TÉCNICO LISBOA

Smart water management (SWM): flood control and water uses

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Thesis for obtaining the Master of Science Degree in

Civil Engineering

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Abstract

The main objective of this work is to analyse a study area, in Seixal, regarding flood risk and flood mitigation techniques. This analysis was performed by computational modelling using DHI software, MIKE SHE. Several scenarios were compared regarding flood risk and SUDS efficiency. To obtain a more accurate analysis was also determined the economic viability of each technique. The flood mitigation capacity of each type of SUDS technique was considered, as well as the community acceptance to their construction and maintenance. Considering factors such as vulnerability to flood and quantity of flooded area, the objective was to define the most efficient system to solve flood situations in Seixal bay. The economic viability of the different scenarios was stablished in two ways: the first one through life cost analysis and the second one taking into account the damages caused by a certain type of flood.

Finally, it was concluded that the best scenario is the one who will minimize the effects of great urbanization and consequently the increase of flood risk, which combines two different measures: permeable pavement and detention basin. This alternative allows to fully explore the mitigation capacity of each technique. The installation of this system proved to be viable, demonstrating a very important improvement in the flood mitigation system in Seixal.

Keywords: Urban flood, flood, modelling, sustainable urban drainage systems, economic viability.

Resumo

O principal objetivo deste trabalho é analisar uma área de estudo, localizada no Seixal, relativamente ao risco de cheia e formas de mitigação de cheia. Esta análise foi realizada por modelação computacional com recurso ao *software* da DHI, MIKE SHE. Vários cenários foram comparados quanto ao risco de inundação e eficiência na aplicação de sistemas de drenagem urbana sustentável, bem como uma avaliação da viabilidade económica de cada sistema de drenagem aplicado em cada cenário. A influência de cada tipo de sistema de drenagem na mitigação da cheia foi determinada, assim como a análise de sensibilidade da comunidade relativamente à sua aplicação e manutenção nos locais determinados. Tendo em conta fatores como a vulnerabilidade da zona de estudo e a quantidade de zona inundada, o objetivo foi determinar qual o sistema mais eficiente para solucionar situações de cheia. O estudo de viabilidade económica dos diferentes cenários foi abordado de duas formas distintas, a primeira através da análise de custo de ciclo de vida, e a segunda tendo em conta os danos causados por uma cheia tipo.

Por fim, verificou-se que para a área de estudo o cenário que melhor minimizará os efeitos decorrentes da grande urbanização e consequente aumento do risco de cheia, passa pela conjugação de diferentes medidas, nomeadamente aplicação de pavimento permeável e construção de uma bacia de detenção, permitindo assim tirar o máximo partido das medidas mitigadoras. A instalação deste sistema provou ser viável, o que significa um melhoramento futuro muito importante no sistema de mitigação de cheia no Seixal.

Palavras-chave: Inundações urbanas, cheias, modelação, sistemas de drenagem urbana sustentável, viabilidade económica.

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Abbreviations

APA	Agência Portuguesa do Ambiente
DHI	Danish hydrological institute
EEA	Europe Environmental Agency
EU	European Union
PoMs	Programmes of Measures
RBDs	River Basin Directives
RBMPs	River Basin Management Plans
SUDS	Sustainable Urban Drainage System
UWM	Urban Water Management
WFD	Water Framework Directive

1. Introduction

1.1. Framework and motivation

Urban drainage systems are in transition from functioning simply as a transport system to becoming an important element of urban flood protection measures (DHI, 2015).

Rapid urbanization combined with the implications of climate change is one of the major challenges facing society nowadays and in the years to come. The increased concerns with water security and ageing of existing drainage infrastructure, have created a valuable opportunity to address these water challenges within cities and to improve urban water management.

Urban water management must ensure access to water and sanitation infrastructure and services, manage rain, waste and storm water as well as runoff pollution, mitigate against floods, droughts and water borne diseases, whilst prevent the resource from degradation. Urban water management takes into consideration the water cycle, facilitates the integration of water factors early in the land planning process and encourages all levels of government and industry to adopt water management and urban planning practices that benefit the community, the economy and the environment.

Floods are the most common type of natural disaster in Europe (EEA, 2015). Flooding often occurs as a result of high rainfall intensity in the catchment area, insufficient storm drainage capacity, river overflows, storm surge or as a combination of these phenomena. The risks of flooding are amplified by the expected effects of climate change and by the increase of impervious areas. The use of sustainable urban drainage systems (SUDS) can reduce urban surface water flooding as well as the pollution impact of urban discharges on receiving waters.

SUDS are more sustainable than conventional drainage techniques, offering benefits such as attenuation of runoff prior to concentration, improvement of water quality, maintenance of groundwater recharge rates through infiltration, minimization of flood impacts on the environment.

In the next few years, it is expected that cities will face resource distribution challenges associated with an increase in population flow, energy issues due to the reduction of fossil fuel resources, escalation maintenance and management costs due to aging infrastructure and improper land resource utilization. Innovative and new sustainable systems are essential to minimize the impact of these challenges.

1.2. Objectives

The main objectives of this work are to give an overview of urban water issues and smart water management as well as the information about possible implementation of sustainable urban drainage systems towards a more sustainable water management.

To achieve the proposed goals is performed an analysis of a case study assisted by a model simulation software (MIKE SHE, by DHI) that allows to represent the benefits of these innovative and sustainable systems. The current research work aims to demonstrate the susceptibility to flood of an area in the old city center of Seixal, ways to prevent these extreme events in the area using sustainable urban drainage systems and a cost/benefit analysis of its implementation.

1.3. Structure of the dissertation

The present dissertation is divided into seven chapters. The first chapter corresponds to the introduction, where a scope to address the subject is made and the main objectives are presented. In chapter 2 an overview of the Water Framework Directive and its implementation in Portugal is presented. Also in this chapter is presented some information about floods and its influence in Europe as well as particularities about sustainable urban drainage systems and criteria for selecting the technique for each type of situation. The simulation model and theoretical fundaments of MIKE SHE are presented in Chapter 3. The case study description and methodology are presented in Chapter 4, describing the study area and the Tagus estuary characteristics. Chapter 5 presents the model testing and validation, specifying all the used input data as well as the scenario simulations obtained for each technique and also the assessment of the best scenario. Chapter 6 presents an economic analysis concerning the viability of SUDS implementation in the case study in two different views: life cost analysis and damage analysis. The last chapter (chapter 7) presents the general conclusions of this thesis and some recommendations for future works.

2. State-of-the-art

2.1. Water Framework Directive and its implementation in Portugal

The Water Framework Directive (WFD) adopted in 2000 established an integrated approach for European Union (EU) members action in the field of water policy. It is centered on the concept of river basin management with the objective of achieving good status of all EU waters by 2015.

The main tools to implement the Directive are the River Basin Management Plans (RBMPs) and the Programmes of Measures (PoMs), which are updated every six years. The River Basin Management Plans and Programmes of Measures, adopted in 2009, are being updated and their final adoption will be by the end of 2015. Examples of measures are: to reduce point source or diffuse pollution, rehabilitation of hydromorphological conditions, protect water bodies, improve aquifer recharge, measures addressing efficient water use, control on water abstraction and discharges. Measures are presented by type (basic, supplementary, complementary and additional); by operational programme (national programmes and plans); by theme (water quantity, monitoring and research); and by responsible entity (Directive 2000/60/EC).

The EU Commission's assessment shows that many Member States have planned their measures based on 'what is in place and/or in the pipeline already' and 'what is feasible'. Instead of designing the most appropriate and cost-effective measures to ensure that their water achieves 'good status', many Member States have often only estimated how far current measures will contribute to the achievement of the WFD's environmental objectives. This leads to a non-clear evaluation of whether measures are taken to progress required by the Directive 2000/60/EC.

Excessive abstraction significantly affects 10 % of surface water bodies and 20 % of groundwater bodies. Where there is already over-abstraction in river basins subject to intense water use, the WFD requires Member States to put in place measures that restore the long-term sustainability of abstraction such as revision of permits or better enforcement. The first RBMPs also showed that most Member States have not addressed the water needs of nature. They often considered only the minimum flows to be maintained in summer periods, without taking into account the different factors that are critical for ecosystems to thrive and to deliver their full benefits. This means that the measures implemented do not guarantee the achievement of 'good status' in many water bodies affected by significant abstractions or flow regulation (e.g. for irrigation, hydropower, drinking water supply, navigation). Changes to the flow and physical shape of water bodies are among the main factors preventing the achievement of good water status but, in general, the first PoMs propose insufficient actions to counter this. The changes are most often due to the development of grey infrastructure, such as land drainage channels, dams for irrigation or hydropower, impoundments to facilitate navigation, embankments or dykes for flood protection (Directive 2000/60/EC).

The Floods Directive of 2007 aims to reduce and manage the risks that floods pose to human health, the environment, cultural heritage and economic activity. By 2015 flood risk management plans must be drawn up for areas identified to be at risk. Unlike the WFD, the Floods Directive does not have a precise calendar of public consultation, but many Member States will consult on the WFD and Flood Plans at the same time, during the first semester of 2015. Natural water retention measures are an example of measures that can contribute simultaneously to the achievement of objectives under the WFD and the FD by strengthening and preserving the natural retention and storage capacity of aquifers, soils and ecosystems. Measures such as the reconnection of the floodplain to the river, re-meandering, and the restoration of wetlands can reduce or delay the arrival of flood peaks downstream while improving water quality and availability, preserving habitats and increasing resilience to climate change. Fluvial is the most common reported source of flooding in the EU, followed by pluvial and sea water. The most commonly reported consequences are economic, followed by those for human health. Only one third of Member States explicitly considered long-term developments in their assessment of flood risk, although the flood losses in Europe have increased substantially in recent decades, primarily due to socio-economic factors such as increasing wealth located in flood-prone areas, and due to a changing climate. It was estimated that by 2007, at least 11 % of Europe's population and 17 % of its territory had been affected by water scarcity, putting the cost of droughts in Europe over the past thirty years at EUR 100 billion. The EU Commission expects further deterioration of the water situation in Europe if temperatures keep rising as a result of climate change. The Programmes of Measures also confirm that incentives to use water efficiently and transparent water pricing are not applied across all Member States and all water-using sectors, partly due to the lack of metering. In order to implement incentive pricing, consumptive uses should by default be subject to volumetric charges based on real use. This requires widespread metering, in particular for agriculture in basins where irrigation is the main water user. Measures to ensure the recovery of environmental and resource costs are limited and needed. There is an absence of cost recovery, including for environmental, resource and infrastructure costs, which will affect those areas facing water scarcity and failing water infrastructure. In this context, the EU Commission is carrying out an assessment of Member States' water pricing and cost recovery policies and requires action plans where deficiencies are detected (Directive 2007/60/EC).

There are three different administrative jurisdictions governing the Water Framework Directive implementation in Portugal: mainland Portugal (PTRH1 to PTRH8) governed by the Portuguese Environmental Agency (APA), the Azores (PTRH9) and Madeira (PTRH10) governed by the respective autonomous region environment authority. According to the RBDMPs, in terms of surface waters, some water bodies are subject to significant pressures from diffuse source pollution. All RBDs except Madeira have some water bodies subjected to water flow regulations and morphological alterations. Most of the jurisdictions have some water bodies subjected to significant pressures from water abstraction. Saltwater intrusion pressure is reported to be significant in Azores. In terms of status of surface water, 57% of natural water bodies and 28% of heavily modified/artificial water bodies were reported to be in good or better ecological status/potential, and 24% of natural surface water bodies and 30% of heavily modified/artificial water bodies were at good chemical status. It is expected that by 2015, about 60% of all water bodies will be in good or better status/potential. In terms of groundwater in 2009, 82% of the groundwater bodies were reported to be at good chemical status and 98 % at good quantitative status. Nitrate was considered to be the most challenging factor. The significant pressure is therefore agriculture and livestock. In 2015 it is expected that 85% of groundwater will achieve good chemical status while the quantitative status is maintained at their very high 2009 level. Overall RBDs reported by Portugal, 80% of basic measures were on-going and 20% not started. No measures had been completed. In particular the Northern Regional Department have not started the implementation of several types of measures. For some types of measures - e.g. Prohibition of direct discharge of pollutants into groundwater - the RBD have changed their views regarding applicability of the measures. Figure 2.1 shows the reported progress of basic measures in Portugal so far (Report on the progress in implementation of the WFD PoMs).

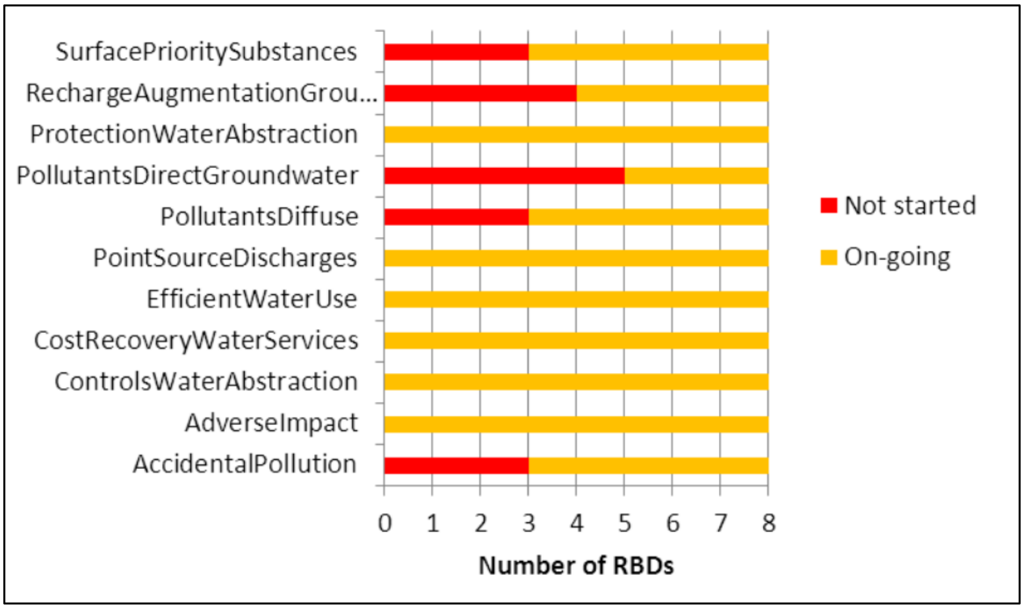

Figure 2.1 - Reported progress with implementation of basic measures (WISE PoMs Aggregation Report 2-2 - Implementation of Other Basic Measures in 2012)

Further consultation with the water authority indicates that about 58% of the measures being implemented in Portugal use EU Structural Funds, while 5% uses Rural Development Fund and 1% uses Cohesion funds. About 39% of the measures are not using EU funds. (Report on the progress in implementation of the WFD PoMs)

Supplementary Measures are those measures designed and implemented in addition to the Basic Measures where they are necessary to achieve the environmental objectives of the WFD. Supplementary Measures can include additional legislative powers, fiscal measures, research or educational campaigns that go beyond the Basic Measures and are deemed necessary for the achievement of objectives. (Report on the progress in implementation of the WFD PoMs) Figure 2.2 and Figure 2.3, shows the progress of implementation of supplementary measures in Portugal, in surface waters and ground water, respectively. Number in brackets is the number of supplementary measures tackling the pressure. Note a measure may tackle more than one pressure.

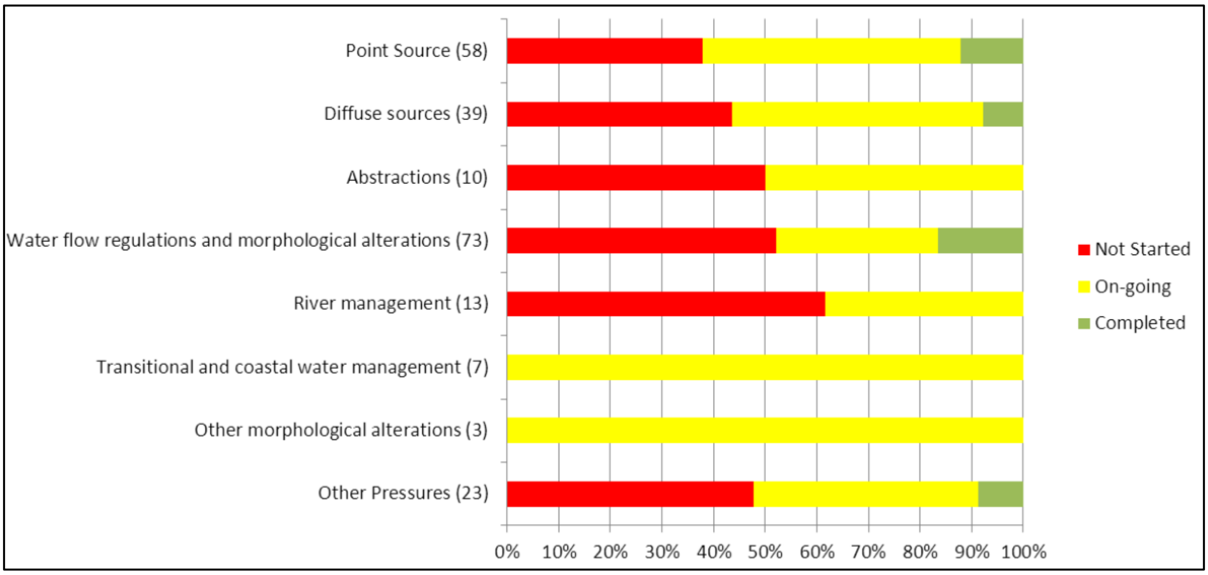

Figure 2.2 - State of implementation of supplementary measures in relation to significant pressures of surface waters in 2012 in Portugal (WISE PoMs Reports, 2015)

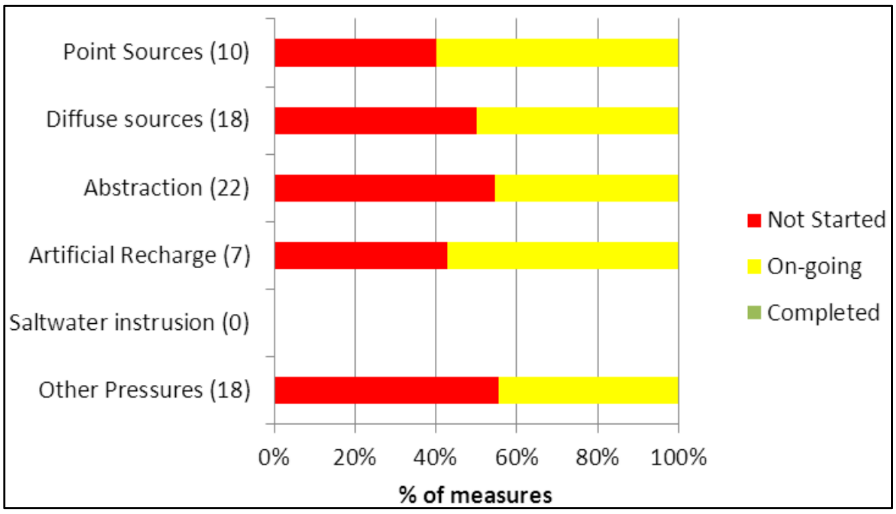

Figure 2.3 - State of implementation of supplementary measures in relation to significant pressures on ground waters in 2012 in Portugal (WISE PoMs Reports, 2015)

For mainland Portugal (Azores and Madeira did not report), 65% of measures were not started, 26% were on-going and 9% completed (WISE PoMs Reports).

2.2. Floods, water scarcity and drought events in Europe

More than three quarters of European citizens live in urban areas and rely on clean water in cities. Approximately one fifth of the total freshwater abstracted in Europe supplies public water systems – water that is directed to households, small businesses, hotels, offices, hospitals, schools and some industries (EEA).

According to EEA (2012) report on urban adaptation to climate change, approximately one fifth of European cities with over 100 000 inhabitants is very vulnerable to river floods. Impermeable surfaces ('soil sealing') can prevent water from draining, leading to increased risk of flooding. However, it is important to be aware that impermeable surfaces are only one factor contributing to increased risk of urban flooding, the increase of temperature and extreme precipitation events could also explain this changes.

