depth, and quality of water in each pipe and channel during a simulation period comprised of multiple time steps."*

The hydraulic processes that produce runoff from urban areas that are included in the software are time-varying rainfall, evaporation of standing surface water, rainfall interception from depression storage, infiltration of rainfall into unsaturated soil layers, percolation of infiltrated water into groundwater layers, interflow between groundwater and the drainage system, nonlinear reservoir routing of overland flow, capture and retention of rainfall/runoff with various types of LID practices.

Adding components of the network to SWMM was done by firstly exporting the manhole points from QGIS – to have exact locations because of the coordinates. Even though files with extension "inp" open primarily in SWMM, they may also be edited in the notepad, and that allows adding the exported points from QGIS to SWMM and they become directly shown at the map. Besides the coordinates, the nodes carry attributes like "Name" (ID), "Invert El." (elevation) and "Max. Depth" (depth of the manhole). Figure 18 shows the attributes' dialog box for junctions.

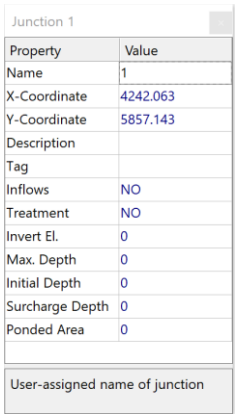


Figure 18. Example of dialog box in SWMM for junctions

After having all the manholes – or nodes – in SWMM, the link feature was used to create the pipes that connect two manholes or the few ones of discharge (from manhole to outfall). Some attributes are automatically created by the program, namely "Inlet Node" and "Outlet Node", which are the ID's of the nodes connected by that link and "Length" after setting the "auto-length" to "on". The remaining attributes such as "Max. Depth" (diameter) and "Roughness" (Manning's coefficient, Figure 19) were manually added to each pipe considering the available data. Figure 20 below presents the dialog box at SWMM for links and its respective attributes.

Conduit Material	Manning n
Asbestos-cement pipe	0.011 - 0.015
Brick	0.013 - 0.017
Cast iron pipe - Cement-lined & seal coated	 0.011 - 0.015
Concrete (monolithic) - Smooth forms - Rough forms	 0.012 - 0.014 0.015 - 0.017
Concrete pipe	0.011 - 0.015
Corrugated-metal pipe (1/2-in. x 2-2/3-in. corrugations) - Plain - Paved invert - Spun asphalt lined	 0.022 - 0.026 0.018 - 0.022 0.011 - 0.015
Plastic pipe (smooth)	0.011 - 0.015
Vitrified clay - Pipes - Liner plates	 0.011 - 0.015 0.013 - 0.017

Figure 19. Manning's coefficients to different materials. Source:ASCE [55] apud Rossman [54])

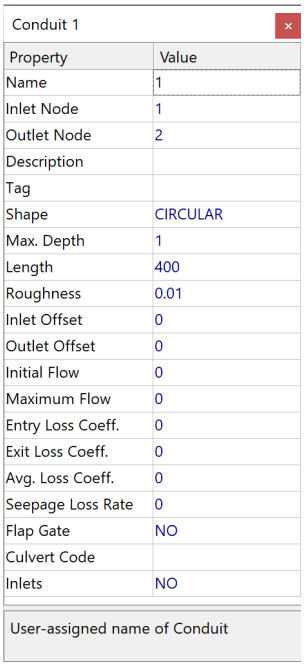


Figure 20. Example of dialog box in SWMM for links

The subcatchments were then drawn by using its feature, where the user must left click all vertices and close the area with a right click. The background image is helpful because it shows where the boundaries of the subcatchment area are, such as streets, buildings, walls, natural barriers, among others. Once drawn, the program calculates the area – in hectares – of each subcatchment which must be associated to a rain gage, i.e. rainfall intensity, and to a manhole that will receive the drained water. There are two other attributes of subcatchments that must be edited, being "Width" (average distance from furthest border to center) and "% Imperv." (percentage of impervious area). Figure 21 presents the attributes inside a dialog box for subcatchment areas.

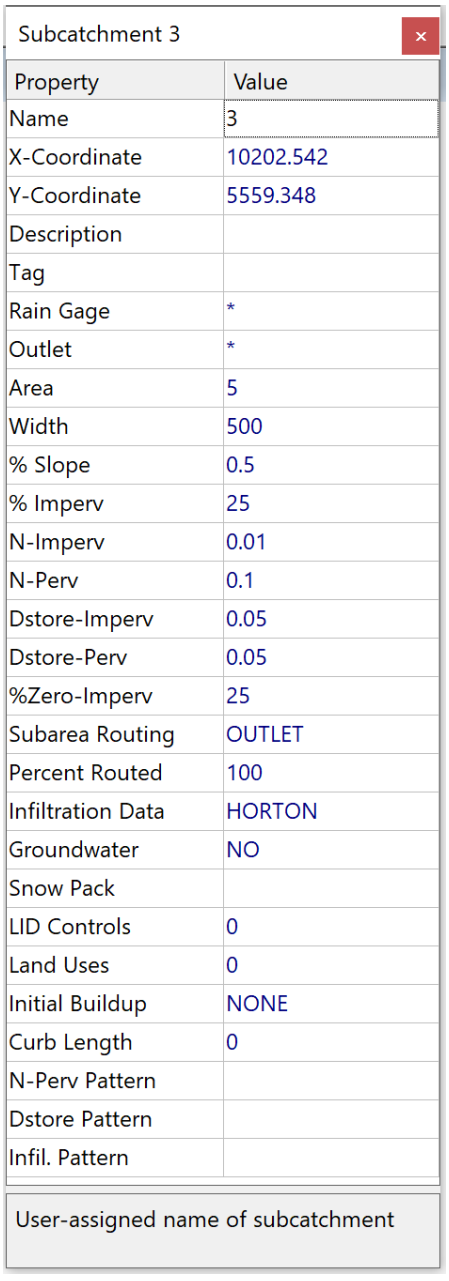
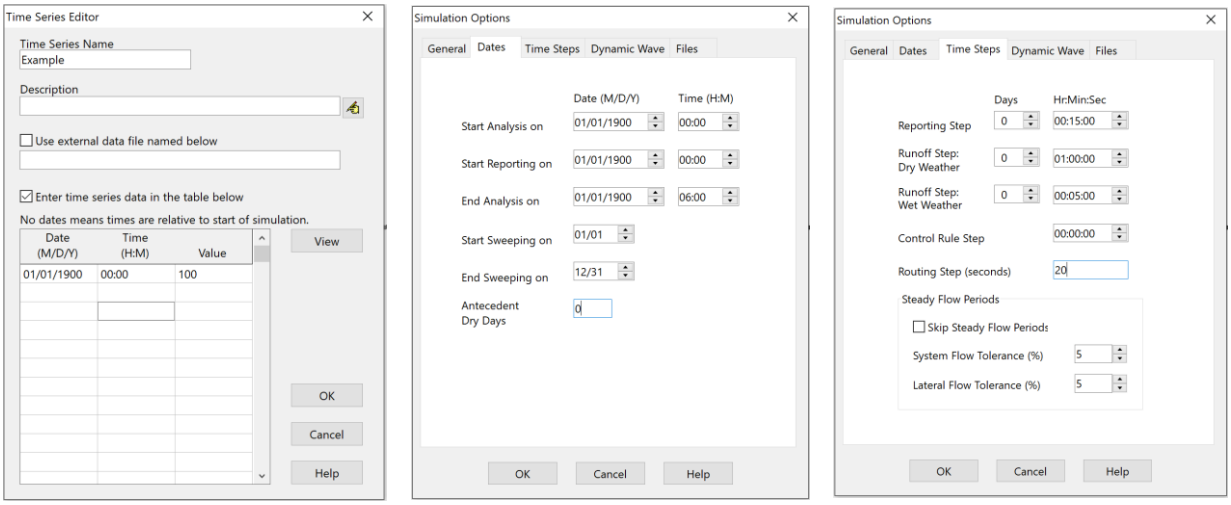