The map in Figure 2.4, shows the average soil sealing degree inside of European core cities. Soil sealing degrees are represented in colored dots. The city dots are overlaid onto a modelled map displaying the change in annual number of days with heavy rainfall between the reference periods 1961-1990 and 2071-2100.

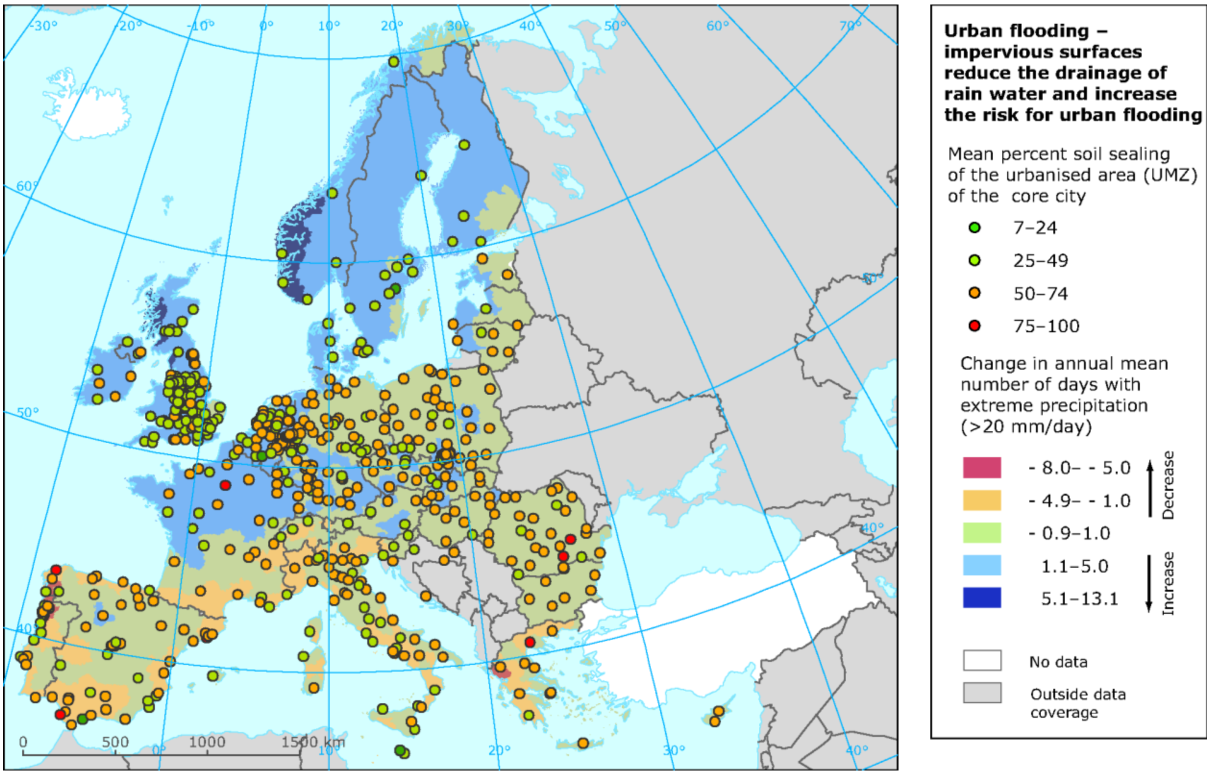

Figure 2.4 - Average soil sealing degree inside of European core cities (European Environment Agency, 2015)

Regions most prone to an increase in drought hazard are southern and south-eastern Europe, but minimum river flows will also decrease significantly in many other parts of the continent, especially in summer, Figure 2.5.

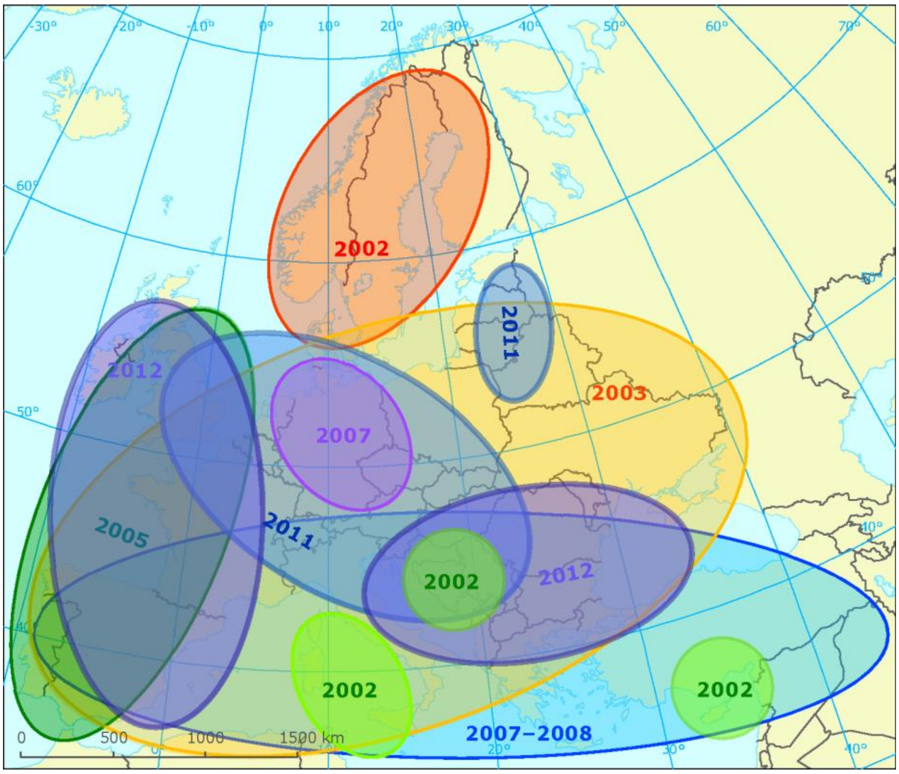

Figure 2.5 - Water scarcity and drought events in Europe during the last decade (European Environment Agency, 2015)

Table 2.1 - Main causes/impacts due to rapid urbanization, adapted from Santos,R. (2011)

Causes	Effects/Impacts
Removal of native vegetation	Increases the amount of surface runoff and the maximum flows Increases flow speed Increases the soil vulnerability against erosion Deposition of sediments leading to obstruction of the pipes and streams
Establishment of the artificial drainage network	Increases flow speed and flood peaks Inadequate drainage systems, i.e., small diameter pipes, increases the risk of flood
Construction in high risk areas (shorelines, watercourses…)	Exposure to periodic floods in natural flooded areas

To prevent urban water crises, it is necessary to manage water resources effectively at every stage: from the supply of clean water to its different uses by the consumers. This could involve reducing consumption as well as finding new ways of collecting and using water. Water management should also be better integrated within wider urban management while taking into account characteristics of the local environment, as shown in Figure 2.6.

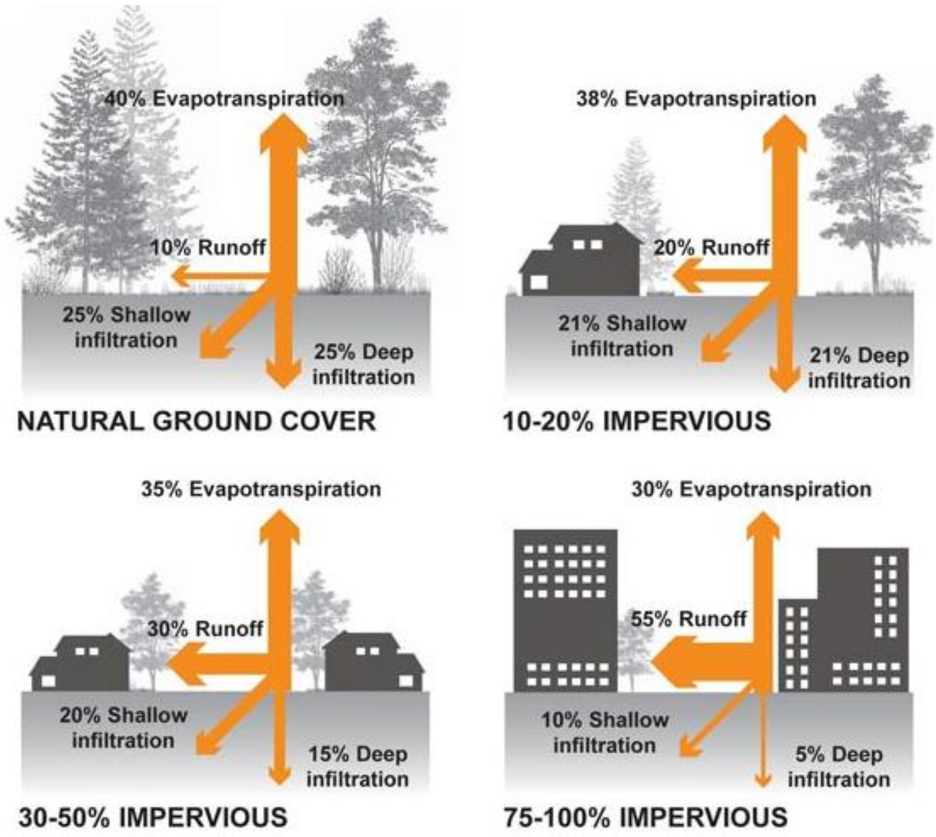

Figure 2.6 - Effects of imperviousness on runoff and infiltration, adapted from US EPA (2015)

2.3. Flood types

A **river flood** typically occur in large basins and is the result of natural processes, in which the river takes its larger bed. Usually caused by long periods of rain.

Storm surge is an abnormal rise in water level in coastal areas, over and above the regular astronomical tide, caused by forces generated from a severe storm's wind, waves, and low atmospheric pressure. Extreme flooding can occur in coastal areas particularly when storm surge coincides with normal high tide.

Storm tide is a rise in local sea level caused by the combination of regular tides and a storm surge.

Inland flooding occurs when moderate precipitation accumulates over several days, intense precipitation falls over a short period, or a river overflows because of an ice or debris jam or dam failure.

A **flash flood** is caused by heavy or excessive rainfall in a short period of time, generally less than six hours. They can occur within minutes or a few hours of excessive rainfall. This type of phenomenon in urban areas is growing, which combined with surfaces unable to absorb large amounts of water in such short period of time, increases the flow velocity and the destructive potential.

2.4. Sustainable urban drainage systems (SUDS)

Drainage systems need to adapt to and manage extreme events including flooding and periods of drought, while helping to reduce carbon emissions. Storage of runoff within a SUDS system is essential for providing the extended detention of flows for water quality treatment, as well as for peak flow attenuation of larger flows for flood protection downstream of the site. Runoff storage can be provided within an on-site system through the use of structural controls and/or nonstructural features and landscaped areas.

Attenuation storage is used to store runoff to enable a reduction in the peak discharge from the site.

Retention storage facilities are designed to contain a permanent pool of water (in stormwater ponds and wetlands) which are used to provide water quality treatment.

The differences between a conventional drainage system and a sustainable drainage system is shown in Figure 2.7.

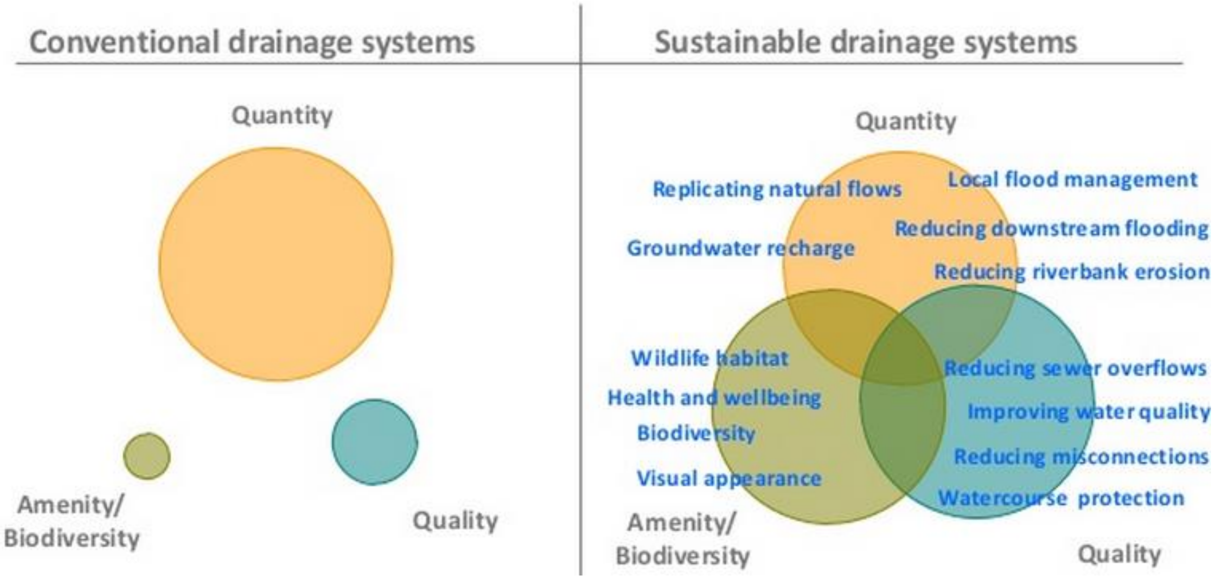

Figure 2.7 - Differences between a conventional drainage system and a sustainable drainage system

2.4.1. SUDS selection criteria

It is important to determine which SUDS techniques are best suited to the proposed land use of the area draining to the system. CIRIA C697 presents the following criteria:

1. Land use characteristics.
2. Site characteristics.
3. Catchment characteristics.
4. Quantity and quality performance requirements.
5. Amenity and environmental requirements.

Figure 2.8 illustrates a possible implementation of SUDS in both housing measures through local source controls to larger downstream site and regional controls.

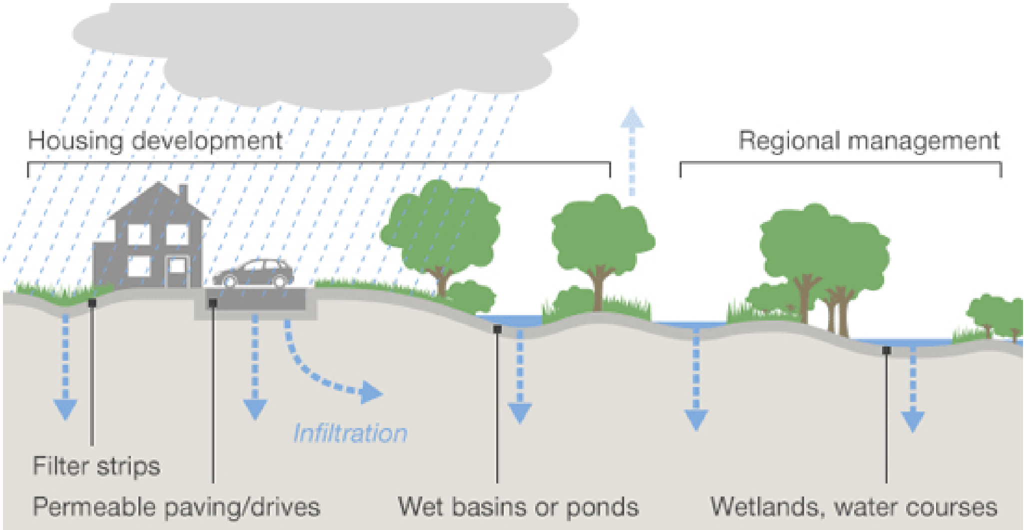

Figure 2.8 - Application of SUDS (Susdrain/CIRIA, 2015)

Hereafter, it is presented brief descriptions of a range of SUDS, divided in the following classifications: Source control, Swales & conveyance channels, Filtration, Infiltration, Retention & detention and Wetlands and Inlets/outlets/control structures.

- **Source control** (pervious surfaces and green roofs)

Pervious surfaces - Pervious surfaces are structures that allow rainwater to infiltrate through the surface into an underlying storage layer, where water is temporarily stored before infiltration to the ground, reuse, or release to a watercourse or other drainage system. There are three types of systems: system with total infiltration where all the rainfall passes through the sub-structure (where it may be stored temporarily) into the soils beneath. Normally, there will be no discharge from the system. However an emergency overflow may be required to cater for events in excess of the design event, or to allow for the system becoming less efficient e.g. as a result of siltation. System with partial infiltration, a series of perforated pipes at formation level that will convey the proportion of the rainfall that exceeds the infiltration capacity of the sub-soils, to the receiving drainage system. By preventing the build-up of water above the sub-grade, the risks to soil stability are reduced. System without infiltration which is generally wrapped in an impermeable, flexible membrane placed above the sub-grade (formation level). Once the water has filtered through the sub-base, it is conveyed to the outfall via perforated pipes or fin drains. A sketch and a picture of this type of technique is shown in Figures 2.9 and 2.10.

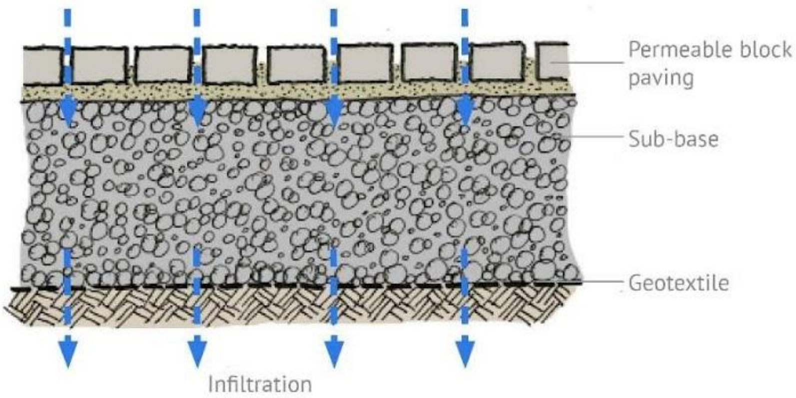

Figure 2.9 - Permeable pavement sketch (Susdrain, 2015)

Figure 2.10 – Permeable pavement (Susdrain, 2015)

Table 2.2 – Pervious surfaces: advantages/disadvantages

Advantages	**Disadvantages**
Reduced peak flows to watercourses reducing the risk of flooding downstream Can be used in high density developments with a range of surface finishes that accept surface waters over their area of use Reduced need for deep excavations for drainage, which can have significant cost benefits Flexible and tailored solution that can suit the proposed usage and design life Lined systems can be used where infiltration is not desirable, or where soil integrity would be compromised No additional land take Removes need for manholes Eliminates surface ponding and surface ice Often very resilient to a lack of maintenance	Cannot be used where large sediment loads may be washed/carried onto the surface Risk of long-term clogging and weed growth if poorly maintained

Green roofs - Green roofs are systems which cover a building's roof with vegetation. They are laid over a drainage layer, with other layers providing protection, waterproofing and insulation. They are designed to intercept and retain precipitation, reducing the volume of runoff and attenuating peak flows. There are three main types of green roofs: extensive green roofs (these covers the entire roof area with low growing, low maintenance plants, they are lightweight and cost effective), intensive green roofs (these are landscaped environments which include plants or trees and are usually accessible, they impose much greater loads on the roof structure and require significant ongoing maintenance), simple intensive green roofs (requiring regular maintenance, however, demands on building structures are moderate). A sketch and a picture of this type of technique is shown in Figures 2.11 and 2.12.

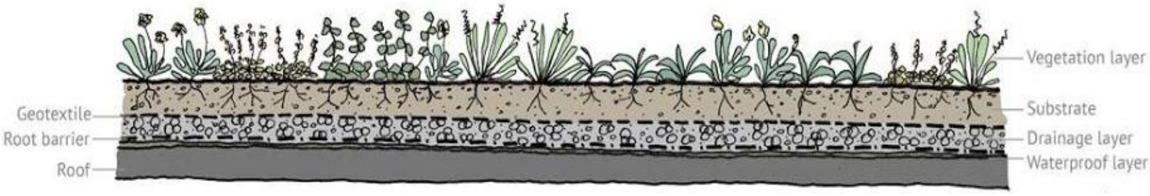

Figure 2.11 - Green roof sketch (www.susdrain.org, 2015)

Figure 2.12 - Green roof in ETAR de Alcântara, Portugal

Table 2.3- Green roofs: advantages/disadvantages

Advantages	**Disadvantages**
Reduced amount of water that runs off a roof and into municipal storm water and sewage treatment systems. Reduced ambient temperature on the roof of a building and contributes to overall cooling of the local climate. Help to filter contaminants from the air. Reduces the heat and creates a roof that is insulated quite well in both the summer and winter. The amount depends on the thickness of the growing media and its' water saturation.	Increased installation costs – often double that of a more conventional roof Increased maintenance costs – potential water, weeding required Increased structural requirements – can vary greatly by type of green roof Difficult to service roof if needed – extensive roof are more easily serviced

Finally, it is important to emphasize that the primary objective of green roofs is not to prevent urban flooding, but is a complementary solution when combined with other prevention systems.

- **Swales & conveyance channels** (Swales and channels)

Swales - Swales are broad, shallow channels covered by grass or other suitable vegetation. They should promote low flow velocities to allow much of the suspended particulate load in the stormwater runoff to settle out, providing effective pollutant removal. Roadside swales can replace conventional gullies and drainage pipes. There are three kinds of swales, each with different surface water management capability: Standard conveyance swale (broad, shallow vegetated channels, particularly effective way of directing and conveying runoff from the drained area); dry swale (vegetated conveyance channel, designed to include a filter bed of prepared soil that overlays an underdrain system. This provides additional treatment and conveyance capacity beneath the base of the swale);

wet swale (This system is equivalent to the conveyance swale, but designed to encourage wet and marshy conditions in the base to enhance treatment processes). A sketch and pictures of this type of technique is shown in Figures 2.13, 2.14 and 2.15.

Figure 2.13 - Dry swale (www.owsc.org, 2015)

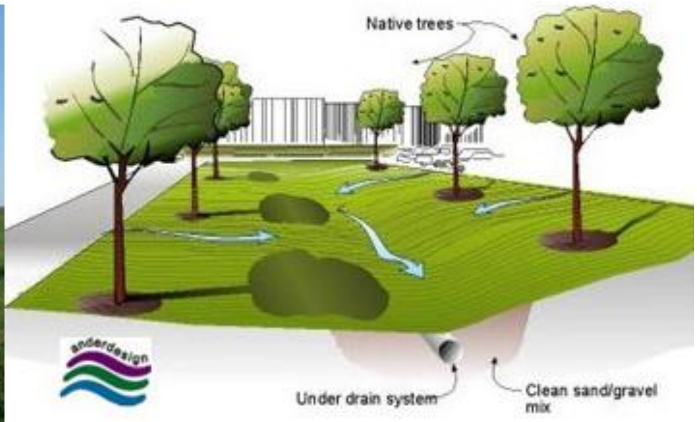

Figure 2.14 - Swale diagram (www.sudswales.com, 2015)

Figure 2.15 - Wet swale (redac.eng.usm.my, 2015)

Table 2.4 - Swales: advantages and disadvantages (Susdrain, 2015)

Advantages	**Disadvantages**
Easy to incorporate into landscaping Good removal of urban pollutants Reduces runoff rates and volumes Low capital cost Maintenance can be incorporated into general landscape management Pollution and blockages are visible and easily dealt with.	Not suitable for steep areas or areas with roadside parking Limits opportunities to use trees for landscaping Risks of blockages in connecting pipe work

- **<u>Filtration</u>** (Filter strips and Bioretention areas)

Filter strips - Filter strips are uniformly graded and gently sloping strips of grass or other dense vegetation designed to treat the water quality event from adjacent impermeable areas through vegetative filtering and infiltration (where appropriate). The runoff is designed to flow as a sheet across the filter strip at a sufficiently low velocity that sediment is filtered out, together with associated pollutants. They are often used as a pre-treatment technique before other SUDS techniques (e.g. swales, infiltration and filter trenches) to extend the life of downstream components. Under low to moderate velocities, filter strips effectively reduce particulate pollutant levels by removing sediments, organic materials and trace metals. Sketches of this type of technique is shown in Figures 2.16 and 2.17.

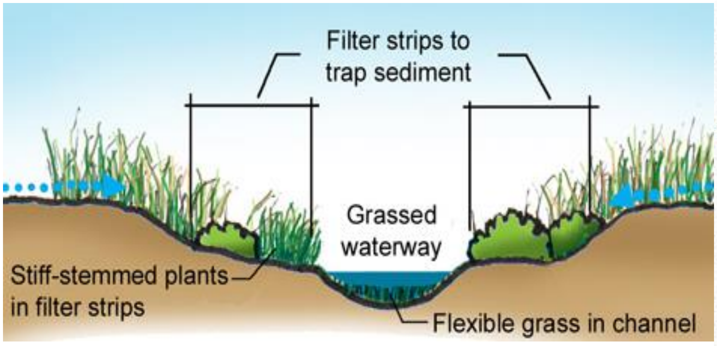

Figure 2.16 - Filter strip diagram (www.sudswales.com, 2015)

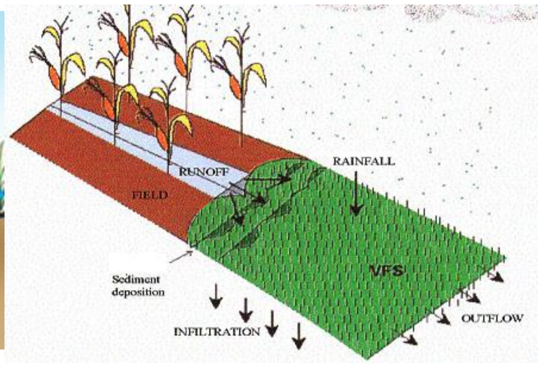

Figure 2.17 - Filter strip (http://nac.unl.edu/, 2015)

Table 2.5 - Filter strips: advantages and disadvantages (Susdrain, 2015)

Advantages	**Disadvantages**
Well suited to implementation adjacent to large impervious areas Encourages evaporation and can promote infiltration Easy to construct and low construction cost Effective pre-treatment option Easily integrated into landscaping and can be designed to provide aesthetic benefits	Not suitable for steep sites Not suitable for draining hotspot runoff or for locations where risk of groundwater contamination, unless infiltration is prevented No significant attenuation or reduction of extreme event flows

Bioretention areas – Bioretention areas are shallow landscaped depressions which are typically under drained and rely on engineered soils, enhanced vegetation and filtration to remove pollution and reduce runoff downstream. They are aimed at managing and treating runoff from frequent rainfall events. A sketch and a picture of this type of technique is shown in Figures 2.18 and 2.19.

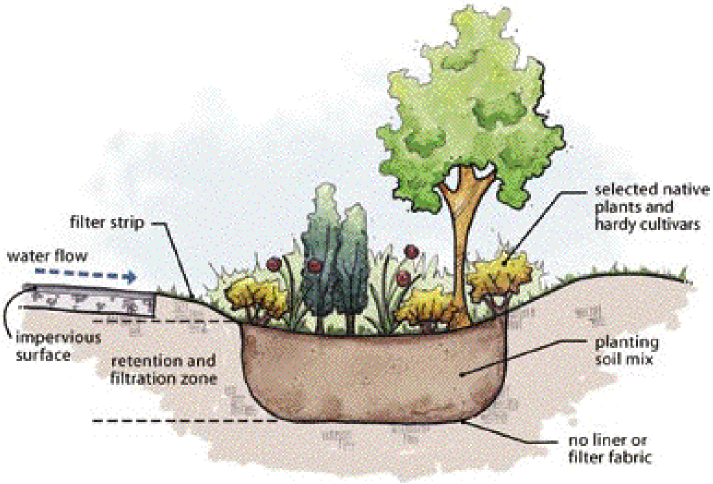

Figure 2.18 - Bioretention area scheme (www.uvm.edu,

Figure 2.19 - Bioretention area (2015)

Table 2.6 – Bioretention areas: advantages and disadvantages (Susdrain, 2015)

Advantages	**Disadvantages**
Can be planned as landscaping features Very effective in removing urban pollutants Can reduce volume and rate of runoff Flexible layout to fit into landscape Well-suited for installation in highly impervious areas, provided the system is well-engineered and adequate space is made available Good retrofit capability	Requires landscaping and management Susceptible to clogging if surrounding landscape is not managed Not suitable for areas with steep slope

- **Infiltration** (Soakaways, Infiltration trenches and Infiltration basins)

Soakaways – Soakaways are square or circular excavations, either filled with rubble or lined with brickwork, pre-cast concrete or polyethylene rings/perforated storage structures surrounded by granular backfill. They can be grouped and linked together to drain large areas including highways. The supporting structure and backfill can be substituted by modular, geocellular units. Soakaways provide stormwater attenuation, stormwater treatment and groundwater recharge. Soakaways are best-suited to the infiltration of stormwater runoff from small areas such as roofs of residential housing. A sketch and a picture of this type of technique is shown in Figures 2.20 and 2.21.

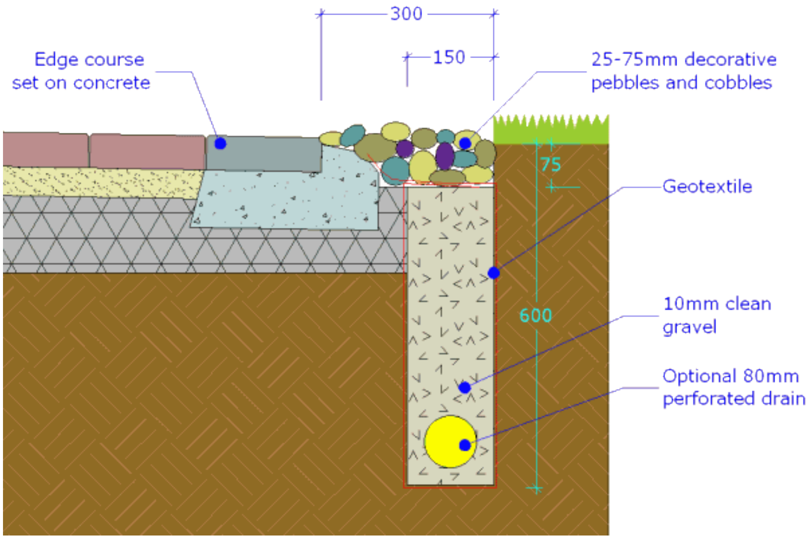

Figure 2.20 - Soakaway scheme (www.sewagesolutions.co.uk, 2015)

Figure 2.21 – Soakaway scheme (www.pavingexpert.com, 2015)

Table 2.7 - Soakaways: advantages and disadvantages (Susdrain, 2015)

Advantages	**Disadvantages**
Minimal net land take Provides groundwater recharge Good volume reduction and peak flow attenuation Good community acceptability Easy to construct and operate Can be retrofitted	Not suitable for poor draining soils Field investigations required to confirm infiltration rates Not suitable for locations where infiltration water may put structural foundations at risk, or where infiltrating water may adversely affect existing drainage patterns Not appropriate for draining polluted runoff Increased risk of groundwater pollution Some uncertainty over long-term performance and possible reduced performance during long wet periods Where the property owner is responsible for operation and maintenance, performance difficult to guarantee.

Infiltration trenches - Infiltration trenches, and filtration trenches/filter drains, are shallow excavations filled with rubble, stone or other void-forming media that creates temporary subsurface storage for either infiltration or filtration for stormwater runoff. Trenches can be used to capture sheet or point flow from a drainage area or can function as an off-line device. Infiltration treats runoff by filtration through the soil, reduces runoff rates and volumes and can help preserve the natural water balance, replenish groundwater and preserve baseflow. Filter trenches are used where underlying soils are impermeable, to drain hotspot runoff, or where groundwater is vulnerable to pollution. Filter trenches provide a quiescent zone for removal of fine silts and also encourage filtration, adsorption and biodegradation processes. Geocellular products can be used as an alternative to stone for infiltration or conveyance systems. They have a higher void ratio but limited treatment capacity, and are often used to provide additional storage zones for higher order events in conjunction with other treatment components. Trenches are not intended to function as sediment traps and must always be designed with an effective pre-treatment system – e.g. grass filter strip for lateral inflow, grass channel, swale, detention basin. They can be used for draining residential and nonresidential runoff and, when lined, can be used to manage stormwater from hotspot/industrial areas. A sketch and a picture of this type of technique is shown in Figure 2.22.

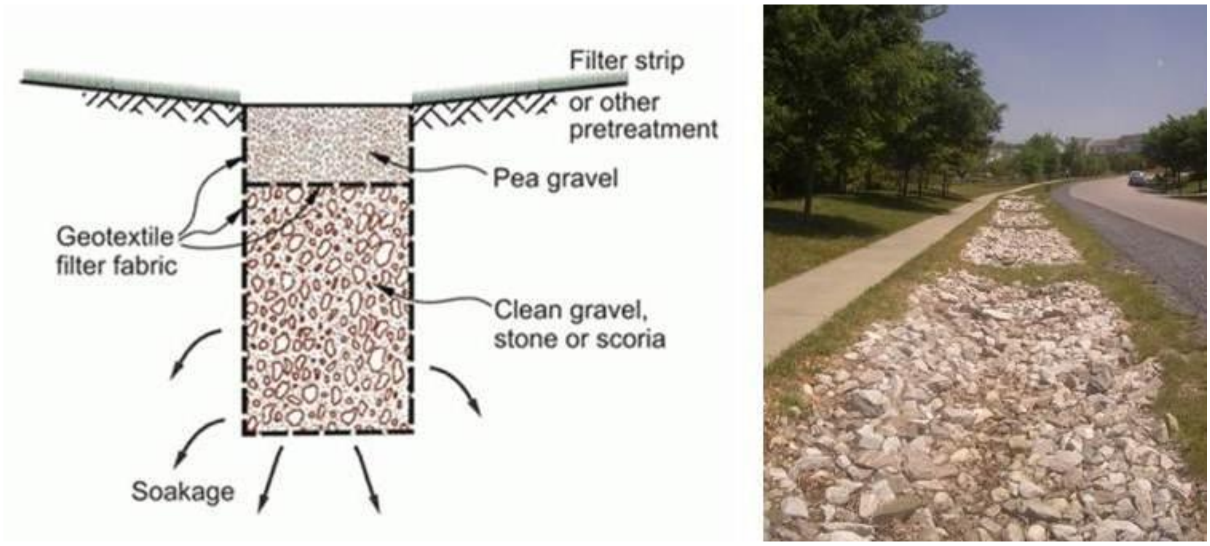

Figure 2.22 - Infiltration trench (www.sswm.info/, 2015)

Table 2.8 – Infiltration trenches: advantages and disadvantages (Susdrain, 2015)

Advantages	Disadvantages
Infiltration can significantly reduce both runoff rates and volumes Infiltration provides a significant reduction in the pollutant load discharged to receiving body Can be incorporated easily into site landscaping and fits well beside roads.	High clogging potential without effective pre-treatment – not for sites with fine particled soils (clay/silts) in upstream catchment Build-up of pollution difficult to see High historic failure rate due to poor maintenance, wrong siting or high debris input Limited to relatively small catchments.

Infiltration basins - Infiltration basins are vegetated depressions in the surface that are designed to store runoff and infiltrate the water gradually into the ground. They may also be landscaped to provide aesthetic and amenity value. They facilitate the recharge of groundwater resources and the replenishment of surface water baseflows, and remove stormwater pollutants via filtration processes occurring within the unsaturated soils beneath the system. In general, infiltration basins should be designed to treat only small storms (i.e. for water quality and groundwater recharge). Infiltration basins tend to be used to drain runoff from a number of properties but should not be used as regional solutions due to the increased risk of sediment loadings and pollution events from large contributing areas. In all cases, effective pre-treatment is required to ensure long-term performance of the basin. A sketch and a picture of this type of technique is shown in Figures 2.23 and 2.24.

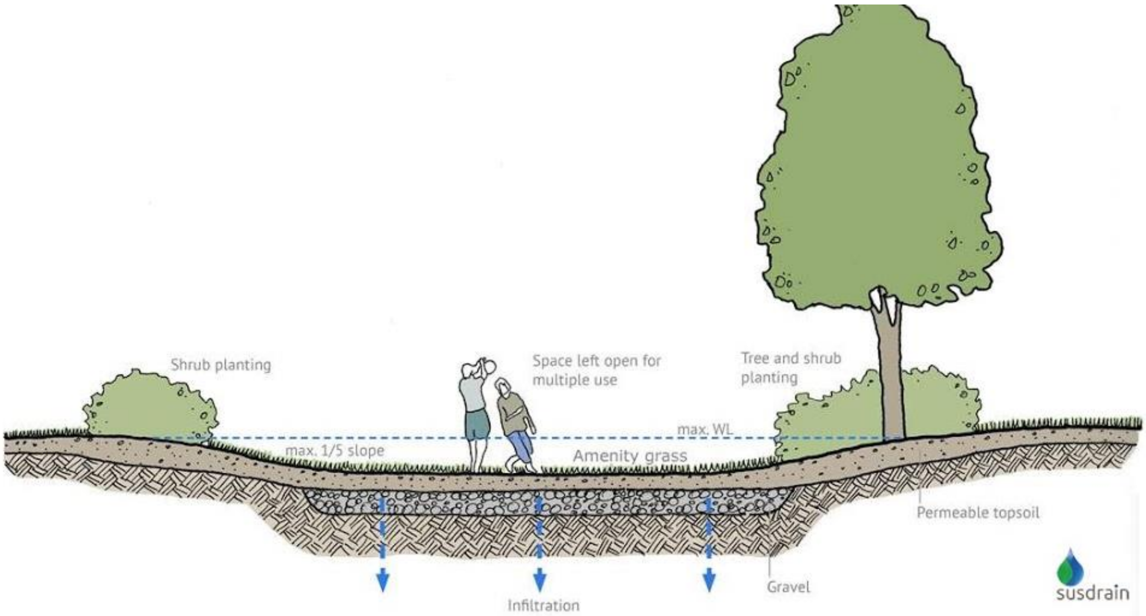

Figure 2.23 - Infiltration basin sketch (www.susdrain.org, 2015)

Figure 2.24 - Infiltration basin (Susdrain, 2015)

Table 2.9 – Infiltration basins: advantages and disadvantages (Source: Susdrain)

Advantages	**Disadvantages**
Reduces the volume of runoff from a drainage area Can be very effective at pollutant removal via filtering through the soils Contributes to groundwater recharge and baseflow augmentation Simple and cost-effective to construct Changes in performance easy to observe.	Potentially high failure rates due to improper siting, poor design and lack of maintenance, especially if appropriate pre-treatment is not incorporated Comprehensive geotechnical investigations required to confirm suitability for infiltration Not appropriate for draining pollution hotspots where high pollution concentrations are possible Requires a large, flat area.

- **<u>Retention and Detention</u>** (Retention ponds and detention basins)

Retention ponds - Ponds are widely used as a cost-effective SUDS technique. Retention ponds are basins that have a permanent pool of water for water quality treatment and other water uses (e.g. hydropower, irrigation). They can be created by using an existing natural depression, by excavating a new depression, or by constructing embankments. They are designed to support emergent and submerged aquatic vegetation along their shoreline. The retention time promotes pollutant removal through sedimentation and the opportunity for biological uptake mechanisms to reduce nutrient concentrations. The pond should be designed for easy maintenance, and should contain several zones: <u>the sediment forebay</u> (optional, allows sediment build-up to be monitored easily, and concentrates any required sediment removal activities within a small area, thereby minimizing potential damage to the rest of the pond); <u>the permanent pool</u> (acts as the main treatment zone and helps to protect fine deposited sediments from re-suspension); <u>the temporary storage volume</u> (provides flood attenuation for the required events) and for energy production and irrigation; <u>the shallow zone</u> (acts as a biological filter and provides ecology, amenity and safety benefits). Additional pond design features should include an emergency spillway, maintenance access, a safety bench, and appropriate landscaping. A sketch and a picture of this type of technique is shown in Figures 2.25 and 2.26.