Figure 21. Example of dialog box in SWMM for subcatchments

To run a simulation in the software, it is important to set up three main conditions. The first is pluviosity, which is the intensity of rainfall in the study area that directly determines the runoff generation and must be attached to at least one rain gage. Note that "Value" is the precipitation, in mm. Second is date options where the starting and ending dates wanted for the simulation are determined. And third is the length of the time steps considered for runoff and routing calculations, and results reporting which are inserted in the *Time Step Options*. With these conditions correctly inputted, accuracy, stability and relevance of the simulation are ensured. Figure 22 presents the dialog boxes where all three set up conditions are inserted.



-a -b -c

Figure 22. Examples of the dialog boxes for setting up the initial simulation conditions. -a represents the pluviosity time series values, -b represents the dates to start and end the simulation, and -c the length of the time steps considered in the simulation

The SWMM program enables an easy visualization of the drainage network since it allows the user to insert a georeferenced background image and to insert the components at their correct locations. Although there are some components available, the ones considered in the design of Rio Leça's drainage network were junctions (manholes), links (pipes), subcatchment (drainage areas), outfall nodes (discharge points) and rain gages (precipitation).

The software has built-in features that ease the obtention of graphs (time series and scatter plot), longitudinal profile, statistics (mean, peak, total, duration and inter-event time), personalized tables (where the user sets the rows and columns that wants to extract)

Another relevant aspect of the software is that it enables using color scales to three themes (subcatchments, nodes or junctions and links) after running the simulation. There are many variables to each theme and the legend values are editable. Figure 23 shows a portion of the study area after the color scale is applied where the variables are subcatchment imperviousness, node flooding and link flow.

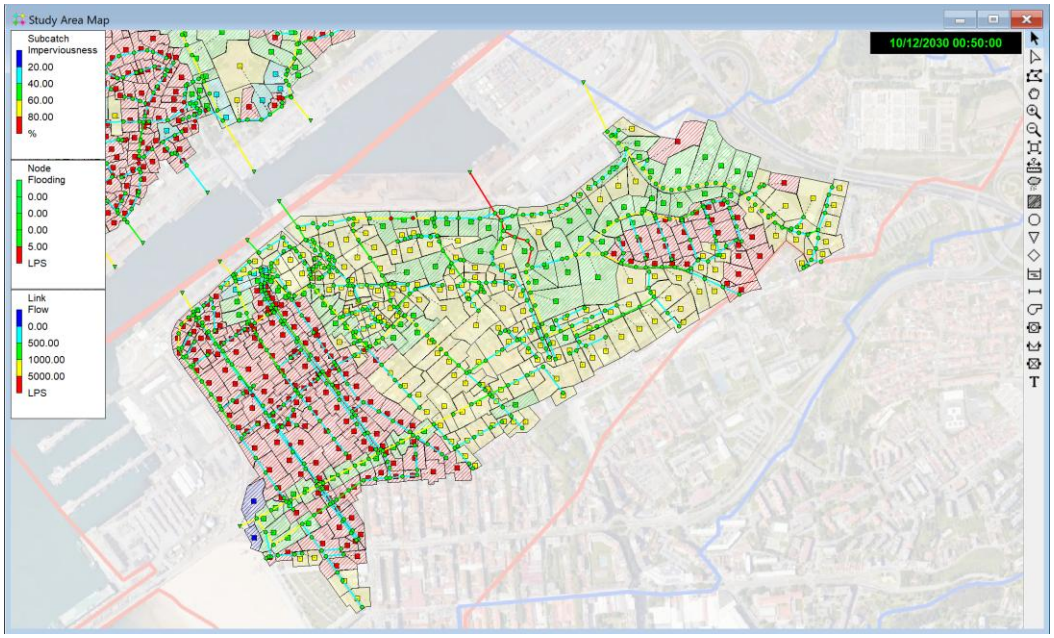


Figure 23. Portion of the study area with the color scale applied to three themes

The pluvial drainage network inside the study area was drawn and the initial set up followed the previously presented, in a way that the pluviosity of each steps one, two and three is present in Table 4, Table 5 and Table 6, respectively. The precipitation values were obtained through calculations using the IDF curve for the region [56] and the respective climate factor was applied, which corresponds to an expected variation percentage in precipitation, defined at projections made by Soares *et al* [48]. To build the following tables that are the inputs to the hyetographs, the alternating block method was used.