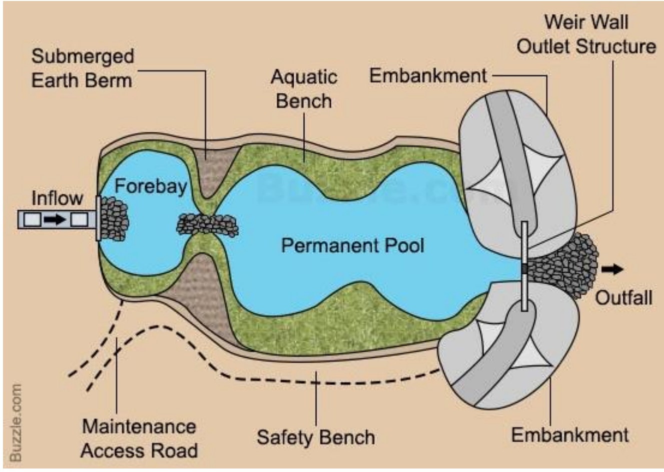

Figure 2.26 - Design of a retention pond (buzzle.com, 2015)

Figure 2.25 - Retention pond (Susdrain, 2015)

Table 2.10 - Retention ponds: advantages and disadvantages (Susdrain, 2015)

Advantages	**Disadvantages**
Can cater for all storms Good removal capability of urban pollutants Can be used where groundwater is vulnerable, if lined Good community acceptability High potential ecological, aesthetic and amenity benefits May add value to local properties.	Anaerobic conditions can occur without regular inflow Land take may limit use in high density sites May not be suitable for steep sites, due to requirement for high embankments Colonization by invasive species could increase maintenance Perceived health & safety risks may result in fencing and isolation of the pond.

Extended detention basins - Extended detention basins are vegetated depressions that are mainly dry. Detention basins are surface storage basins or facilities that provide flow control by providing temporary storage and controlled release of detained runoff. They also facilitate some settling of particulate pollutants. They may be designed with a small permanent pool at the outlet to help prevent re-suspension of sediment particles by high intensity storms and to provide enhanced water quality treatment for frequent events. Detention basins may be constructed as on-line or off-line facilities. On-line facilities have surface runoff routed through them during storm events. They have a restricted outflow that allows the basin to fill, which attenuates flows. Off-line facilities usually receive runoff via a flow diverter or overflow, by which flows in excess are diverted from the main flow path into the detention basin and temporarily stored. The water from the detention basin is passed back into the main system when the inflow falls below the diversion threshold. Off-line detention basins should be avoided where treatment of the runoff is important. A detention base scheme is shown in Figure 2.27.

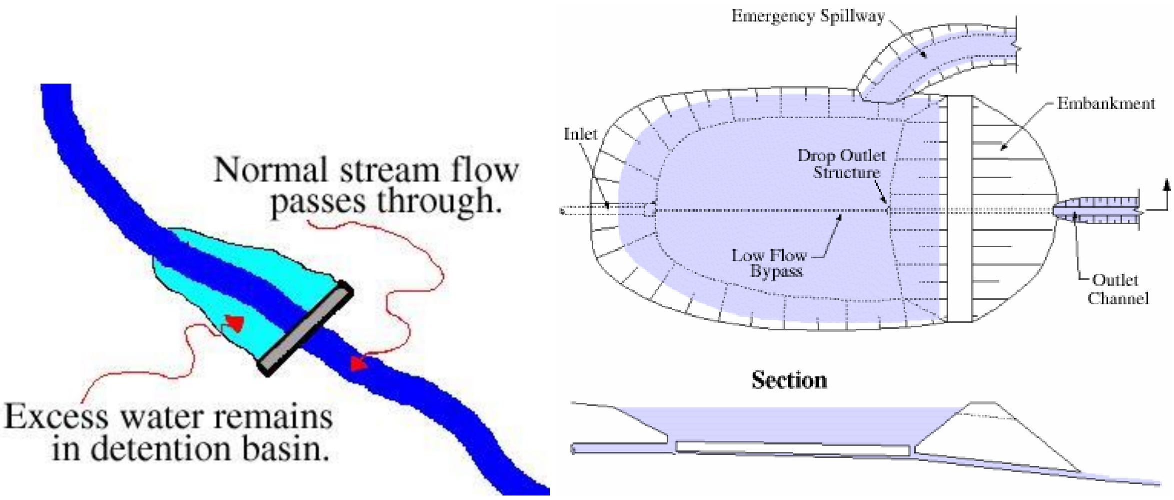

Figure 2.27 – Detention basin scheme (http://water.me.vccs.edu, 2015)

Table 2.11 - Detention basins: advantages and disadvantages (Susdrain, 2015)

Advantages	Disadvantages
Can cater for a wide range of rainfall events Can be used where groundwater is vulnerable, if lined Simple to design and construct Potential for dual land use Easy to maintain Safe and visible capture of accidental spillages.	Detention depths may be constrained by system inlet and outlet levels.

Buried reservoirs - used in dense urbane zones, where there are space limitations. Situated below the level of the ground, it consists in armed concrete walls. This type of basins can be divided in two categories: offline reservoirs (alternative) and online reservoirs (permanent). An offline reservoir only functions for specific events previously defined. An online reservoir functions even for low intensity rainfall. An alternative is to use online reservoirs but designed for events with different return periods.

- **Wetlands**

Constructed wetlands - Constructed wetlands are ponds with a range of deep and shallow water areas covered almost entirely in aquatic vegetation, designed to treat urban stormwater runoff. Well-designed and maintained wetlands can offer important aesthetic, amenity and wildlife benefits to an area. Constructed wetlands require a continuous baseflow to support a plant-rich community including aquatic vegetation and micro-organisms. Without such baseflow, salts and algae can concentrate in the water column (potentially discharging at the start of a storm event) and may cause the wetland to die off. A comprehensive water budget analysis is necessary to ensure the viability of a wetland. Wetlands should consist of the following elements: shallow, vegetated areas of varying depths; permanent pool or micropools; small depth range overlying the permanent pool, in which runoff control volumes are stored; sediment forebay, or equivalent (if required); emergency spillway; maintenance access; safety bench. A sketch of this type of technique is shown in Figures 2.28.

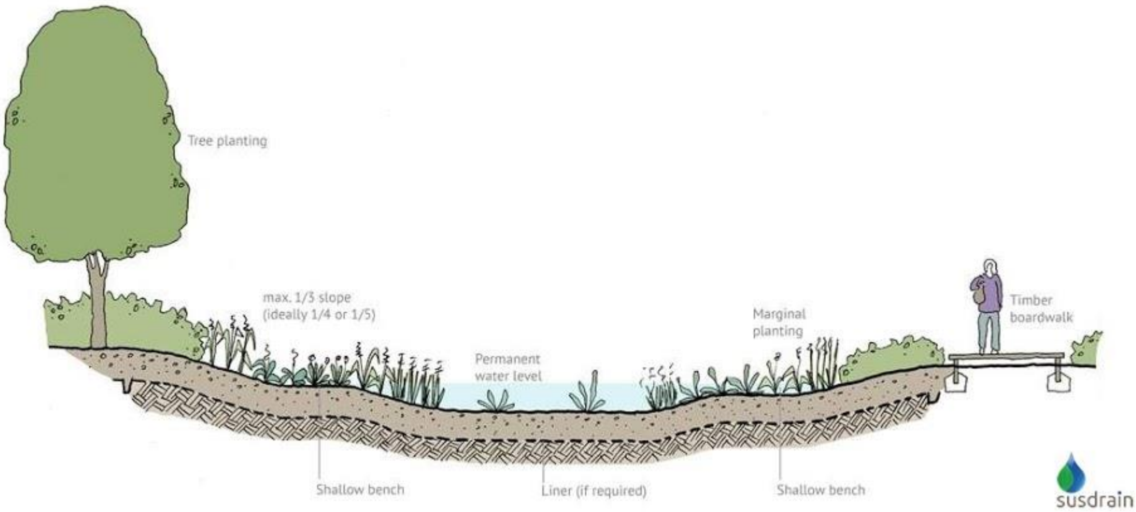

Figure 2.28 - Wetland sketch (www.susdrain.org, 2015)

Table 2.12 - Wetlands: advantages and disadvantages (Susdrain, 2015)

Advantages	**Disadvantages**
Good removal capability or urban pollutants If lined, can be used where groundwater is vulnerable Good community acceptability High potential ecological, aesthetic and amenity benefits May add value to local property.	Land take is high Requires baseflow Limited depth range for flow attenuation May release nutrients during non-growing season Little reduction in run volume Not suitable for steep sites Colonization by invasive species would increase maintenance Performance vulnerable to high sediment inflows.

3. Simulation model

3.1 MIKE SHE software

A hydrologic and hydrodynamic models are used to understand why a flow system is behaving in a particular way and to predict how a flow system will behave in the future (Fetter, 2001). These two uses, understanding observed flow and predicting future behavior, are integral in creating real world infrastructure that will be able to sustainably exist within the hydrologic and hydraulic systems. Models can be classified as physical, analog, or mathematical in nature. Mathematical models can be represented in a number of ways depending on the input output relationships and what laws and principles they abide by. A mathematical model can use theoretical equations that follow the laws of nature and be classified as physically based, or the model can use experimental based relationships to draw equations and be classified as empirically based. A model that spatially or temporally varies the input parameters is a distributed model, in contrast to a lumped model, which has a spatially or temporally uniform input parameter set. Models can also either be event based which simulate a particular event of process for a short period; or a model can be continuous in nature and output several years' worth of data. The extent to which model parameters are determined can further classify models. A deterministic model has every parameter fully determined by governing equations, a stochastic or probabilistic model has incomplete determination and some variable are totally or partially described by probability equations (DHI, 2004).

MIKE SHE is a fully integrated, physically based, distributed model, capable of both event based and continuous simulations. The model is able to simulate hydrology in plot, field, and watershed scales, particle tracking of solutes, and can be linked with MIKE 11 to simulate watershed-river relationships. The MIKE SHE model was originally developed by three European organizations (Danish Hydraulic Institute, British Institute of Hydrology, and a French consulting company SOGREAH) in 1977. DHI has taken the lead in development and research of MIKE SHE for improvements and additions (DHI, 2004).

The physically based nature of the model lends inclusion of natural topography and watershed characteristics such as vegetation, soil, and weather parameter sets. The distributed nature of the model allows the user to spatially and temporally vary parameter sets such as soil profiles, land use conditions, drainage practices, weather and evapotranspiration data sets, and overland flow values. The spatial distribution is accomplished through an orthogonal grid network that allows for horizontal or vertical discretization, as applicable within each parameter set (Abbot et al., 1986).

Temporal distribution allows users to either vary parameters by time step, or set constant values for parameters for the entirety of the simulation period. The user can also change the complexity of the model simulation by adjusting the modular setup of the model within the GUI (graphic user interface). One can choose to include the modules such as Overland Flow (OF), Rivers and Lakes (OC), Unsaturated Zone (UZ), Evapotranspiration (ET), and Saturated Flow (SF). If the saturated flow module is included than the unsaturated zone and evapotranspiration modules must be included as well.

3.2 MIKE SHE in drainage applications

A series of research studies (Al-Khudhairy, et al 1997, 1999, Thompson, et al 2004) investigated the effects of changes in hydrology of marshland in Southeast England. The former two works address a 10 km^2 area near the North Kent Marshes; the later paper by Thompson (2004) addresses the adjacent 8.7 km^2 of the Elmey Marshes on the Isle of Sheppey. This marshland was drained for grazing in the past century and the authors were investigating the effects that restoration of the ground to its former state would have (Al-Khudhairy, 1997; Thompson, 2004). A pseudo-differential split sample was used to assess the MIKE SHE predictions of the effects on hydrology of changes in land use. Coefficient of correlation values for observed monthly flow reached 0.87 for the baseline model flow and 0.92 with the baseline model with macropore flow. These results support Jayatilaka’s conclusion that shrink-swell characteristics of soil profiles are important in describing preferential flow in the unsaturated zone (Al-Khudhairy, 1999). Thompson (2004) found that the coupling MIKE SHE with MIKE 11 to describe marshland piezometric head and surface water extent lead to a high degree of precision. Observed head values at piezometer locations throughout the research area had coefficients of correlation ranging from 0.41 to 0.78 for testing and 0.56 to 0.92 for validation. Thompson (2004) concluded that the MIKE SHE model was sufficient to describe the water table elevation of marshland in the Southeastern region of England and postulated that it may be sufficient to model marshland area in other regions as well.

Several investigators have used MIKE SHE in dissimilar conditions to analyze and develop solutions to hydrological problems within the parent region. In the mountainous regions of Hawaii, irrigation is less of an issue than flash flooding resulting from short but intense rainfall events (Sahoo, 2004). The study area investigated included two watersheds in the Manoa-Palolo stream system adding up to 27.28 km^2 on the Hawaiian island of Oahu. Flow data was collected at 15 minute intervals in order to accurately describe the sudden onset of flash flood events within the watershed. Deviations from other investigations include unique topography (mountainous) and soil parameters (volcanic parent material); horizontal saturated hydraulic conductivity Kh was 190 times greater than the vertical saturated hydraulic conductivity Kv. It was concluded that MIKE SHE reached a correlation coefficient of 0.70 with watershed discharge and could be used to predict the severity of flood events with a given precipitation depth.

3.3 The MIKE SHE model

3.3.1 Brief introduction

This section will describe the model components used in this investigation and present the mathematical basis for each module. The process starts with user input precipitation, a fraction of which is intercepted by vegetation before it reaches the surface. This intercepted precipitation is either stored on the plant material and later evaporated back into the atmosphere or detained on the soil surface where it can undergo surface runoff or infiltration, depending on soil conditions. As infiltration continues, the unsaturated zone will become saturated and after all surface storage areas are taken up overland flow will begin downward from one cell to the next based on topographic data.

3.3.2 Mathematical Description

MIKE SHE is a physically based model, based on physical laws which are derived from forms of the laws of conservation of mass, momentum and energy. The evapotranspiration model is calculated using the Kristensen and Jensen methods, although user input reference ET can be calculated in different ways. Channel flow is handled using one dimensional (1-D) diffusive wave Saint-Venant equations and overland flow is calculated using two dimensional (2-D) diffusive wave Saint-Venant equations. Water infiltrating into the unsaturated zone can be modeled using the 1-D Richards flow or gravity flow. The saturated zone is modeled using a three dimensional (3-D) Boussinesq equation which uses finite difference methods to solve the partial differential equations (PDE’s).

3.3.2.1 Overland Flow Components

There are two methods to determine overland flow in MIKE SHE; the first follows the physically-based diffusive wave approximation of the Saint-Venant equations and the second is a simplified version of overland flow routing which is a semi-distributed approach based on the Manning’s equation. Overland flow depends on a variety of factors including topography (slope), soil properties, detention storage, evaporation, and infiltration.

i. Diffusive Wave Approximation of the Saint-Venant Equations

The approximations of the fully dynamic Saint-Venant equations neglect the momentum losses due to local and convective acceleration and lateral inflows perpendicular to the flow of the direction (Ramos, 1986). Therefore momentum equations in two dimensions are:

$$Sfx = S0x - \left(\frac{\partial h}{\partial x}\right) - \left(\frac{u}{g}\frac{\partial u}{\partial x}\right) - \left(\frac{1}{g}\frac{\partial u}{\partial t}\right) - \left(\frac{qu}{gh}\right) \quad (3.1)$$

$$Sfy = S0y - \left(\frac{\partial h}{\partial y}\right) - \left(\frac{v}{g}\frac{\partial v}{\partial y}\right) - \left(\frac{1}{g}\frac{\partial v}{\partial t}\right) - \left(\frac{qv}{gh}\right) \quad (3.2)$$

In the x direction this reduces to:

$$Sfx = S0x - \left(\frac{\partial h}{\partial x}\right) \quad (3.3)$$

where,

Sfx is the friction slope;
$S0x$ is the ground slope;
h is the flow depth above the ground surface;
x is the direction of flow,

simplifying slope, the original equation in the x direction reduces to:

$$Sfx = \left(\frac{\partial zg}{\partial x}\right) - \left(\frac{\partial h}{\partial x}\right) \tag{3.4}$$

where

z_g is the ground surface level the relationship $z = z_g + h$ further reduces to

$$Sfx = -\left(\frac{\partial z}{\partial x}\right) \tag{3.5}$$

and in the y direction:

$$Sfy = -\left(\frac{\partial z}{\partial y}\right) \tag{3.6}$$

3.3.2.2 Saturated Zone Components

MIKE SHE allows the user to pick one of two methods to calculate flow in the saturated zone module of the model. The first is a three dimensional finite difference method and the second is a linear method. In this investigation, the three dimensional finite difference method was selected and will be discussed in this section.

i. 3-D Finite Difference Method

This method takes advantage of Darcy's law and continuity with a similar approach using finite difference techniques. It is calculated in three dimensions and can either use a preconditioned conjugate gradient (PCG) or the successive over-relaxation solution (SOR) technique. The preconditioned conjugate gradient was chosen for this investigation because of the difference in formulation of potential flow and the way source and sink terms are treated. In the PCG method, sources and sinks interact with the saturated zone either implicitly or explicitly in the 3-D partial differential equation given as:

$$\frac{\partial}{\partial x}\left(Kxx\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(Kyy\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(Kzz\frac{\partial h}{\partial z}\right) - L = S\left(\frac{\partial h}{\partial t}\right) \tag{3.7}$$

where

x, y, z are unique axes in the Cartesian coordinate system;
Kxx, Kyy, Kzz are hydraulic conductivities along the x, y, and z axes;
h is the hydraulic head;
L is the sink/source term;
S is the specific storage coefficient.

Two special features should be noted about the above equation. First the equation is nonlinear when the flow is confined. Second, the storage coefficient switches between the specific storage coefficient when confined and the specific yield for unconfined conditions.

(ii) The Preconditioned Conjugate Solver (PCG)

The PCG is an alternative to the successive over relaxation (SOR) solver. The PCG keeps both an inner iteration loop (where dependent boundaries are constant), and an outer iteration loop (where head dependent terms are updated). The default user settings are set up for convergence, but if individual simulations encounter slow convergence or divergence then adjusting the solver settings is recommended. The PCG is also identical to the solver used in MODFLOW (McDonald and Harbaugh, 1988). The potential flow calculated is obtained using Darcy's law:

$$Q = \Delta h C \qquad (3.8)$$

where

Δh is the piezometric head difference;

C is the conductance of the cell.

The horizontal conductance is calculated using the horizontal conductivity and the geometric mean of the layer thickness; this creates a harmonic mean. On the other hand, the vertical conductance is the weighted serial connection vertical hydraulic conductivity which is calculated from the middle of one layer to the middle of another. In dewatering situations, the saturated zone cells are calculated with a correction term added to the right side of the differential equation using the head of the last iteration:

$$qc = C_{v_{k+1/2}}(h_{k+1} - Z_{top,k+1}) \qquad (3.9)$$

where

Cv is the vertical conductance;

Z is the layer thickness;

k + 1 is the number of the node.

The storage capacity for the cell is calculated by:

$$\frac{\Delta w}{\Delta t} = \frac{S2\,(h^n - z_{top}) + S1\,(z_{top} - h^{n-1}}{\Delta t} \qquad (3.10)$$

where

n is the time step;

S1 is the storage capacity at the start of the iteration;

S2 is the storage capacity at the last iteration.

So for confined cell the storage capacity is given as:

$$S = \Delta x^2 \Delta z S_{art} \qquad (3.11)$$

where

S_{art} is storage capacity of the confined cell

and in unconfined aquifers the storage capacity is given as:

$$S = \Delta x^2 S_{free} \quad (3.12)$$

where

S_{free} is the storage capacity of an unconfined cell

Boundaries for this method are the ground surface (upper bound) and the water table (lower bound). The lower boundary is generally a pressure boundary. The model is set up for hydrostatic initial conditions (equilibrium, no flow).

4. Case study

4.1. Description

Estuaries are especially sensitive to changes since these areas experience different interactions between multiple forcing factors and ecological systems. Floods in estuaries are associated to particular climatological conditions, as the coincidence of very high tidal levels and large fresh-water discharges, or of high tides and storm surge conditions (e.g. spatial distribution of floods in the Tagus estuary is shown in Figure 4.1). In addition to these progressive phenomena, that are possible to predict and react, episodes of very intense and concentrated in time rainfall can lead to urban flooding in areas with insufficient drainage conditions and flash floods in small watersheds tributary to the estuary. The effects of high water levels in estuaries can be exacerbated by human interventions in the system, particularly in urban areas where drainage system behavior has to be considered. Rising sea levels and more extreme climate conditions will increase the vulnerability to inundation of estuarine margins (Project Molines). At the same time estuaries are ecologically important areas and anthropic factors such as dense occupation of the estuarine fringe, land reclamation or salt marsh degradation add complexity to the systems (e.g. Townend and Pethick, 2002; Gedan et al., 2009).

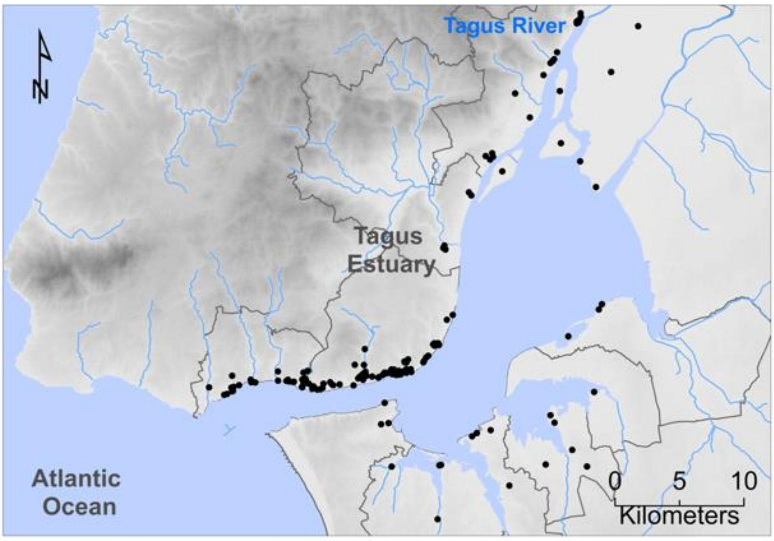

Figure 4.1 - Spatial distribution of database estuarine flood occurrences in the Tagus estuary (Rilo et al., 2015)

4.2. Study area

The Tagus estuary has a high potential to flooding from different sources along its margins, due to the intense occupation. The estuary is included in the territorial unit of Lisbon and Tagus Valley, involving 18 municipalities in the metropolitan area of Lisbon, for which estimated a population exposed directly or indirectly of about 2.8 million inhabitants. This study was conducted in a restricted area (Figures 4.2, 4.3, 4.4 and 4.5) located in the southeastern margin of the estuary, that was selected due to past record of flood episodes and relatively diverse land use occupation, with a total area of 491127m^2 and 1170m of margin length. The territorial occupation of this area is associated to relevant industrial sites that were built in Seixal (steel industry). Due to this important industrial presence urban areas grew nearby. These local industrial developments went into decline in the late 1990s and most of the facilities closed. At present, some management territorial plans indicate the intention of transforming a large part of these abandoned industrial sites into urban areas (which includes residential, services and logistics facilities).

Figure 4.2 - Study area location

Figure 4.4 - Study area

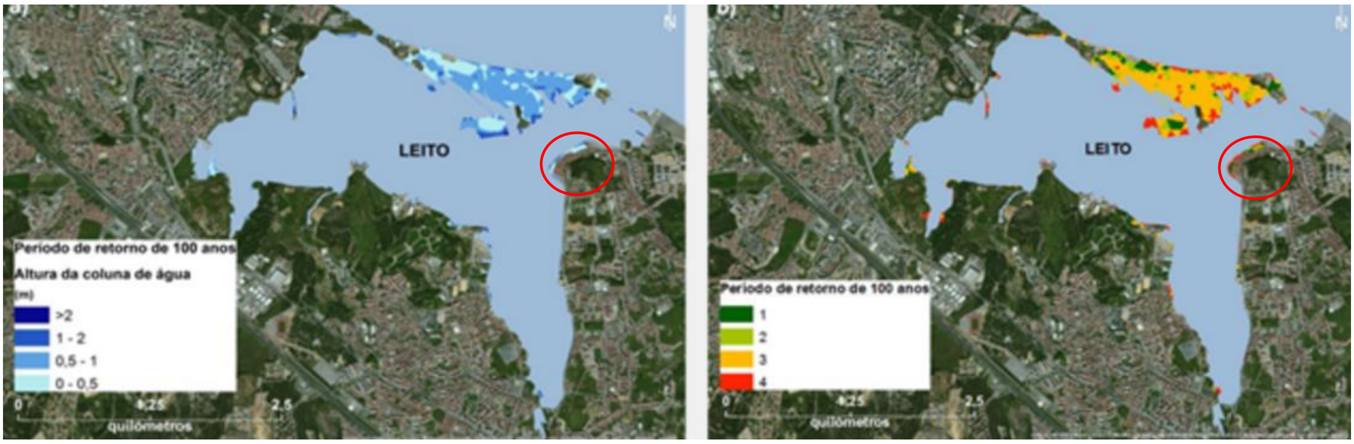

Figure 4.3 - Cartographic representation of flood hazard in Seixal Bay for the 100-year return period scenario: a) extent and depth of flooding, b) hazard index (Freire et al, 2015)

Figure 4.5 - Risk index in the Seixal municipality for a 100-year return period scenario (Project Molines)

4.3. The Tagus estuary

As one of the largest estuaries in Europe, the Tagus estuary covers 320 km^2, with a deep, long and narrow tidal inlet linking the Atlantic Ocean to a shallow, tide-dominated basin, with extensive tidal flats and marshes that cover about 40% of the inner estuary (Figure 4.6 and Table 4.1). About 40 km upstream, the estuary significantly narrows at the bay head. The saline tide reaches about 50 km upstream from the mouth, near Vila Franca de Xira. The estuarine bottom is mainly composed of silt and sand, of both fluvial and local origins; marine sands are confined to the mouth and inlet channel (Freire et al., 2007).

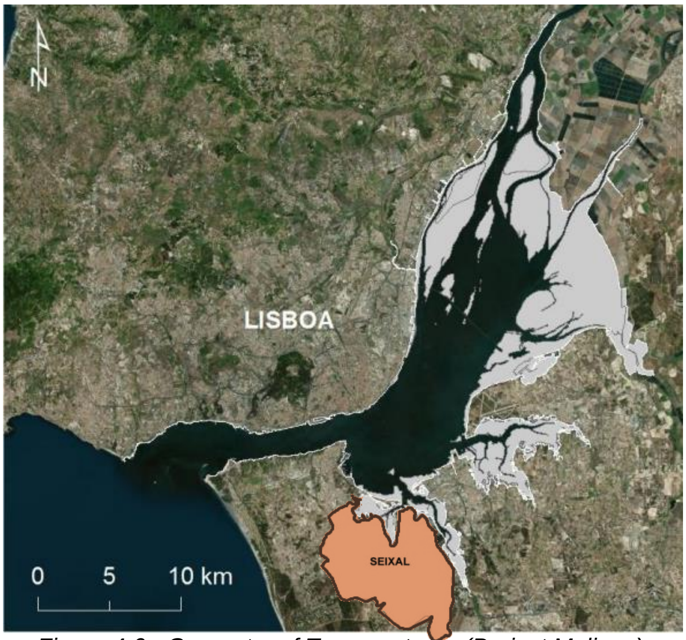

Figure 4.6 - Geometry of Tagus estuary (Project Molines)

Table 4.1 - Tagus estuary data

Extension up to the end of the dynamical tide (Muge)	80 km
Extension up to the limit of salt water intrusion (VFX)	50 km
Total area (up to VFX)	320 km^2
Area between tides	40% of the total area
Maximum width	15 km
Average width	4 km
Maximum depth	46 m
Average depth	11 m
Length of estuarine margin	360 km

Tidal ranges vary between 0.55 and 3.86 m in the open coast (Cascais data) but resonance significantly amplifies the semi-diurnal tidal constituents within the estuary (Fortunato et al., 1999). Simultaneously, the estuary is strongly ebb-dominated due to the large extent of the tidal flats (Fortunato et al., 1999).

The average river flow is 368 m^3/s (Neves, 2010), and the estuary is usually well mixed. However, stratification has been observed at high flow rates (Neves, 2010). River discharge may significantly influence water levels, but only further than 40 km upstream of the mouth (Vargas et al., 2008). Downstream, the levels are mainly controlled by tide and storm surges. Ocean waves do not penetrate significantly in the estuary. However, the large extent (fetch) of the estuary allows locally-generated waves to develop and rework the southern embankment (Freire & Andrade, 1999).

Wave propagation is influenced by the interaction with bottom bathymetry and environmental conditions (e.g. currents, wind). The bathymetry of the Tagus estuary (Figure 4.7), and the semi-daytime tide – significantly amplified in the interior of the estuary between Cacilhas and Vila Franca de Xira, leads to wind generated waves and consequently, extreme events, as shown in Figures 4.8.

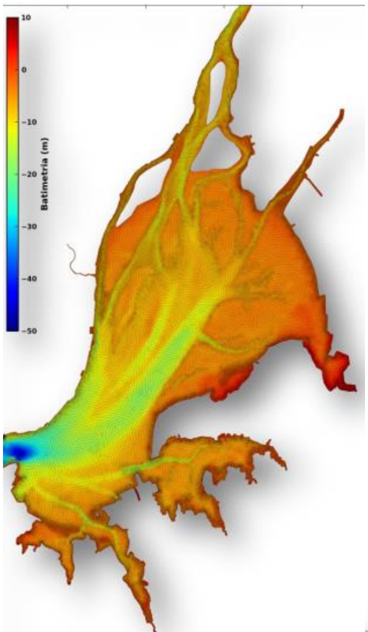

Figure 4.7 – Tagus estuary bathymetry (Guerreiro et al., 2012)

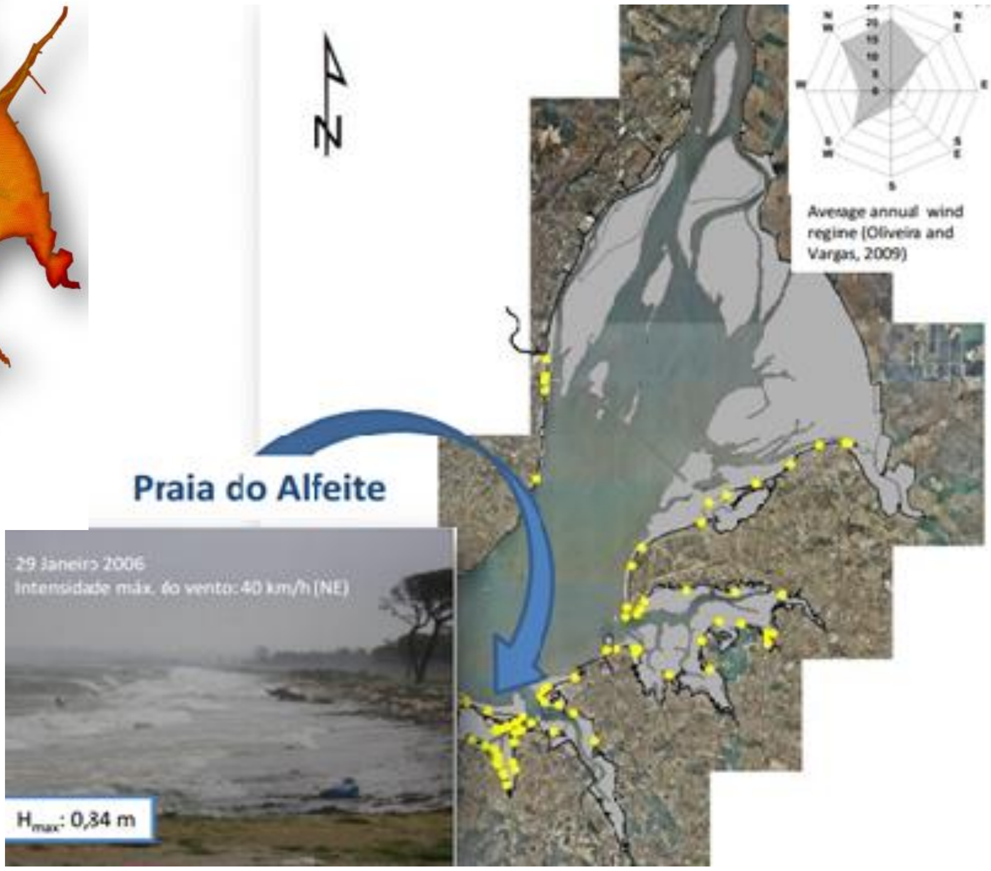

Figure 4.8 – Wind waves in the estuary (Freire et al., 2013; Oliveira et al., 2013)

Tidal asymmetry is particularly relevant to sediment dynamics (Aldridge, 1997). Shorter ebbs promote higher average flow velocities on ebb than on flood because the same volume of water flows in a shorter period of time. Under those circumstances, the estuary is said to be ebb-dominant. Since the sediment fluxes depend non-linearly on the velocity, an ebb-dominated estuary will tend to export sediments. In contrast, a flood-dominant estuary will tend to silt-up more rapidly (Lanzoni & Seminara, 2002).

Studies confirm that the estuary is ebb-dominated in the 40 km reach upstream from the mouth (Fortunato et al., 1999) and show that it switches to flood-dominated further upstream. The reduction of the ebb-dominance from km 40 upstream is likely associated to the change in morphology, from a wide bay with extensive tidal flats to deep and narrow channels. Sea level rise (SLR) will increase the depth of the estuary, hence reducing the tidal amplitude to depth ratio. As a consequence, flood dominance should increase. The extent of the tidal flats will decrease, further reducing ebb dominance: the intertidal area in the Tagus estuary decreases by 40% for a SLR of 1.5 m. In summary, while SLR will significantly reduce ebb-dominance in the Tagus estuary, sedimentation in the tidal flats will tend to enhance it. The balance may tend either way, depending on the rate of SLR, the changing sedimentation rates, and how the marginal areas are allowed to flood. The simulations carried out show that SLR will have significant effects on estuarine hydrodynamics. In the case of the Tagus they will be particularly significant due to the occurrence of resonance, which amplifies the semi-diurnal constituents of the tide. SLR will trigger two major direct effects: Tidal asymmetry will decrease significantly. The present ebb-dominance will be reduced, and the estuary may even become flood-dominant. This behavior appears to be mostly due to a significant reduction of the intertidal areas (roughly 40% for a 1.5 SLR) and will be partly compensated by sedimentation in the tidal flats. And the resonance within the estuary will be strengthened, increasing the tidal amplification. As a result, the maximum levels in the estuary will increase slightly faster than the SLR (Guerreiro *et al*, 2015).

4.4. Extreme water levels

Marginal flooding in the Tagus estuary can have adverse effects. Some urbanized marginal areas, such as Seixal, are low-lying, so that the potential human and material costs of a flood are high. One of the most severe historic episodes described was originated by the combination of extreme storm surge levels and locally generated waves during the February 15, 1941, windstorm, causing high human casualties and property damages along the estuarine margins (Muir-Wood, 2011).

Recently, the effects of the Xynthia windstorm, that reached the Portuguese coast on February 27, 2010, were also observed along the estuary margins, where significant damages in infrastructures occurred. In the upper area of the estuary, with extensive agricultural areas, floods may induce salinization and loss of fertile land. Raising the mean sea level (MSL) implies more frequent floods of marine origin. In the particular case of the Tagus estuary, this problem will be exacerbated by the increased tidal amplification due to resonance. The results point out that about 16.1% of the estuarine marginal fringe will be vulnerable to flood for the 2050 scenario, rising up to 23.7% for the 2100 scenario. Urban and industrial areas are the most affected ones in both scenarios: 4.0% and 4.6% (2050) and 6.0% and 7.8% (2100), respectively. The effects of high water levels in urban areas can be exacerbated due to the drainage system behavior, which should be prepared for new baseline conditions. In general, agriculture parcels and green spaces and leisure facilities would be the less affected sites, given their low representativeness at the study area. However, the Alfeite sand spit, an important recreational area that also contributes to the maintenance of Seixal bay ecosystem, will be totally flooded in both scenarios. Vargas et al. (2008), analyzed the vulnerability of the Alfeite spit to inundation using a combination of hydrodynamic and morphodynamic models under SLR effects and predicted that in the worst case scenario almost all the spit would be flooded promoting the spit migration to south. This fact might represent a significant morphological change at the Seixal bay that can potentially modify the local hydrodynamic behavior leading to a significant change in natural habitats, Figure 4.9, namely sandy beaches and salt marshes (Guerreiro *et al*, 2015).

Figure 4.9 - Impact of the urbanization in the tide line, Seixal, (Rilo et al., 2012)

The ongoing rise in sea level affects tidal propagation and circulation in estuaries, and these changes can have far reaching consequences on the sediment dynamics, water quality and extreme water levels. The increasing of population is also causing a major impact, the induced erosion may cause accelerated siltation and the urbanization will increase the runoff. The consequences will be the growth of water's turbidity, the acceleration of sedimentation and the spread of silts, muds and clay throughout the estuary, which leads to a major vulnerability of its margins as shown in Figures 4.10 and 4.11.

Figure 4.10 – Flood event, Seixal, 2010

Figure 4.11 – River margin, Seixal, 2010

5. Model testing and validation

5.1 Modelling

5.1.1 Input and output data

MIKE SHE is a physically based model, which relies upon physical laws of nature and representative data from the site under hydrological modeling. This section will outline the data types and sources used for all inputs involved in testing and validation of MIKE SHE in this application.

MIKE SHE allows users to easily visualize the parameters that are being introduced and to create output image data.

Background: In order to place the visual data at the geographic site, it was used a georeferenced google satellite image of the study area. To create an readable image by MIKE SHE was used the software QGis 2.12.0 which allows to georeference a normal google satellite image with Google OpenLayers plug in. This is necessary once MIKE SHE uses georeferenced inputs such as shapefiles and gridfiles. Every input and output data is shown over this image, giving the geographic information.

Foreground: With the software QGIS 2.12.0 was created a polygon shapefile of the study area. The shape acts as a boundary within which every calculation is made. This appears represented in every output image given by the software and allows the user to study a specific area.

5.1.2 Simulation specification

One of the necessary inputs to define the simulation is the duration of the simulation and time step period.

Duration of the simulation: Choosing a too small simulation period can lead to inaccurate results if smaller than the warm up period. A too large simulation period requires too much calculation time. The simulation period chosen was 2 months. This period was enough to simulate the extent of the wanted outputs and made possible to run several simulations to perfect the model.

Time step: The time steps used in the model for efficient simulation were: initial unsaturated zone time step 6 (hours); maximum unsaturated zone time step (1 hour); maximum saturated zone time step (4 hours); maximum overland flow time step (1 hour). If the time step is too large, this will oversimplify the model and can lead to an imprecise description of the hydrology of the watersheds. If the time step is too short, the computational and temporal resources required will surpass an allowable limit. The proper time step settings are crucial for minimizing water balance errors that appear in simulations.

5.1.3 Meteorological data

The meteorological data consisted in three main inputs: precipitation rate, net rainfall fraction and infiltration fraction. These inputs were fixed at the most demanding registered values in order to simulate the worst case scenario. Precipitation rate was set as uniform and with a constant temporal distribution. The value assumed was 3.5 mm/day (i.e. average precipitation in the rainiest month, November), where the rainfall data was collected from Climate-Data.org, Figure 5.1. It was considered that precipitation was equally distributed in the study area and only 10% of the rain was infiltrated. Since the time step for the model was sub-daily, the precipitation rate was amortized over the 24 hours according to the time step.