Table 4. Rainfall event with a return period of 2 years

Date (MM/DD/YYYY)	Time (HH:MM:SS)	Precipitation ($mm \cdot h^{-1}$)
10/12/2030	00:00:00	19.62
10/12/2030	00:05:00	21.80
10/12/2030	00:10:00	24.80
10/12/2030	00:15:00	29.27
10/12/2030	00:20:00	36.99
10/12/2030	00:25:00	55.18
10/12/2030	00:30:00	82.31
10/12/2030	00:35:00	43.67
10/12/2030	00:40:00	32.52
10/12/2030	00:45:00	26.78
10/12/2030	00:50:00	23.17
10/12/2030	00:55:00	20.63
10/12/2030	01:00:00	18.74

Table 5. Rainfall event with a return period of 50 years

Date (MM/DD/YYYY)	Time (HH:MM:SS)	Precipitation ($mm \cdot h^{-1}$)
10/12/2030	00:00:00	38.36
10/12/2030	00:05:00	42.21
10/12/2030	00:10:00	47.44
10/12/2030	00:15:00	55.16
10/12/2030	00:20:00	68.22
10/12/2030	00:25:00	98.10
10/12/2030	00:30:00	141.06
10/12/2030	00:35:00	79.32
10/12/2030	00:40:00	60.69
10/12/2030	00:45:00	50.88
10/12/2030	00:50:00	44.60
10/12/2030	00:55:00	40.15
10/12/2030	01:00:00	36.79

Table 6. Rainfall event with a return period of 100 years

Date (MM/DD/YYYY)	Time (HH:MM:SS)	Precipitation ($mm \cdot h^{-1}$)
10/12/2030	00:00:00	44.76
10/12/2030	00:05:00	49.10
10/12/2030	00:10:00	54.99
10/12/2030	00:15:00	63.65
10/12/2030	00:20:00	78.21
10/12/2030	00:25:00	111.22
10/12/2030	00:30:00	158.16
10/12/2030	00:35:00	90.51
10/12/2030	00:40:00	69.83
10/12/2030	00:45:00	58.85
10/12/2030	00:50:00	51.80
10/12/2030	00:55:00	46.78
10/12/2030	01:00:00	42.97

5 Results and Discussion

5.1 Step 1

To simulate a rain event with a return period of 2 years the following hyetograph was inputted in SWMM (Figure 24).

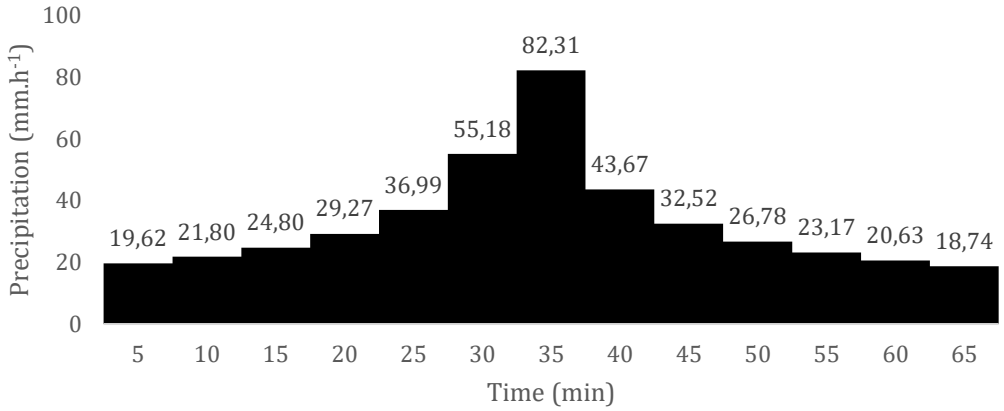


Figure 24. Hyetograph inputted in SWMM to simulate a rain event of a 2-year return period.

The increased infiltration values of the simulation compared to the baseline of a rain event under the same return period are presented in Table 7. The baseline simulation considered impervious surfaces of the study area as they currently are, while the TR=2 simulation decreased the percentage of impermeable surfaces to consider the use of SCM over highly urbanized areas, in this case, green roofs. The method consisted in decreasing by 50% the impermeable surface of peripheral subcatchments that drain water to a conduit with flooding over 10 $L{\cdot}s^{-1}$. That way, it is expected a 25% reduction in runoff since 40-50% of the impermeable surfaces of cities are the roofs [15]. An example of a fragment of the current network baseline scenario and the TR=2y simulation are presented in Figure 25 and Figure 26. To understand the increase in soil infiltration after applying step 1, each subcatchment is evaluated by its infiltration rate and categorized in section ranges of 2% as shown in Figure 27.

Table 7. Baseline and TR=2y simulation results.

Parameter	Without NbS	With NbS
Precipitation (mm)	36.48	36.48
Average infiltrated volume (mm)	00.61	01.05
Average runoff (mm)	35.87	35.43

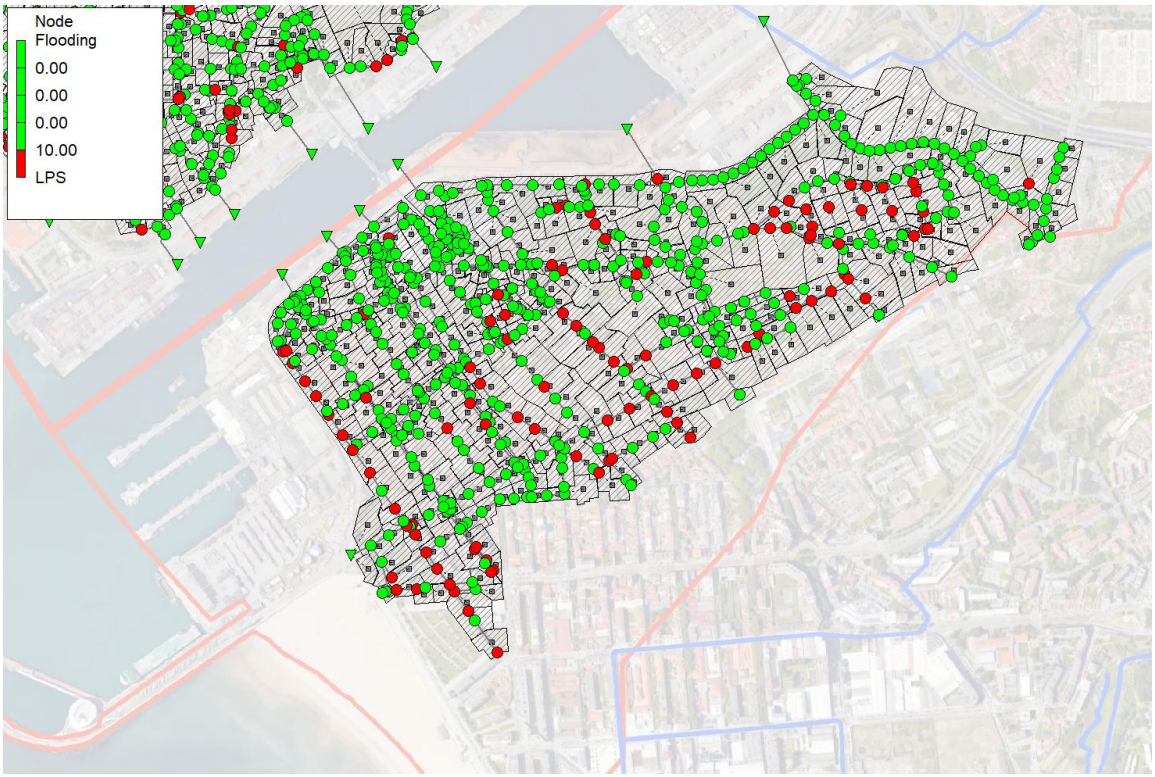


Figure 25. Baseline scenario of node flooding for a fragment of the current network south of Port of Leixões.