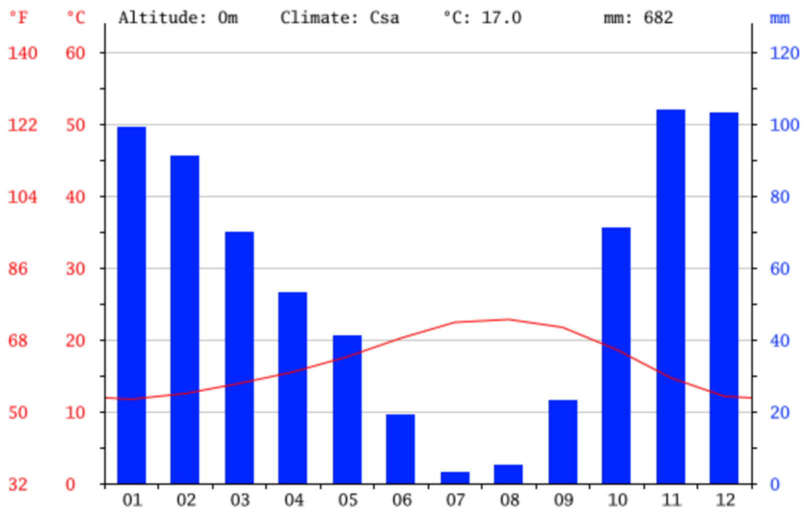

Figure 5.1 - Climate characteristics of Seixal (Climate-Data.org, 2016)

5.1.4 Hydro-geological data: surface and subsurface geology

Hydro-geological composition of the study area is essential to define overland flow, subsurface drainage and deep seepage out of the watershed. The main inputs to determine overland flow are topography and soil hydraulic parameters. To improve precision within the MIKE SHE model it is important to increase the resolution in the upper unsaturated zone by decreasing the cell height in the vertical discretization of the soil profile.

The difference between equal cell height and increased resolution in the upper unsaturated zone is that with the increased resolution profile it can lead to Hortonian ponding at the ground surface, characterized by high rainfall intensity on dry, low permeable soil. The ponding occurs in the model at higher resolutions when the relationship between moisture content and soil profile depth can more accurately reproduce the nonlinear aspect of observed infiltration and ponding by allowing more points in the soil profile to be explicitly described, as opposed to a lower resolution approach, which may be more linear in nature. In this application due to the low resolution it was not possible to simulate the ponding effect.

The rest of the soil profile parameters, drain location and depth, help determine the influence of subsurface drainage on each simulation.

5.1.5 Topography

The digital elevation model (DEM) that was acquired with a 7.5 arc-seconds resolution GeoTIFF data (with a RMSE range is between 26 and 30 meters) was converted into a point file suitable for MIKE SHE using QGIS 2.12.0. The elevations in the point file were triangularly interpolated into a 10 by 10 meter resolution inside MIKE SHE. Figure 5.2 shows the topography as it appears in MIKE SHE in the study area.

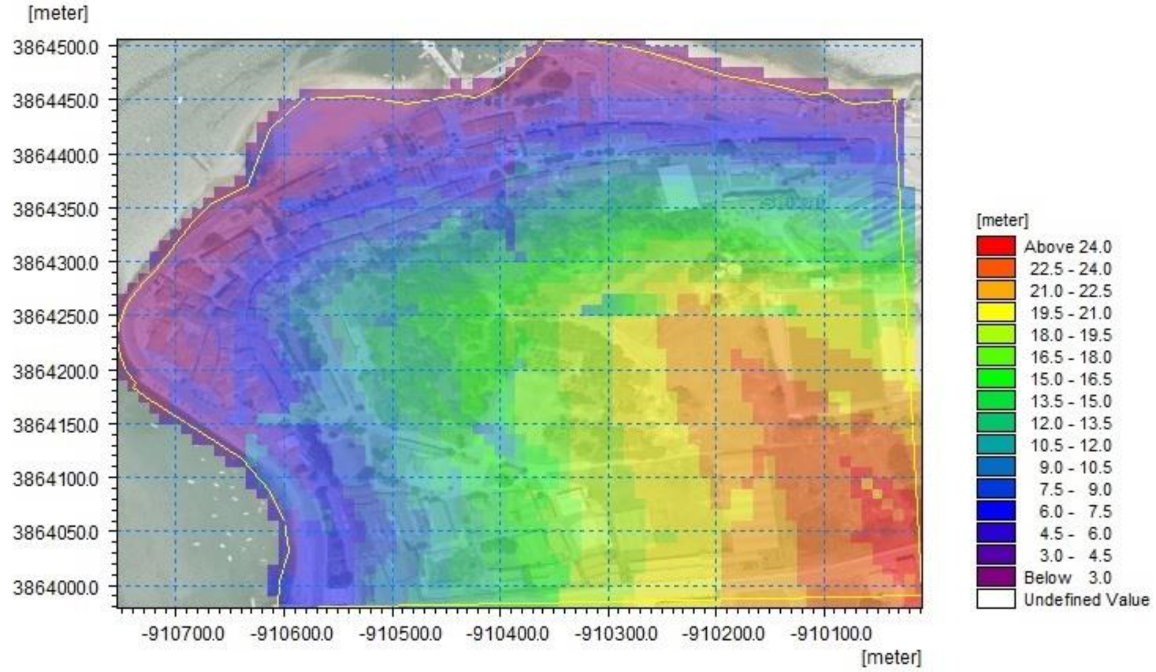

Figure 5.2 - Topography map of the study area as an input file in MIKE SHE

5.1.6 Properties and boundary conditions

Properties affecting subsurface activities include saturated hydraulic conductivity of the saturated zone layers, specific yield and specific storage. Specific yield (10^{-6}) and specific storage (0.0001 1/m) were kept at default values in the MIKE SHE model since the aquifer was considered to be unconfined and established values for similar soil types fit the default values and with uniform special distribution. For this testing a single soil layer was used once the main objective of this work was not to consider the presence of water at the subsurface.

In the study area were introduced two types of outer boundaries: the river boundary and the land boundary. In order to force a flood occurrence was considered a river boundary has a constant flux of $50m^3/s$, which represents the effect of the high tide. This value was obtained through an iterative simulation. The land boundary was used has a theoretical barrier which isolates the study area, not allowing water to pass beyond the boundary creating a much worse scenario (Figure 5.3). To design the land boundary was taken into account streets and was considered a fixed head with the used initial value of the software.

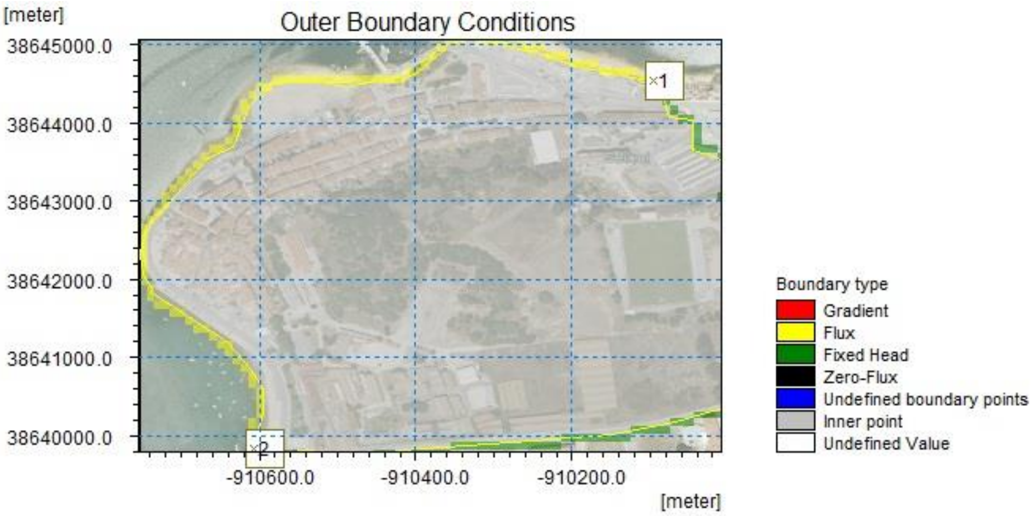

Figure 5.3 - Outer boundaries of the study area in MIKE SHE

5.1.7 Drainage

MIKE SHE requires a reference system for linking the drainage to a recipient node or cell. The option chosen was “drainage not routed, but removed from model” witch is simply a head dependent boundary that removes the drainage water from the model. This method does not involve routing and simplifies the calculation. The MIKE SHE model was run under various land management scenarios to investigate the effect that land use has on the hydrological model. There are two main land uses on the study area: green areas (Figure 5.4) and paved areas (Figure 5.5).

Figure 5.5 - Green areas adopted in the study area

Figure 5.4 - Paved areas adopted in the study area

5.1.1 Storing of results

The integrated nature of MIKE SHE means that large amounts of output can be generated during a simulation. The output in MIKE SHE can be divided into two types: Time series and Grid Series. From a practical point of view, time series output generated during the simulation is saved at every simulation time step, while grid series output is saved at a specified time interval.

5.2 Scenario simulations

Several simulations were analyzed and performed in order to verify if the outputs given by MIKE SHE model were the same has the flood data registered in the study area. Modeled flood outputs from these simulations were compared and adapted to real and observed conditions. In Figure 5.6 it is presented the MIKE SHE model used for final testing of the different scenarios. From this point forward risk index is shown in the maps subtitles as Very High (100% probability of flooding), High (75% probability of flooding), Moderate (50% probability of flooding), Low (35% probability of flooding), Very Low (10% probability of flooding) and No Vulnerability (0% probability of flooding).

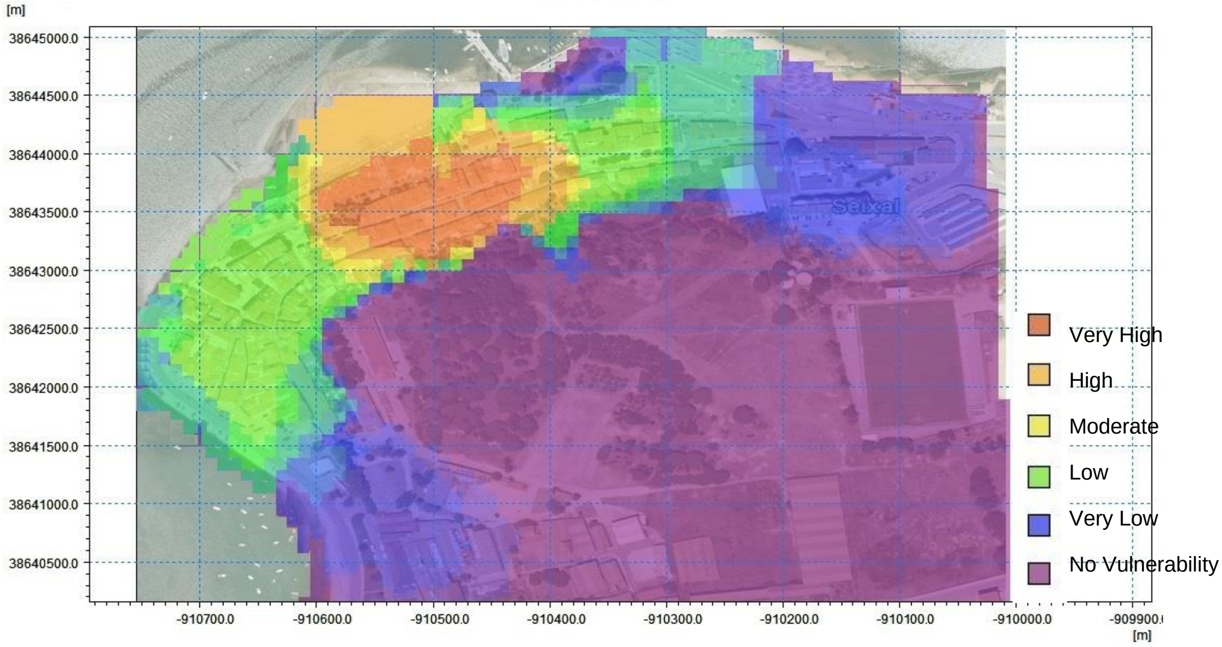

Figure 5.6 - MIKE SHE model used in the flood scenario simulations

The results showed that the model simulated flooding much like what would occur in nature. After the model definition it was possible to start the scenarios simulation for each SUDS alternative.

First it was important to determine which SUDS techniques were best suited to the proposed land use of the area draining to the system. For this reason it was defined the population density (Figure 5.7).

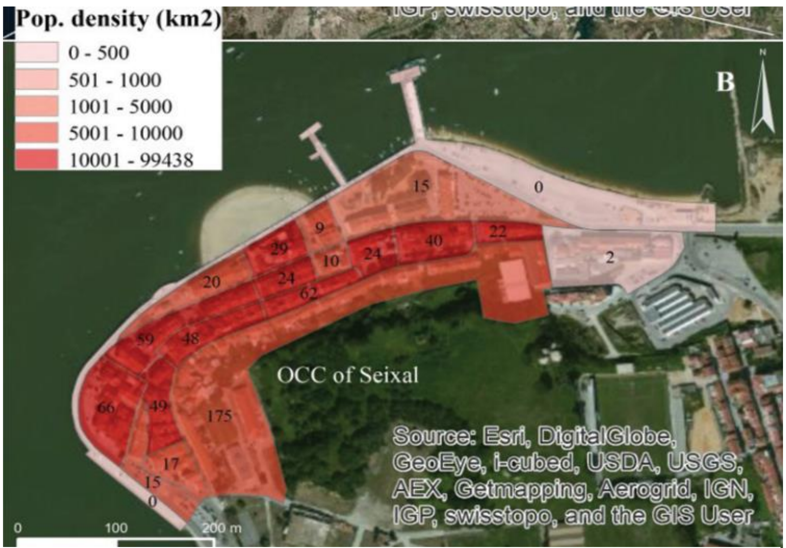

Figure 5.7 - Population density in the study area (Esri, Digital Globe, 2016)

The study area is a built-up area among the most densely inhabited around the estuary's margins. The area totals 672,016 inhabitants in 670.39 km^2. For this study it was considered as a Residential and Commercial area.

It was determined whether there were any site characteristics that may restrict or preclude the use of a particular SUDS technique. The area is almost impermeable due to the roads and buildings, has 491.197m^2 (>2ha) and gentle slope (nearly flat). There is a lack of space for new facilities. Analyzing the characteristics it was concluded that only these techniques were valuable at this point: retention pond, wetland, infiltration trench, soakaway, filter strips, filter trench, detention basin, green roof and permeable pavement.

Construction and maintenance costs can vary widely between techniques and the long term costs of SUDS should be considered at an early stage. In selecting a design from a series of options, both capital and operational costs should be considered using a whole life costing approach. To select the techniques with more acceptance by the community was used the matrix presented next in Table 5.1.

Table 5.1 – Community and environmental factors selection matrix, CIRIA, 2015

Technique	Maintenance	Community Acceptance	Cost	Habitat creation potential
Retention Pond	Medium	High	Medium	High
Wetland	Medium	Low	High	Medium
Infiltration trench	Low	Medium	Low	Low
Soakaway	Low	Medium	Medium	Low
Filter strip	High	High	Medium	High
Filter trench	Medium	Medium	Medium	Low
Detention basin	Low	High	Low	Medium
Green roof	High	High	High	High
Permeable Pavement	Medium	Medium	Medium	Low

Under this analysis it was concluded that the techniques valuable for the study area were infiltration trench, detention basin and permeable pavement.

5.2.1 Infiltration trench

Trenches are shallow excavations filled with rubble or stone that create temporary subsurface storage for either infiltration or filtration of stormwater runoff. Infiltration trenches allow water to exfiltrate into the surrounding soils from the bottom and sides of the trench.

To apply the technique were selected streets with most vulnerability to flood and where the normal circulation of people and vehicles was not affected, as seen in Figure 5.8.

Figure 5.8 - Infiltration trenches technique applied in QGIS

After applying infiltration trenches, it was simulated a flood using the flood model (Figure 5.6) in MIKE SHE and Figure 5.9 shows the results obtained compared with the flood model.

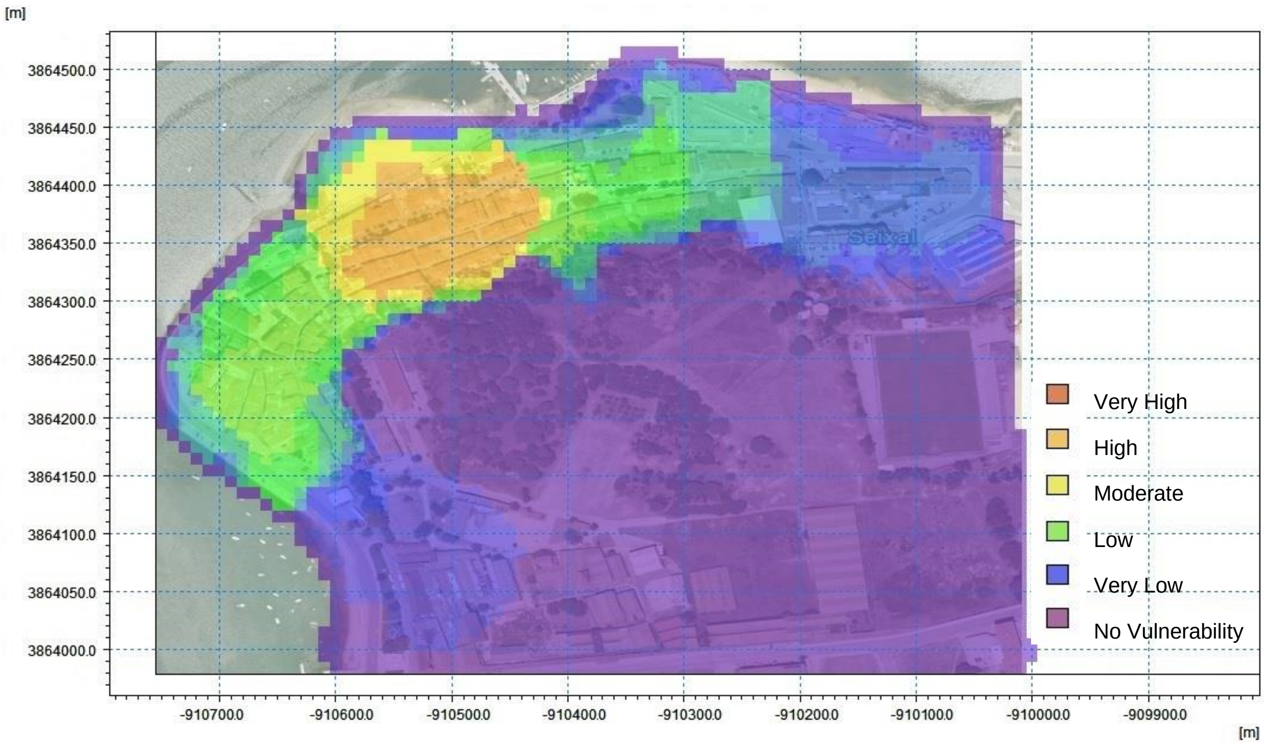

Figure 5.9 - MIKE SHE model for flood with infiltration trenches technique applied

5.2.2 Detention basin

Detention basins are surface storage basins or facilities that provide flow control through attenuation of stormwater runoff. Normally they are dry parcels of land that may also function as a recreational facility. To apply the technique were selected places with space near areas with most vulnerability to flood and where the normal circulation of people and vehicles was not affected and could be used as recreational facilities, as seen in Figure 5.10.

Figure 5.10 – Detention basin technique applied in QGIS

After applying detention basins where possible, it was simulated a flood using the flood model (Figure 5.6) in MIKE SHE and Figure 5.11 shows the results obtained compared with the flood model.