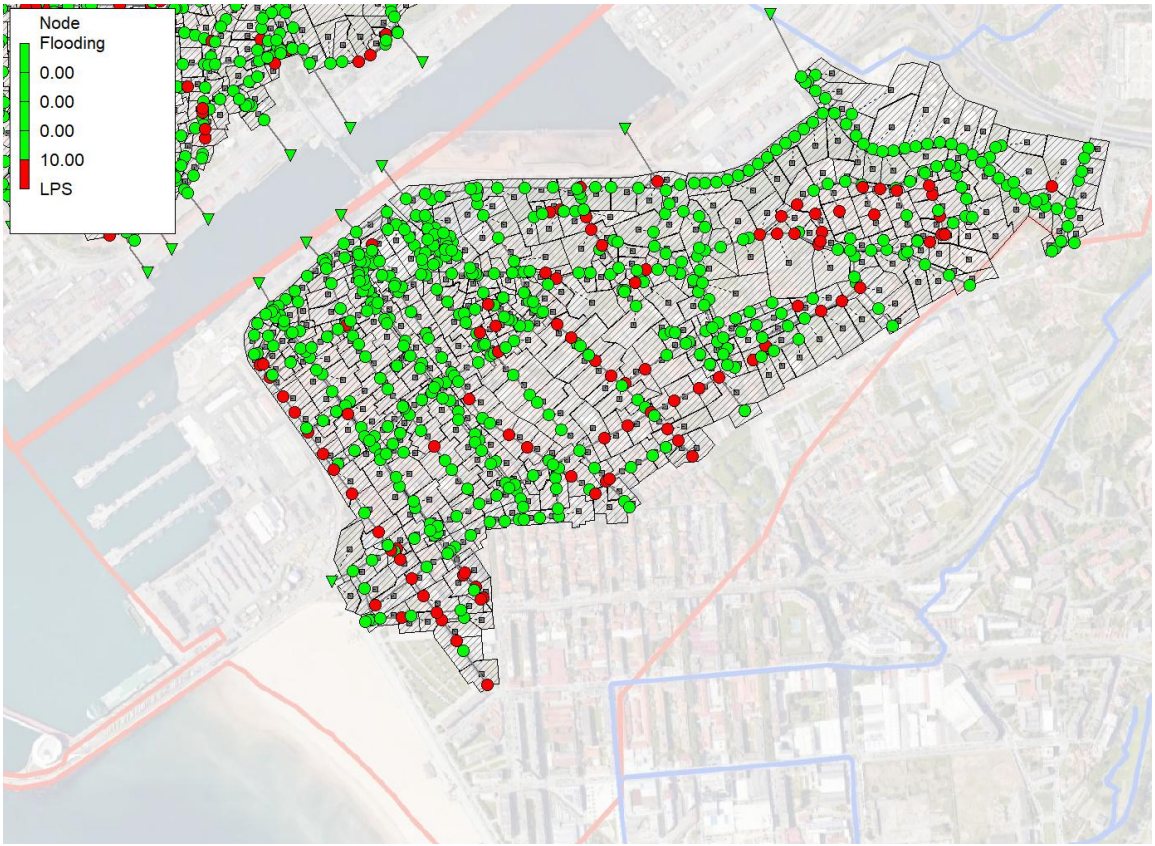


Figure 26. TR=2y simulation of node flooding for a fragment of the current network south of Port of Leixões.

Under the same step, Lerer *et al* [17] obtained a 42% reduction, and that value corresponds to the amount of water that is not being sent to the WWTP after redesigning the drainage network and implementing bioretention units in some areas. Although the drainage network used in this study is completely separated in a way that no rainwater ends at WWTP, both results culminate in a reduction of superficial runoff and increase in infiltration, helping to unburden the networks. Also, Sciuto *et al* [57] simulated five scenarios return period of 10 years and verified that a reduction both in volume and in peak flow is observed. When comparing the results, the reduction in volume is greater than the peak flow, which can be related to the higher infiltration observed in this study, even though the maximum reduction in volume was lower than the one observed in Table 7. This exemplifies the huge benefits that can be obtained after applying SCM at cities and how local, decentralized urban water management can relieve the drainage networks, as proposed by Paus [18]. After increasing infiltration in soil of adjacent subcatchments that drain to the network, flooding was successfully mitigated at 37 nodes that were previously experiencing inundation, and the average flooding flow for the whole network decreased from 80.06 $L \cdot s^{-1}$ to 73.85 $L \cdot s^{-1}$.

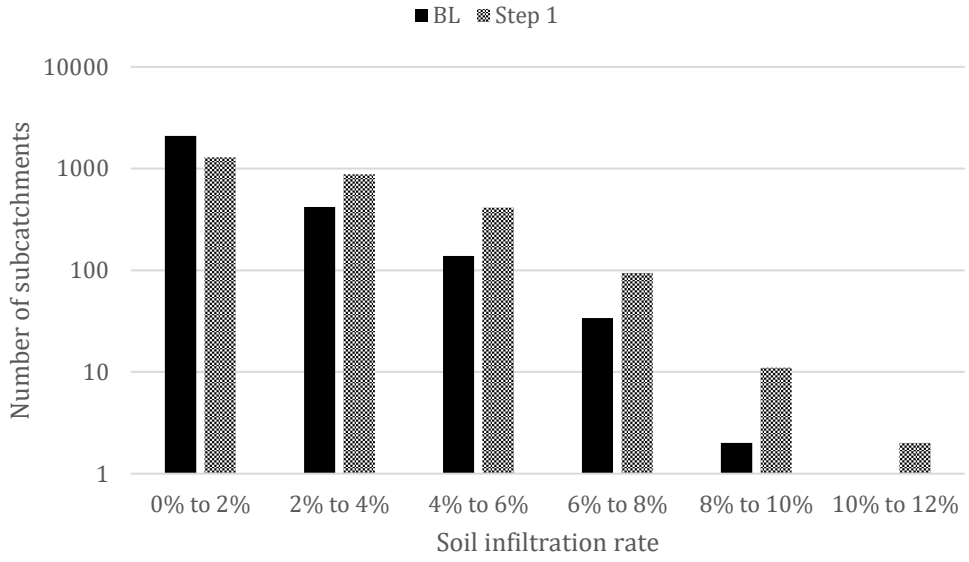


Figure 27. Boxplot indicating an increase in infiltration after applying step 1.