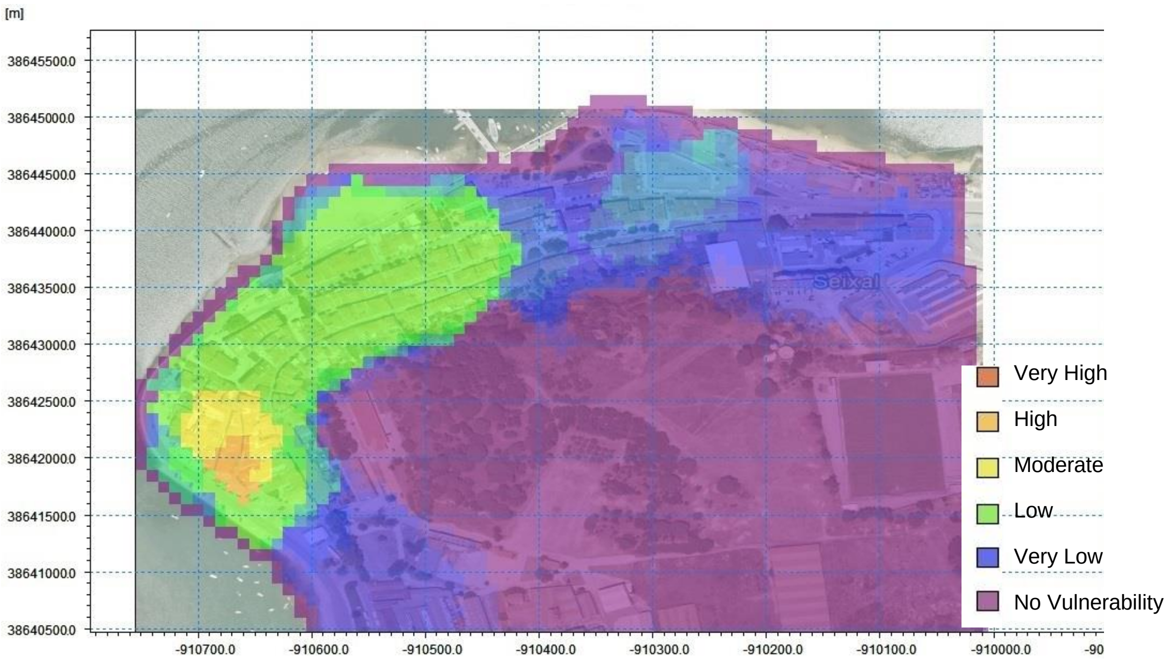

Figure 5.11 - MIKE SHE model for flood with detention basin technique applied

5.2.3 Permeable pavement

Permeable pavements provide a pavement suitable for pedestrian and/or vehicular traffic, while allowing rainwater to infiltrate through the surface and into the underlying layers. The water is temporarily stored before infiltration to the ground, reuse, or discharge to a watercourse or other drainage system. To apply the technique were selected all the streets with most vulnerability to flood since the normal circulation of people and vehicles was not affected, as seen in Figure 5.12.

Figure 5.12 – Permeable pavement technique applied in QGIS

After applying permeable pavement where possible, it was simulated a flood using the flood model (Figure 5.6) in MIKE SHE and Figure 5.13 shows the results obtained compared with the flood model.

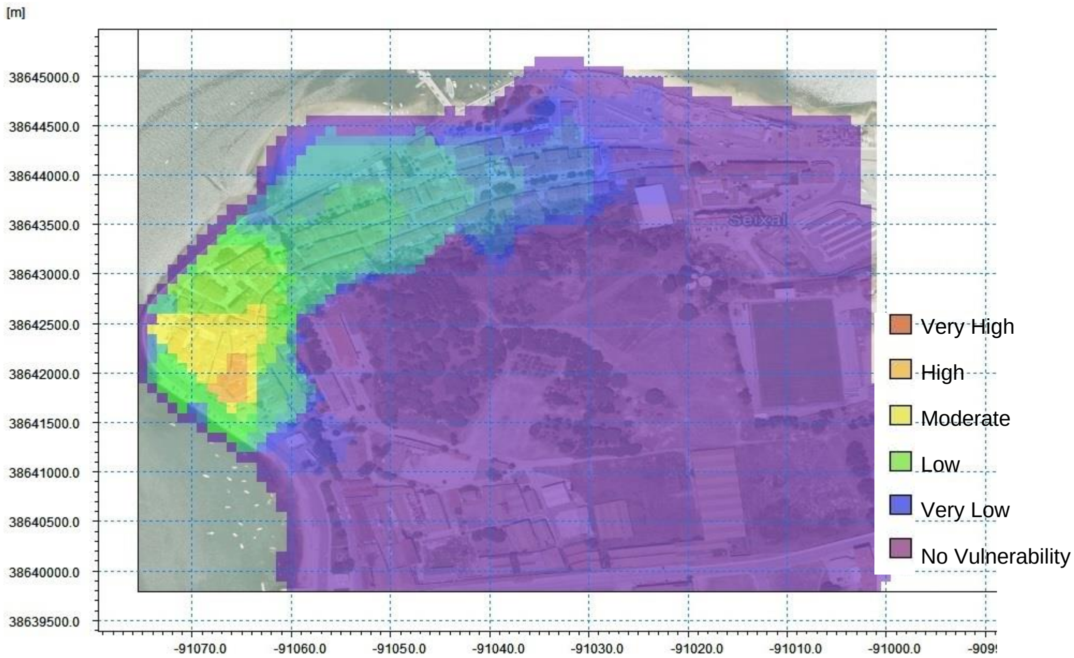

Figure 5.13 - MIKE SHE model for flood with permeable pavement technique applied

5.3 Assessment of the best scenario and influence of SUDS in flood risk

Taking into account the simulations performed for the different scenarios the flood risk areas were calculated for each situation. First it was evaluated the flood risk of the MIKE SHE model (Figure 5.6) and the results obtained are shown in Table 5.2

Table 5.2 - Flood risk of the study area

Risk	Affected area
No Vulnerability	53.47%
Very Low	18.67%
Low	18.47%
Moderate	1.10%
High	4.09%
Very High	4.20%

The results showed the probability of flooding like what would occur in nature. After the model analysis it was possible to do the same assessment for the scenarios simulation for each SUDS alternative. While visualizing the graphic models it was noticeable that the risk Very High was mitigated, so it was not considered on the following calculations.

Table 5.3 - Comparison of flood risk between different scenarios

Risk	Affected area without intervention	Affected area with infiltration trenches	Affected area with detention basin	Affected area with permeable pavement
No Vulnerability	53.47%	52.66%	50.52%	79.37%
Very Low	18.67%	19.81%	28.13%	10.72%
Low	18.47%	19.54%	19.34%	20.24%
Moderate	1.10%	3.74%	1.41%	2.20%
High	4.09%	4.26%	0.60%	0.43%
Very High	4.20%	-	-	-

The calculations (Table 5.3) showed that both techniques - detention basin and permeable pavement, have a major impact in flood risk attenuation. Although the results are acceptable, the intervention areas are considerable and may reduce the community acceptance and the economic viability. For this reason it was simulated another scenario that combined both techniques. Similarly to the previous scenarios, were selected places with space near areas with most vulnerability to flood and where the normal circulation of people and vehicles was not affected (Figure 5.14).

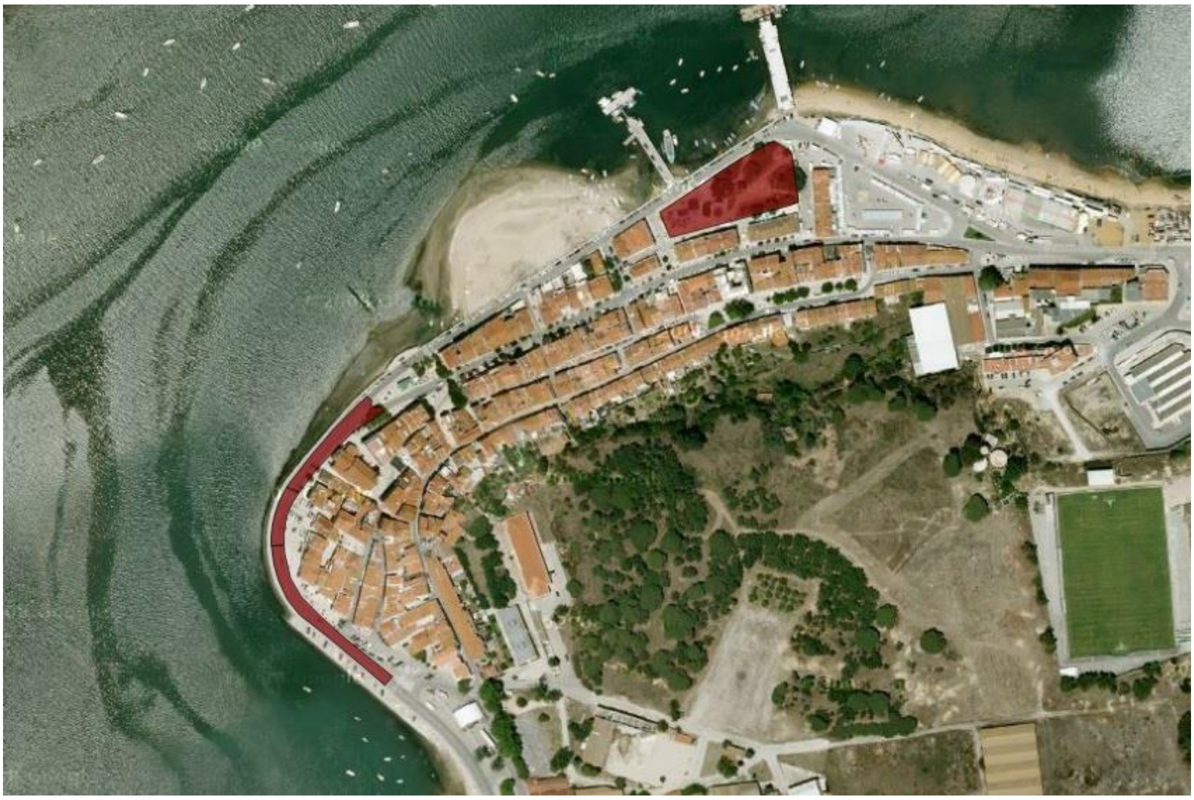

Figure 5.14 – Combination of detention basin and permeable pavement techniques applied in QGIS

After applying the combination of both techniques it was simulated a flood using the flood model (Figure 5.6) in MIKE SHE and Figure 5.15 shows the results obtained.

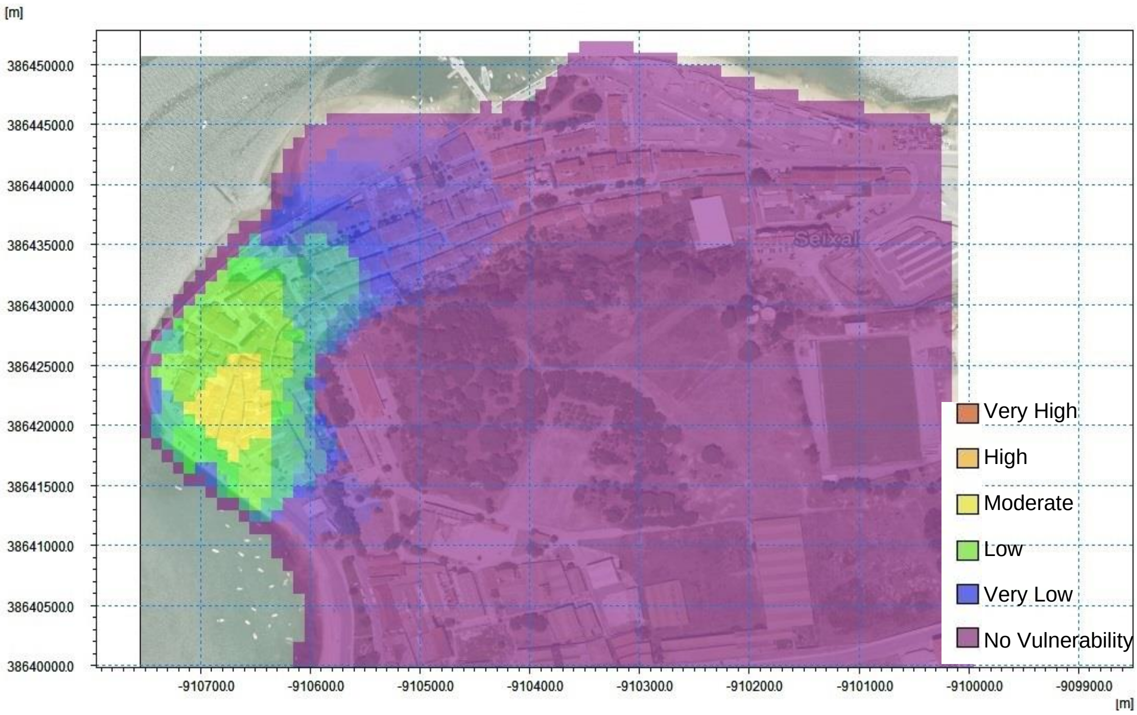

Figure 5.15 - MIKE SHE model for flood with combined techniques applied

After the model analysis it was possible to do the same comparison between the other scenarios. While visualizing the graphic model it was noticeable that for the combined scenario the risk Moderate was mitigated, so it was not considered on the following calculations.

Table 5.4 - Comparison of flood risk between different scenarios

Risk	Affected area without intervention	Affected area with infiltration trenches	Affected area with detention basin	Affected area with permeable pavement	Affected area with combined techniques
No Vulnerability	53.47%	52.66%	50.52%	79.37%	81.74%
Very Low	18.67%	19.81%	28.13%	10.72%	9.65%
Low	18.47%	19.54%	19.34%	20.24%	7.26%
Moderate	1.10%	3.74%	1.41%	2.20%	1.35%
High	4.09%	4.26%	0.60%	0.43%	-
Very High	4.20%	-	-	-	-

Under this analysis (Table 5.4) it was concluded that all the techniques are valuable for the study area since the first reaction of the model was to mitigate the risk Very High. When considered only the first three scenarios, infiltration trenches was the worse alternative and permeable pavement was the most effective technique. For both economic and viability reasons, was considered a scenario with the combination of detention basin and permeable pavement techniques, which revealed that could be a reliable option.

The calibration of the this model was done comparing it with the different guides given by DHI in their manual.

6. Economic viability of SUDS in the case study

6.1 Quantification and evaluation of flood damage

The quantification and evaluation of flood damage is an important factor to be considered in the decision process to evaluate alternative intervention strategies in terms of their relative benefits and costs, to be able to make better choices and to introduce more effective flood risk management strategies.

It is essential to consider all known types of flood damage in flood risk analysis and flood damage evaluation. It is, therefore, necessary to specify the different types of flood damage that need to be involved in the analysis. The term 'flood damage' refers to all varieties of harm caused by flooding. Flood damages are mostly categorized firstly in direct and indirect damages and secondly in tangible and intangible damages (Smith & Ward 1998; Parker et al. 1987; Penning-Rowsell et al. 2003; Messner & Meyer 2005).

Direct, tangible damages: those where the loss is due to direct contact with flood water, such as damage to buildings and their contents. These are tangible when they can be easily specified in monetary terms.

Indirect, tangible damages: losses that occur due to the interruption of some activity by the flood, e.g. the loss of production due to business interruption in and outside the affected area or traffic disruption. These also include the extra costs of emergency and other actions taken to prevent flood damage and other losses. These are tangible when they can be specified in monetary terms.

Indirect damages: losses that occur due to the interruption of some activity by the flood, e.g. the loss of production due to business interruption in and outside the affected area or traffic disruption. These also include the extra costs of emergency and other actions taken to prevent flood damage and other losses. These are tangible when they can be specified in monetary terms.

Intangible damages: Casualties, health effects or damages to ecological goods and to all kind of goods and services which are not traded in a market are far more difficult to assess in monetary terms. They are therefore indicated as "intangibles".

Table 6.1 – Typology of flood damages with examples

		Measurement	
		Tangible	Intangible (i.e. difficult to quantify)
Form of loss	Direct	Damage to building and contents	Loss of an archaeological site
	Indirect	Loss of industrial production	Inconvenience of post-flood recovery

For economic analysis of the different scenarios were considered two distinct schemes: life cost analysis and damage analysis. For the first scheme was determine the direct cost associated to each type of SUDS technique. For the damage scheme it was taken into account the worst scenario, a flood with 60cm of water high. Using a tool of floodsmart.org which estimates the damage in a residential home with approximately 90m^2 were estimated for the study area the costs that a flood like this would have. Then using the MIKE SHE model and the different simulation scenarios, was calculated the damage cost for each type of risk.

6.2 Life Cost analysis

Life Cost analysis consider all relevant and identifiable financial cash flows regarding the acquisition and use of an asset. In order to compile whole life costs, the following parameters may be required:

- Procurement and design costs;
- Capital construction costs;
- Operation and maintenance costs;
- Monitoring costs;
- Replacement or decommissioning costs.

6.2.1 Procurement and design costs

Although enabling costs will vary depending on the size of the development or scope of works, costs associated with the planning and design of SUDS are typically 15% of the capital costs (CIRIA, 2007).

6.2.2 Capital construction costs

The construction of SUDS is highly variable and depends on the proposed design and construction methods. Solutions are site-specific and heavily dependent on the size of the associated catchment area. Capital cost estimates will require consideration of the following: Site investigation costs; Design costs; Project management, planning and supervision costs; Clearance and land preparation costs; Materials; Construction costs; Design and planning of subsequent maintenance responsibility; Landscaping and planting costs (post construction).

The cost associated with land purchase may be relevant in some circumstances. Land costs can be zero where the site has dual use or where the scheme is located within public open space. However, in urban areas (our study area) the cost of land purchase can be significant. Unit costs for particular SUDS components are available in a number industry references. These have been compiled in the following table.

Table 6.2 - SUDS components capital cost ranges (adapted by CIRIA 2007)

Component	Cost	Unit
Infiltration trench	€70 – €85	/m^3 stored volume
Detention basin	€20 - €25	/m^3 detention volume
Permeable pavement	€40 - €50	/m^2 permeable surface

The above costs are provided as an indicative cost for each type of SUDS. Whilst they provide a range of costs for each type of techniques used in the case study, the costs associated with any specific site will depend on a number of factors such as: Scale and size of development; Hydraulic design criteria (design event, volume of storage required and impermeable catchment area); Inlet/outlet infrastructure design (volume and velocity of anticipated flows and the capacity of drainage system beyond site boundary); Water quality design criteria; Soil types (permeability and depth of water table), porosity and load bearing capacity; Materials availability; Specific utilities requirements; Proximity to receiving watercourse; Amenity, public education and safety requirements.

The installation of SUDS in new housing developments will not make a significant contribution to reducing existing flood risk as these systems are designed to offset the impact of the developments for a defined pluvial flood event. The ability to retrofit SUDS to existing developments has the potential to reduce urban water quality and flooding problems through the disconnection of stormwater from the normal drainage system and installing source control SUDS instead. The methods employed are similar or the same as those already discussed, but the costs may differ due to the secondary costs arising from disconnection and transfer of storm water from the existing systems. Previous studies have assumed that the secondary costs are approximately 20% of the cost of the actual SUDS construction (SNIFFER, 2006).

6.2.3 Operation and maintenance costs

Sustainable drainage systems require ongoing maintenance to ensure the system remains in good working order and the design life of the system is extended as long as possible. Operation and maintenance activities will include: monitoring and post-construction inspection, regular and planned maintenance and repair maintenance. Costs associated with maintenance will depend on the frequency of maintenance activities required. These frequencies may be specified by manufacturers for specific asset types. In the absence of these, the following maintenance items and frequencies (Table 6.3) have been based on material in the SUDS Manual (CIRIA, 2007).

Table 6.3 - Typical maintenance works and frequencies, CIRIA

Technique	Annual or sub annual maintenance	Intermittent
Infiltration trench	Monthly - litter and debris removal Annual - weed/root management Annual - removal and washing of exposed stones Annual - removal or sediment from pre-treatment devices	Replacement of filter material (20-25 years)
Detention basin	Monthly - litter and debris removal, grass cutting of landscaped areas Half yearly - grass cutting of meadow grass Annual - manage vegetation including cut of submerged and emergent aquatic plants and bank vegetation cutting	Remove sediment. Repair of erosion or other damage. Repair/rehabilitation of inlets, outlets and overflows
Permeable pavement	4 monthly - brushing and vacuuming	Stabilize and mow contributing areas, removal of weeds. Remedial work to any depressions or broken blocks. Rehabilitation of surface and upper sub-structure where significant clogging occurs. Replacement of filter material (20-25 years).

Table 6.4 indicates possible annual maintenance cost ranges, based on a review of literature and some UK costs, undertaken in 2004 by HR Wallingford.

Table 6.4 - Indicative annual maintenance cost (HR Wallingford, 2004)

Technique	Annual maintenance costs
Infiltration trench	€0.25 - €1.30 / m² of filter surface area
Detention basin	€0.15 - €0.35 / m² of detention basin area €0.35 - €1.30 / m³ of detention volume €300-€1200 per basin
Permeable pavement	€0.7 - €1.30 / m³ of storage volume

Intermittent maintenance - Intermittent operations may be needed for certain SUDS measures to ensure that they achieve the stated benefits of the works. Costs for these items are particularly site specific and variable with few real examples from which to base cost estimates on. If regular inspection and monitoring of the system is undertaken, the necessary activities and frequencies will be able to be defined more accurately for a particular system.