5.2 Step 2

The SWMM simulation of a rain event with a return period of 50 years was run using the hyetograph presented in Figure 28. This step focus in storing and delaying runoff, so with an individual volume of 1,000 m^3, the retention basins were introduced in subcatchments that drain to manholes with flooding and where there was available space to implement them. The maximum value for occupied area was defined as 15% of the total area of the subcatchment, and that was achieved by including one or more in each area, since a single has an area of 500

m^2. Even at the smallest subcatchment where only one retention basin was introduced that percentage was below 15%. Four examples of runoff at subcatchments that exemplify the behavior are presented in Figure 30. All graphs are similar and that indicates a good and replicable that will receive water, store, and release it gradually after the end of the rain event. In the examples runoff was roughly reduced by half and the runoff after opening the drain did not pass the peak runoff, which indicates that the retention basins are working as they should.

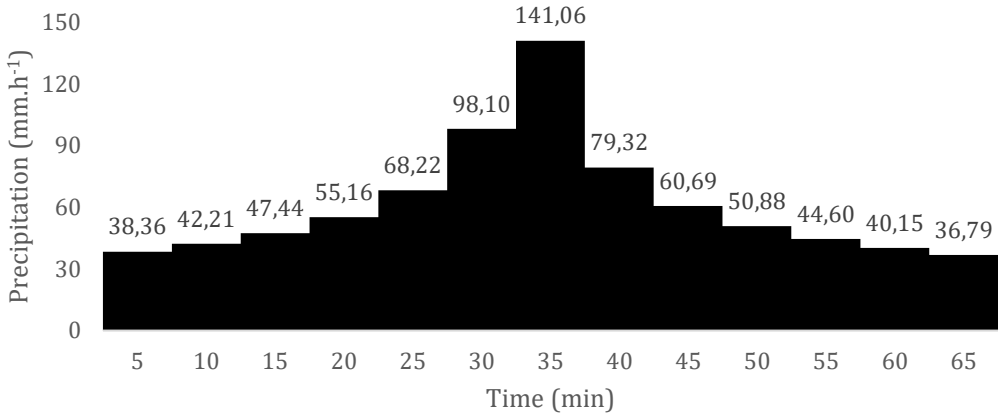


Figure 28. Hyetograph inputted in SWMM to simulate a rain event of a 50-year return period.

To apply step 2 in the network the main consideration is to have retention basins that will receive, store, and gradually release water from the rain event to reduce peak runoff. That can be clearly observed in Figure 29, that shows that peak runoff was reduced in all subcatchments where retention basins were introduced. The chosen areas to receive those basins were not too densely constructed and that was made using satellite images. The average reduction, i.e. difference between peak runoff before and after step 2 considerations, across the 120 subcatchments with applied is 152 $L{\cdot}s^{-1}$, with a maximum value of 631 $L{\cdot}s^{-1}$, a minimum of 30 $L{\cdot}s^{-1}$ and the distribution of peak runoff reduction by ranges is presented in Table 8.

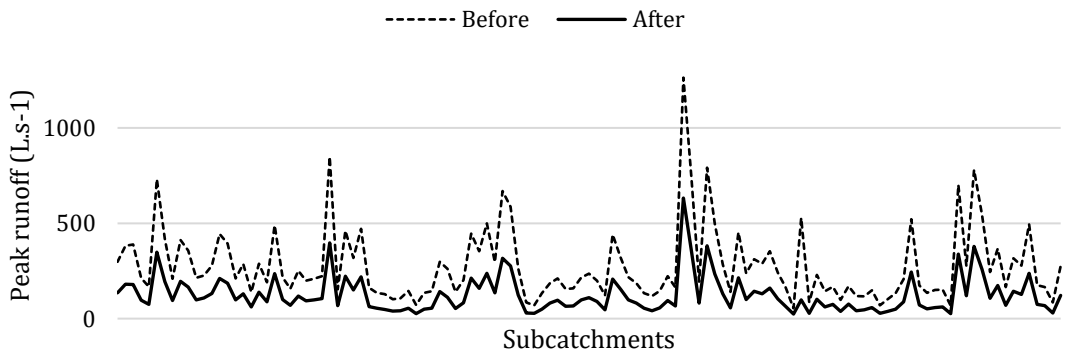


Figure 29. Peak runoff reduction in subcatchments where retention basins were introduced.

Table 8. Subcatchments reduction in peak runoff divided by ranges.

Peak runoff reduction range (L.s^{-1})	Number of subcatchments
0 to 100	44
100 to 200	50
200 to 300	17
300 or more	10

Qin *et al* [58] also experienced a reduction in runoff after applying a series of which culminated in a better performance of the stormwater network, relieving pressures, and increasing water quality before being sent to the nearby river. Additionally, the presence of a retention basin resulted in a significant reduction in flood depth and increased lag time in several rivers in Ghana, and that was observed by Acheampong *et al* [59].