6.2.4 Calculated costs

For the life costs analysis were considered only the techniques tested in the MIKE SHE model, using the data given by the simulation scenarios, the results of this analysis are shown in the following tables.

Table 6.5 – Capital construction costs

Component	Cost	Unit	Case Study
Infiltration trench	€70 – €85	/m³ stored volume	€142,212.50
Detention basin	€20 - €25	/m³ detention volume	€52,643.07
Permeable pavement	€40 - €50	/m² permeable surface	€317,925.00
Combined techniques	-	-	€209,243.07

Table 6.6 – Operation and maintenance costs

Technique	Annual maintenance costs	Case Study
Infiltration trench	€0.25 - €1.30 / m² of filter surface area	€1,422.13
Detention basin	€0.15 - €0.35 / m² of detention basin area	€584.92
	€0.35 - €1.30 / m³ of detention volume	
	€300-€1200 per basin	
Permeable pavement	€0.7 - €1.30 / m³ of storage volume	€7,065.00
Combined techniques	-	€3,910.84

Table 6.7 - Secondary costs (15% of the Operation cost, CIRIA, 2015)

Component	Cost
Infiltration trench	€28,442.50
Detention basin	€10,528.61
Permeable pavement	€63,585.00
Combined techniques	€41,848.61

Secondary costs covers all labor costs, expropriation and tests.

Table 6.8 - Total Cost

Component	Cost
Infiltration trench	172,077.13 €
Detention basin	63,756.61 €
Permeable pavement	492,783.75 €
Combined techniques	255,002.53 €

Under this analysis it was concluded that the detention basin technique is the most economical even with one of the largest area. Although infiltration trench shows to be an economical technique, it was concluded previously that its capacity to reduce flood risk is inferior to the others, therefore it is not a reliable option. As presented previously the scenario with the combined techniques (combination of detention basin and permeable pavement techniques) is the best scenario for mitigate flood risk, for this reason the relation between cost/effectiveness appears to be acceptable.

6.3 Damage analysis

The damage analysis considered three main aspects: flood cost/m^2, data given by MIKE SHE model over flood risk and influence risk area.

- Flood cost/m^2: it was taken into account the worst scenario, a flood with 60 cm of water high (this data corresponds to the worst flood event in the past three years). Using a tool of floodsmart.org which estimates the damage in a residential home with approximately 90 m^2 were estimated for the study area the costs that a flood like this would have. The results showed that for this flood would cost approximately 325€/m^2. This tool considers costs involving cleaning, doors/base trim/windows, electrical and plumbing, finished floor repair, interior wall finishes, wall insulation, drywall or paneling, kitchen and bath cabinets, appliances, repairs to furnace/AC, bedroom furniture, dining room table and chairs, kitchen ware and food, living room furniture, computer accessories, television, washer machine, accent furniture and accessories, loss of personal items.
- MIKE SHE data over flood risk: it was attributed to the data of the simulation scenarios a weighting system:

Table 6.9 - Weighting system

Risk	Weight
No Vulnerability	0%
Very Low	20%
Low	30%
Medium	50%
High	70%
Very High	90%

- MIKE SHE data over influence risk area: using QGis to georeference the output images given by the simulation scenarios was possible to calculate the urban areas under the influence of the different type of risk for each scenario.

The three referred aspects were combined in order to calculate the damage cost for each scenario, as shown in the following tables. All the scenarios were compared with the MIKE SHE model that simulates flooding much like what would occur in nature (Figure 5.6).

Table 6.10 - Comparison between estimated damage costs for different simulated scenarios

Risk	Affected area without intervention	Affected area with infiltration trenches	Affected area with detention basin	Affected area with permeable pavement	Affected area with combined techniques
No Vulnerability	-	-	-	-	-
Very Low	€6.514.259	€ 3.474.910	€ 4.362.509	€ 1.812.087	€ 4.794.334
Low	€5.337.568	€ 4.957.725	€ 4.839.746	€ 5.397.790	€ 2.296.978
Moderate	€628.090	€ 1.306.412	€ 422.569	€ 1.464.443	€ 1.049.828
High	€1.931.644	€ 4.811.403	€ 1.397.274	€ 535.126	-
Very High	€5.417.045	-	-	-	-
Total	€19.928.607	€ 14.550.452	€ 11.022.099	€ 9.209.446	€ 8.141.142
Saving	-	€ 5.278.155	€ 8.806.507	€ 10.619.160	€ 11.687.464

Under this analysis (Table 6.10) it was concluded that all the techniques are valuable for the study area since all of them have a lower cost comparing with the scenario without intervention. When considered only the first three scenarios, infiltration trenches was the worse alternative and detention basin was the most effective technique. For both economic and viability reasons, was considered a scenario with the combination of detention basin and permeable pavement techniques, which revealed that could be a reliable option and less expensive.

7. Conclusions

7.1 General conclusions

The ongoing rise in sea level affects tidal propagation and circulation in estuaries, and these changes can have far reaching consequences on the sediment dynamics, water quality and extreme water levels. This dissertation aims at analyzing the evolution of prone to flood areas in Seixal bay and covers the application of sustainable urban water drainage systems towards a more efficient way for flood mitigation. The study was conducted with a MIKE SHE model, forced by present and future conditions. The impacts of climate change on estuaries should be anticipated in order to allow the implementation of adaptation measures and to inform decision-makers about possible interventions. This paper contributes to this anticipatory procedure in the case of the Seixal bay.

The simulations undertaken in this study show that SUDS application in the case study would have significant effects on flood mitigation. In the case of a combination of two techniques this effects would be particularly substantial due to the decrease of prone to flood areas.

MIKE SHE software has important characteristics that helped in this study: simulates water movements from different sources, under different soil layers and pre-established time steps, which allows to compare different flood models in the same study area; takes into consideration various characteristics such as topography, precipitation, existence of rivers nearby and soil specific proprieties. In this work was possible to test flood models in the same restricted area, just by taking in consideration the same boundary conditions.

In order to calibrate and validate the model successfully, it is important that the input data, in terms of rainfall, and calibration data, i.e. observed discharge, must be reliable and correct. As there is no guarantee for this problem may be one of many reasons for the bad correlation shown in some results during model validation.

Some difficulties of a proper model representation could also be explained by some software restrains: the data to define a model requires point/line shapefile or grid-file format, which implies a considerable work changing data in software like ArcGis; the model requires a considerable number of different parameters to be assigned in every grid cell, which implies many parameter values to be set - naturally, this involves great effort for setting up the model; to optimize the model is necessary to run it several times manually, adjusting values iteratively in order to obtain results similar to what would occur in nature – besides being a time consuming process, it was difficult to obtain sufficient amount of real data (the immense requirement of input data is sated as one of the main reasons for the difficulty of using MIKE SHE); the system depends on the definition of simulation time and time step which is an equally iterative process and there are frequent errors that inhibit the calibration; representing the influence of the Tagus river was a complicated task since it was not possible to describe all of the tidal system, for this reason it was necessary to admit a rather simple model with a constant flow represented in the boundary conditions of the study area; fully integrated model, including groundwater component, is crucial for evaluating the hydrological effects of urbanization and SUDS if sub-domain response of heterogeneous land use is to be taken into account.

7.2 Further developments

Although this work has covered a wide range of scenarios and sensitivity analyses of several parameters there are some more analyses that would be interesting to perform.

Concerning the case study area it would be relevant in future works to prepare a model of the riverside area around the municipality of Seixal in parallel with a model that simulates the Tagus river behavior and its impacts in the area. An analysis with a major scale might be a study with potential to be submitted to the authorities being led to appreciation as a possible investment in flood mitigation.

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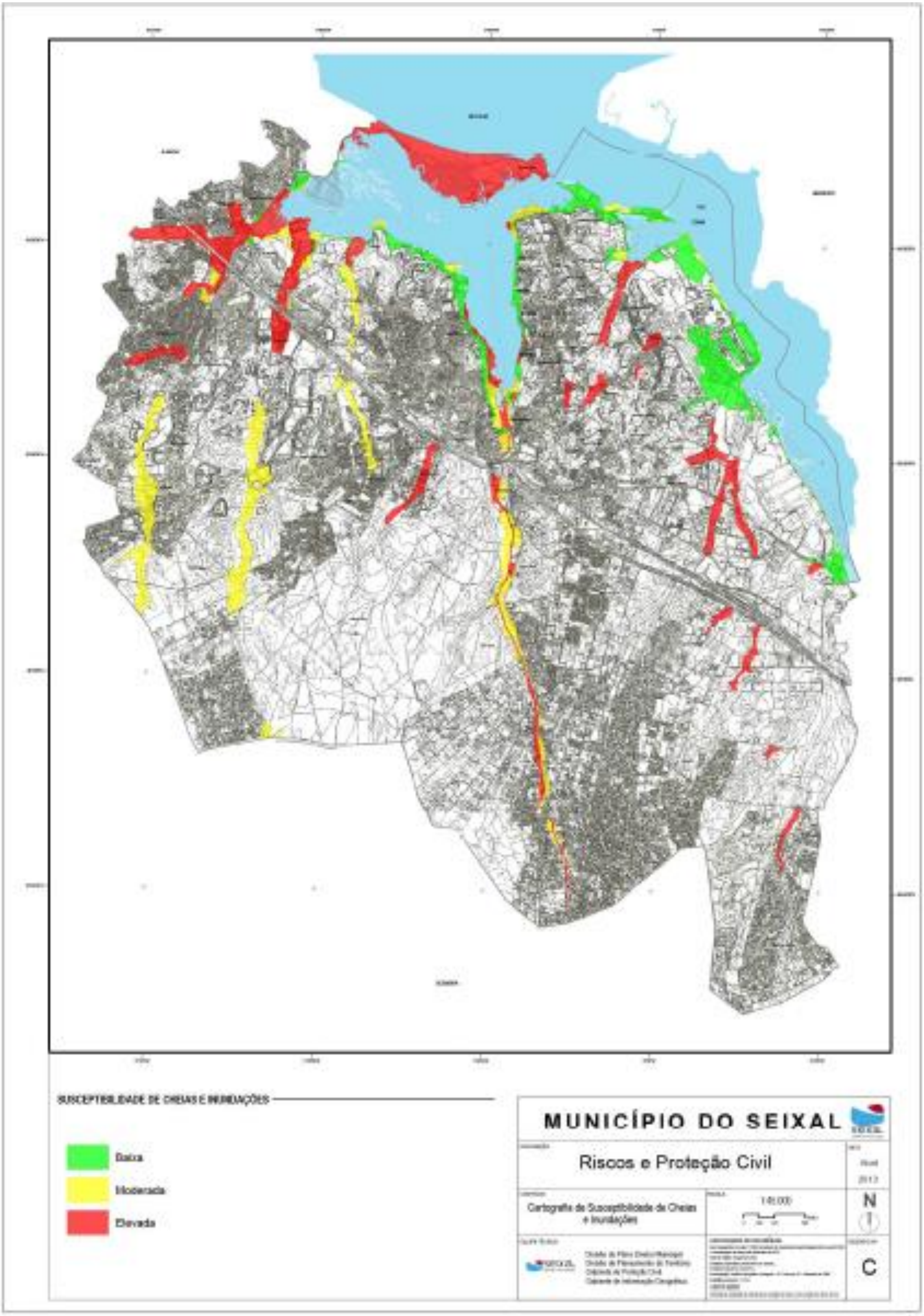
Appendices

APPENDICE 1


SUSCEPTIBILIDADE DE CHEIAS E INUNDAÇÕES
Baixa
Moderada
Elevada
MUNICÍPIO DO SEIXAL
Riscos e Proteção Civil
Cartografia de Suscetibilidade de Cheias e Inundações
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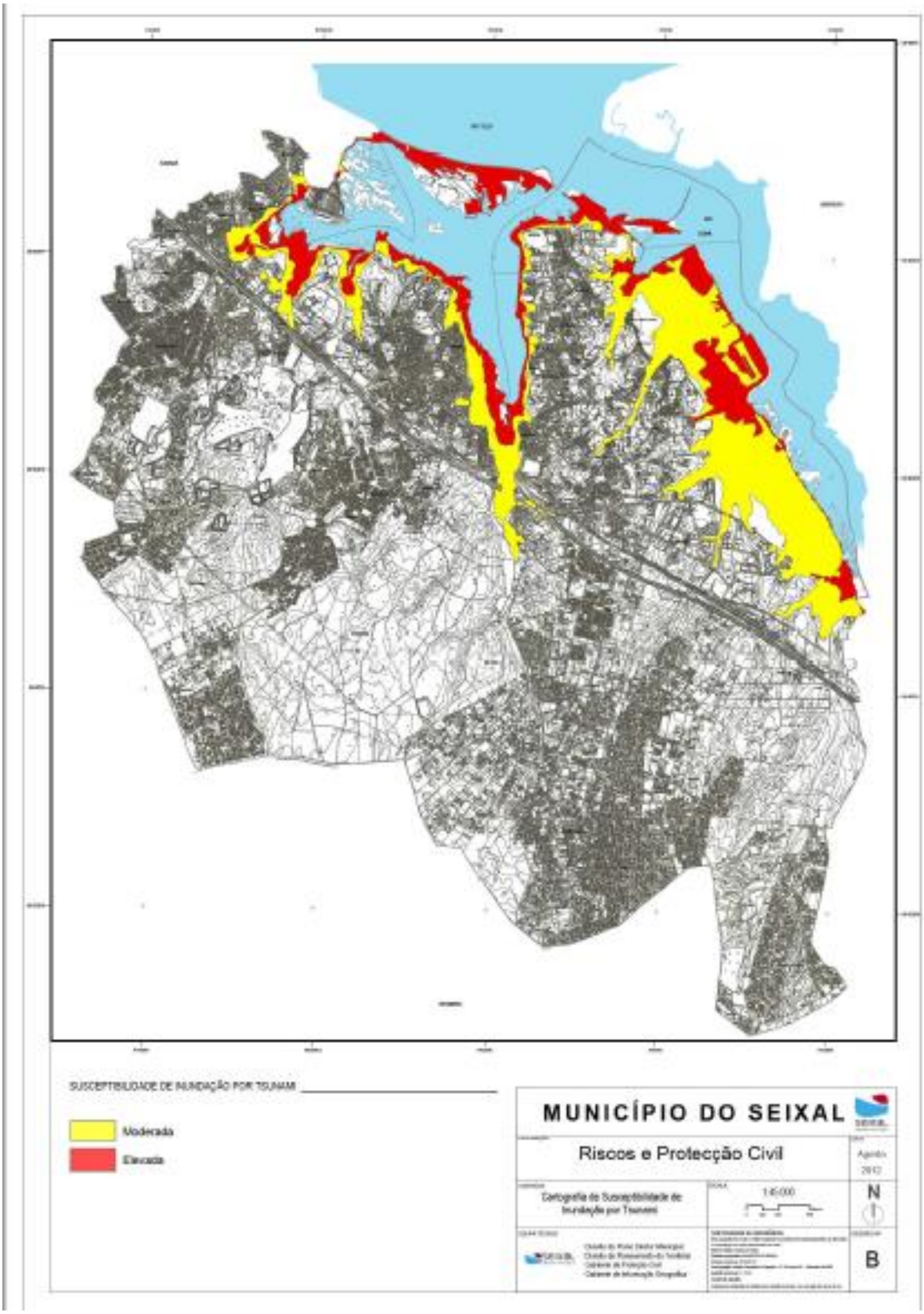
APPENDICE 2


SUSCEPTIBILIDADE DE INUNDAÇÃO POR TSUNAMI
Moderada
Elevada
MUNICÍPIO DO SEIXAL
Riscos e Protecção Civil
Cartografia de Susceptibilidade de Inundação por Tsunami
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APPENDICE 3

Flood cost	€/m^2	325

No intervention scenario:

id	AREA		
No vulnerability	30271.16	30271.16	0.140073
Very Low	44202.81	100219.4	0.463741
Very Low	29536.3		
Very Low	26480.26		
Low	16453.38	54744.29	0.253316
Low	38290.91		
Medium	2112.969	3865.169	0.017885
Medium	1752.201		
High	6289.817	8490.743	0.039289
High	2200.926		
Very High	18519.81	18519.81	0.085696
total		216110.5	

id	% Area	Influenced area	Flood probability	Estimated cost
No vulnerability	14.01%	30271.16065	0	- €
Very Low	46.37%	100219.3706	0.2	6,514,259.09 €
Low	25.33%	54744.29053	0.3	5,337,568.33 €
Medium	1.79%	3865.169434	0.5	628,090.03 €
High	3.93%	8490.743164	0.7	1,931,644.07 €
Very High	8.57%	18519.81494	0.9	5,417,045.87 €
			Total	19,828,607.39 €

Detention basin scenario:

id	AREA		
No vulnerability	18448.46	18448.46	0.128164
Very Low	46982.57	67115.53	0.466259
Very Low	20132.96		
Low	42602.62	49638.42	0.344844
Low	7035.807		
Medium	2600.426	2600.426	0.018065
High	6141.867	6141.867	0.042668
total		143944.7	

	% Area	Influenced area	Flood probability	Estimated cost
No Vulnerability	12.82%	18448.4624	0	- €
Very Low	46.63%	67115.52979	0.2	4,362,509.44 €
Low	1.81%	49638.42383	0.3	4,839,746.32 €
Medium	1.81%	2600.425781	0.5	422,569.19 €
High	4.27%	6141.867188	0.7	1,397,274.79 €
Very High	0.00%	0	0.9	- €
			Total	11,022,099.73 €
			Saving	8,806,507.65 €

Infiltration trenches scenario:

id	AREA		
No vulnerability	45341.87	45341.87	0.253535
Very Low	27666.58	53460.16	0.298929
Very Low	25793.58		
Low	33052.75	50848.47	0.284325
Low	17795.72		
Medium	4687.618	8039.461	0.044954
Medium	2666.438		
Medium	685.4048		
High	21149.03	21149.03	0.118257
total		178839	

	% Area	Influenced area	Flood probability	Estimated cost
No Vulnerability	25.35%	45341.86572	0	- €
Very Low	29.89%	53460.16162	0.2	3,474,910.51 €
Low	28.43%	50848.46631	0.3	4,957,725.47 €
Medium	4.50%	8039.461426	0.5	1,306,412.48 €
High	0.00%	21149.02686	0.7	4,811,403.61 €
Very High	0.00%	0	0.9	- €
			Total	14,550,452.06 €
			Poupança	5,278,155.33 €

Permeable pavement scenario:

id	AREA		
No vulnerability	62004.01	62004.01	0.395918
Very Low	5241.089	27878.26	0.178013
Very Low	22637.17		
Low	45878.91	55361.95	0.353506
Low	9483.038		
Medium	9011.958	9011.958	0.057545
High	2352.204	2352.204	0.01502
TOTAL		156608.4	

	% Area	Influenced area	Flood probability	Estimated cost
No Vulnerability	39.59%	62004.00586	0	- €
Very Low	17.80%	27878.2627	0.2	1,812,087.08 €
Low	35.35%	55361.9502	0.3	5,397,790.14 €
Medium	5.75%	9011.958008	0.5	1,464,443.18 €
High	1.50%	2352.203613	0.7	535,126.32 €
Very High	0.00%	0	0.9	- €
			Total	9,209,446.72 €
			Poupança	10,619,160.67 €

Combined techniques scenario:

id	AREA		
No vulnerability	60632.28	60632.28	0.368786
Very Low	40817.2	73759	0.448627
Very Low	24536.64		
Very Low	8405.158		
Low	9674.144	23558.76	0.143292
Low	13884.61		
Medium	6460.485	6460.485	0.039295
Total		164410.5	

	% Area	Influenced area	Flood probability	Estimated cost
No Vulnerability	36.88%	60632.28125	0	- €
Very Low	44.86%	73758.99902	0.2	4,794,334.94 €
Low	14.33%	23558.75733	0.3	2,296,978.84 €
Medium	3.93%	6460.485352	0.5	1,049,828.87 €
High	0.00%	0	0.7	- €
Very High	0.00%	0	0.9	- €
			Total	8,141,142.65 €
			Poupança	11,687,464.74 €