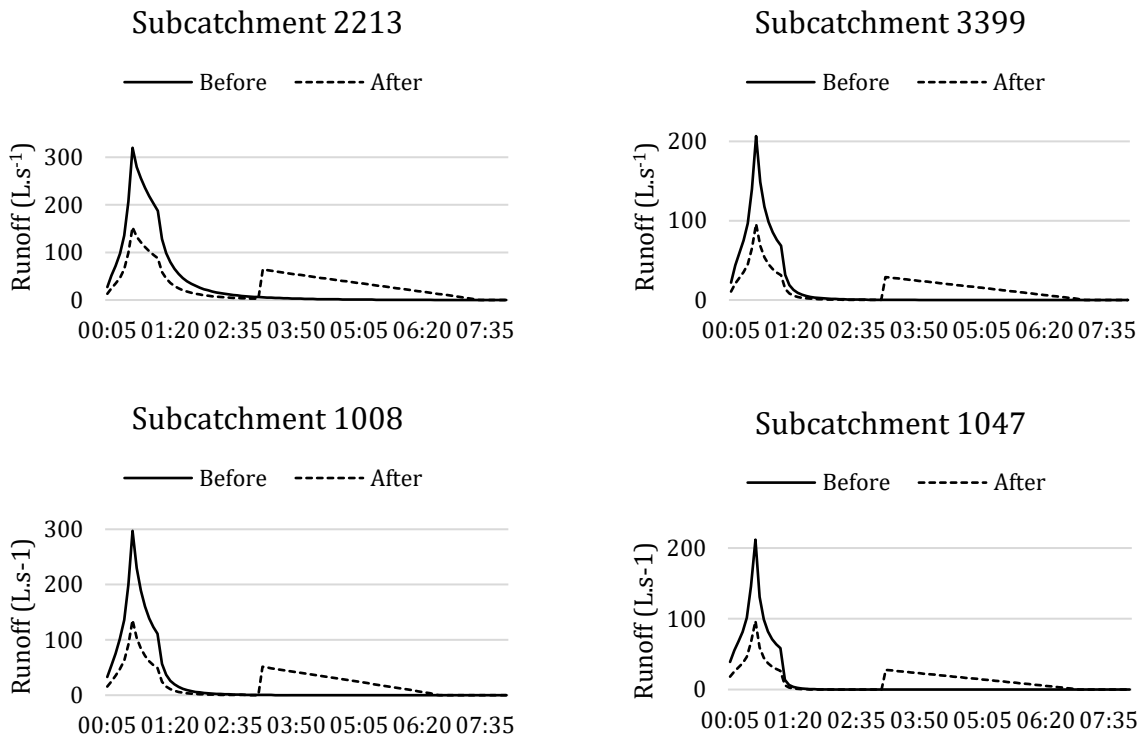
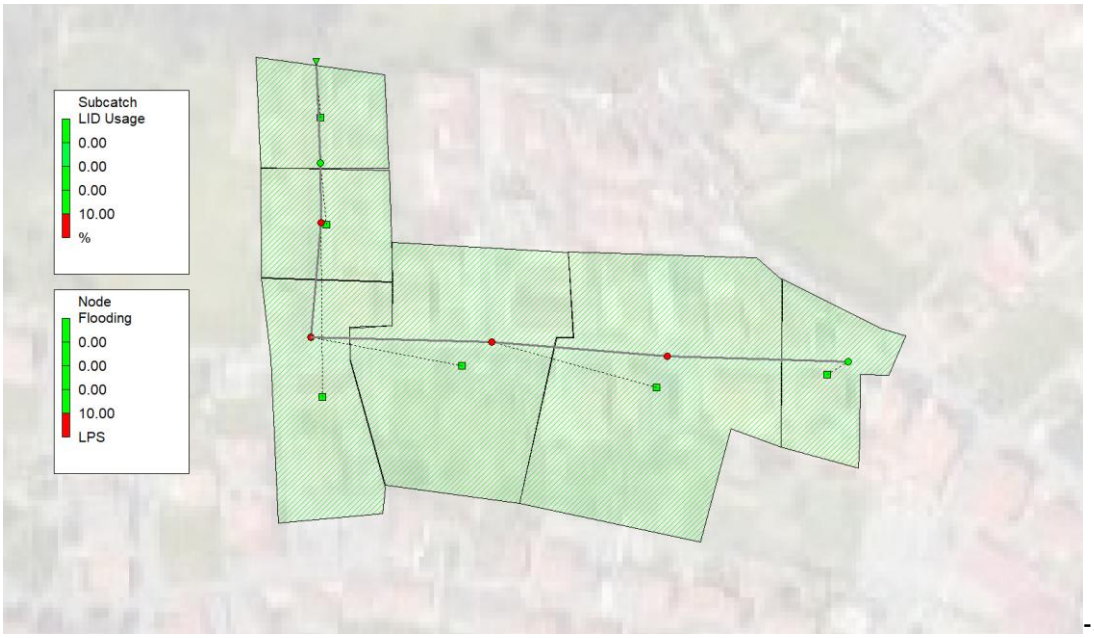


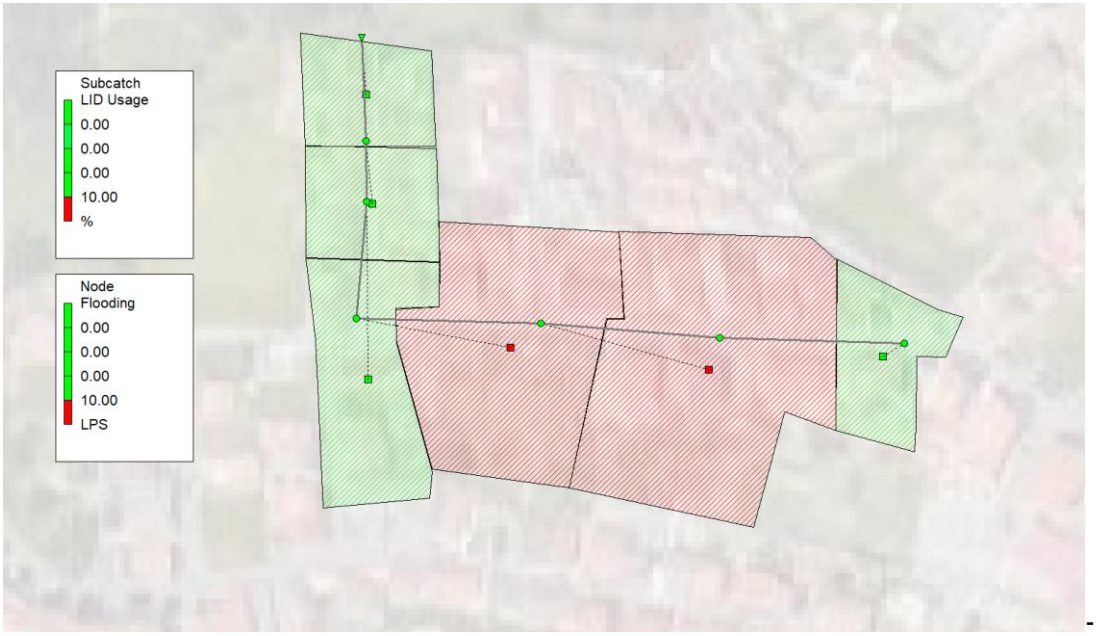
Figure 30. Runoff reduction in four subcatchments – the numbers are the IDs – and the retention basin water release happening 3 hours after rain starts.

To try to understand more the behavior of this type of a detailed analysis of a fragment of the network was done in SWMM. This analysis was done to try to answer the following question: retention basins should be applied in all subcatchments with flooding manholes or if applied upstream, flooding downstream is prevented? Figure 31-a presents the analyzed fragment without applied and with four manholes experiencing flooding of more than 10 L·s^{-1}. Once retention basins were introduced in two subcatchments, all four manholes were relieved (Figure 31-b), indicating that these structures should be well planned in order to find the best

individual volume and spot to place them to reduce environmental impacts and costs, and increase performance and efficiency of these structures.



-a



-b

Figure 31. -a Fragment of the network without retention basins, and -b with those structures considered in the simulation.

5.3 Step 3

The SWMM simulation of a rain event with a return period of 100 years was run using the hyetograph presented in Figure 32 to analyze the third step.

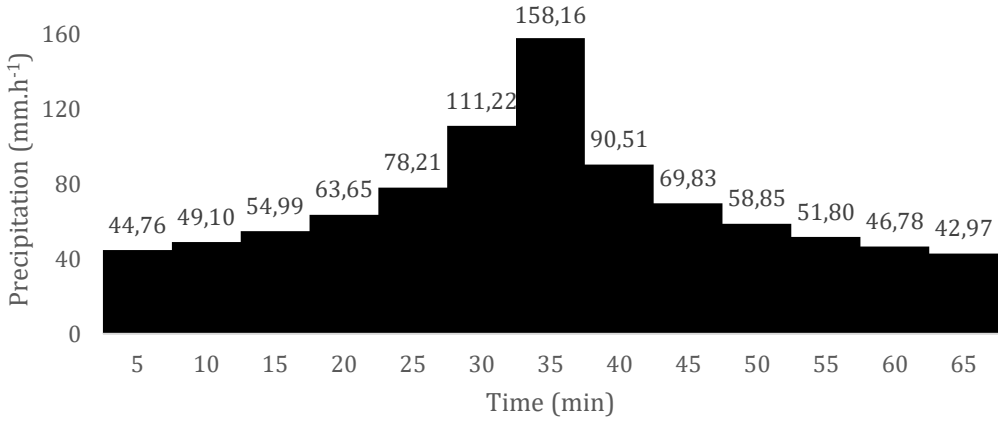


Figure 32. Hyetograph inputted in SWMM to simulate a rain event of a 100-year return period.

Bearing in mind that step three focuses on ensuring the existence of safe floodways under extreme rain events and without considering the NbS applied in steps one and two, the nodes were classified in SWMM by the flooding flow values from 200 to 2000 $L \cdot s^{-1}$ (Figure 33). That way, a visual understanding of where are the most critical points of the drainage network is enabled. By that, the subcatchments that drain rainwater to the manholes under the worst flooding regime were selected to receive large bio-retention cells that focus on infiltrating and storing water to decrease runoff, in this case simulating the rain gardens. Also, the selected subcatchments were all areas without any type of construction since the cells need direct contact with rainwater to infiltrate and perform properly.

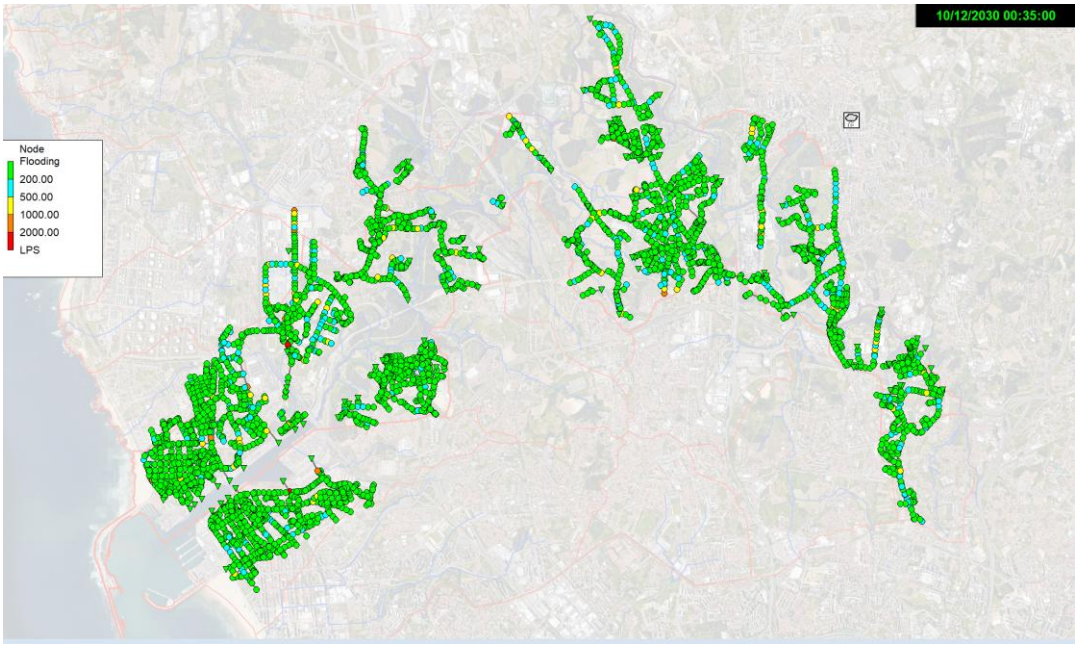


Figure 33. All nodes of the network with a color scale indicating extreme flooding.

Node flooding was mitigated as seen in Figure 34, and Hassan *et al* [60] had similar results, indicating that low mitigation – or even an increase in node flooding – is expected to

future worse case scenarios. This indicates that current technology might not be sufficient to extreme climate change future scenarios. On the other hand, Pace *et al* [61] found out that green infrastructure solutions should be strategically designed to reduce harmful extreme weather events, indicating that new investments and changes in the urban context can be positive to achieve reduced damage of rain events and increase urban resilience.

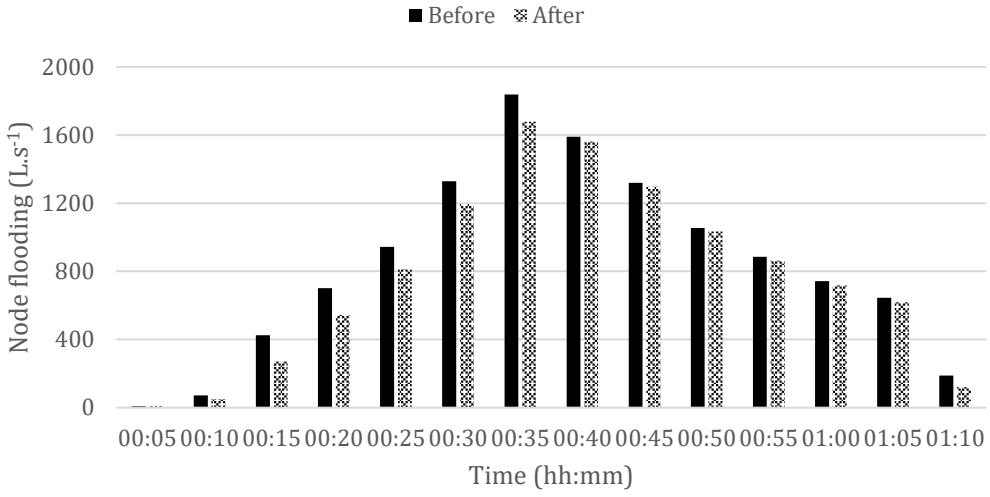


Figure 34. Node flooding before and after inserting bio-retention cells in the simulation for step three.

Besides node flooding, subcatchment peak runoff was also mitigated with the implementation of bio-retention cells. By reducing this parameter, less water is flowing through the catchment areas and, therefore, damage risk is also reduced. Figure 35 presents the peak runoff reduction across all subcatchments were introduced. In some cases, the reduction was close to 100%, which indicates that the implementation of bio-retention cells was an effective method of relieving stress of the drainage network.

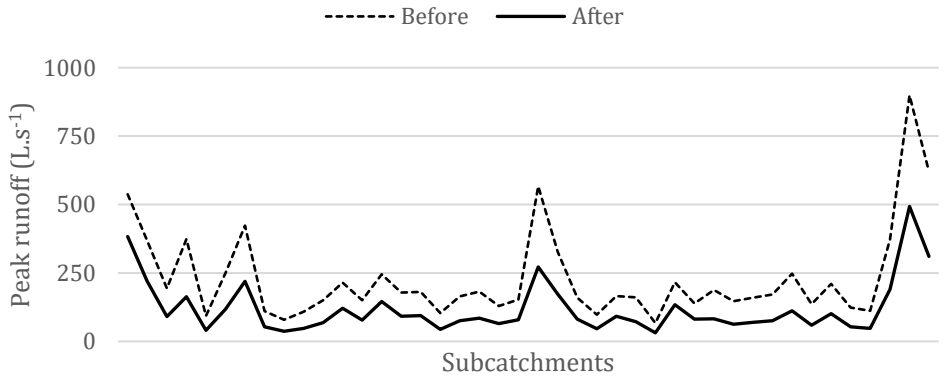


Figure 35. Peak runoff reduction across all subcatchments where NbS were implemented.

Skrede *et al* [62] found out that flood velocity, flood depth, transportation capacity, total flooding extent, flood duration, and activation frequency are the most important hydraulic performance criteria to evaluate the occurrence of floodways inside the urban

context. However, to apply these criteria to the network of this study, further investigation is needed and complementary software analysis helps a better understanding of how the current network would react and to design the floodways.

5.4 Connecting the 3 steps

The three steps presented above aim to mitigate the impacts of rainwater in the urban context, based on three intensity ranges (RP of 2, 50 and 100 years), through the implementation of NbS. Each step lies on a complementary approach to improve the drainage system performance, increasing soil infiltration and reducing total volumes of superficial runoff and flooding.

In step one the focus is to increase water infiltration in the soil in urban areas with the objective of increase infiltration and reduce runoff under rain events of a 2-year return period. By simply changing excerpts of pavements from impermeable to permeable showed significant positive impacts at infiltration, from 0.61 mm to 1.05 mm, as well as mitigating 37 flooding nodes of the system.

In step 2, under a heavier rainfall scenario (RP=50y), retention basins were introduced in some areas to temporarily store large volumes of water and release them slowly after the rain stops. That strategy is complementary to the first step since it acts on subcatchments with available ground to green infrastructures and reduced the peak runoff by 631 $L \cdot s^{-1}$ maximum, while improving the overall drainage system performance.

Finally, step three focuses on extreme rain events of 100-year return periods and the implementation of bio-retention cells that act as very large spaces that can store, infiltrate and release water gradually. These cells were placed in green areas since that way no building would be destroyed and/or families replaced. This step contributed to the understanding of where the floodways are placed and how less water could be expected after applying the bio-retention cells.

Although the three steps were studied individually, there is a thread that connected the three of them, which is the application of NbS adapted to the intensity of the rain event and to the local urban morphology to decrease damage from those events. Aditionally, the three steps together represent an integrated strategy of urban water management with focus on green infrastructure, urban planning, and hydrologic modelling.

6 Conclusions

6.1 General conclusions

Increasing extreme rain events and impermeable surfaces are challenges that the world might face soon. That is why proposing a methodology to ease urban water management and the decision-making process across stakeholders was importantly achieved through the adaptation of the S3SA to Portugal's reality and considering a climate changing scenario. Some more flood-susceptible countries such as Norway, Denmark, and the Netherlands, are already a step further in flood management. This work developed and provided tools to urban water management that can help Portugal's decision makers to also become prepared and well-structured to face those extreme events.

Computational modelling is very important to this type of studies, in which future scenarios are drawn and based on that information, action is undertaken at the most critical points to minimize potential damage. Stakeholders must rely on scientific and reliable data to focus on solutions that provide the best outcome with the least use of resources. SWMM is a versatile and strong software that should be widely used to analyze pluvial networks, how they respond to rainfall events of different return periods and where, geographically, are the most critical points of a city.

Under step one, the 72% increase in soil permeability is surely a great indicator that applying NbS in cities is a promising and cheap solution that should be priority to construction companies and politicians. Even though it is a recent and not so known topic, it could be more widespread across the different stakeholders, so they become able to implement easy and still helpful solutions.

Step two has proven to be the most impactful since it promoted the highest reductions in peak runoff (631 $L \cdot s^{-1}$). This exemplifies where efforts should be concentrated, merging the building of retention basins with the precise sizing and at the right areas – the most critical ones after running the simulations – is the best path to a complete formation of a resilient city. Yet, these structures might also serve as an opportunity to rainwater harvesting, but there is still margin for improvement in this area since there are not many studies indicating optimization procedures to that subject.

Since step three is the most critical one, current technology is still underdeveloped to handle such amounts of water in a rainfall event. Besides that, simulation results were positive by reducing flooding flow at all nodes and considering that the bio-retention cells are one of the cheapest, easiest to install and most natural structures, they should be more explored and implemented across cities.

6.2 Further investigation

Finally, further investigation is strictly needed in step three, where the mapping of safe floodways depends on deeper and more complex analysis, which consequently depends on more robust software and processing speed. That type of development also needs a combination of more than one software, making the understanding of the whole problem way more complex. Further studies should focus in reducing model complexity, processing time for hardware and the dependence of the combination of several software in order to achieve reliable results.

Another relevant aspect to consider for further investigation is evaluate specific critical areas that have been identified in this study, for example. Investigate in a more detailed way what are the relevant points and how to optimize those areas in terms of network infrastructure response to rain events. Also, comparing the efficiency of the application of different NbS is a way of finding the optimal solutions to a specific critical area.

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