Water sensitive cities:

A vision for Lisbon’s Alcântara watershed

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"No problem can be solved by the same kind of thinking that created it."

Albert Einstein

ABSTRACT

Cities are emerging as humanity's habitat of choice, as they are vital for social, political and economic transformation. However the development of cities has often been characterised by short-term economic benefit and environmentally unsustainable consumption and production practises. Over the last few decades there has been an increase in the number of natural disasters and in the number of people affected by natural disasters, many of which are water-related, such as flooding or water scarcity events. This has been shown to be as a result of three main factors: climate change, rapid urbanisation, and the resultant settlement of people in at-risk areas. The strategic spatial planning of urban development can be an important tool in addressing the exposure of people and places to environmental risks, and in designing a more resilient city that employs flexible solutions to cope with an uncertain and changing future.

This thesis focuses on the use of sustainable urban water management (SUWM) strategies as a tool to design water sensitive cities that are more resilient to water-based hazards, support human and ecological needs, and are appropriate to their geographic and climatic context. The thesis analyses the different known SUWM strategies, including Best Management Practises (BMPs), Sustainable Drainage Systems (SuDS), Water Sensitive Urban Design (WSUD), and Nature-Based Solutions, and proposes an integrative approach that employs concepts and measures from each one. The case study for this thesis is the Alcântara watershed in Lisbon, Portugal. An analysis of the historical, ecological and anthropic factors affecting water management in the case study area is undertaken, followed by a proposal for the sustainable management of water resources in the city of Lisbon and its surroundings.

275 words

Keywords: Water sensitive cities; Resilient cities; Sustainable Urban Water Management; Floods and water scarcity; Alcântara valley

RESUMO

As cidades estão a emergir como o habitat preferencial da humanidade, uma vez que são essenciais para a evolução social, política e económica das sociedades. Contudo, os processos de urbanização têm sido caracterizados pela procura de benefícios económicos a curto-prazo e por práticas de produção e consumo pouco sustentáveis. A par desta crescente urbanização, ao longo das últimas décadas tem-se registado um aumento na frequência e no número de pessoas afectadas pelos desastres naturais, em particular os relacionados com a gestão da água (i.e. cheias ou secas). Isto deve-se a três factores principais: as alterações climáticas, a urbanização desregrada e a fixação de pessoas em zonas de risco. Assim, o ordenamento do território constitui uma ferramenta indispensável para os processos de urbanização que identifica a exposição de pessoas e bens a riscos ambientais e que apoia a concepção de cidades resilientes que possam dar uma melhor resposta a um futuro cada vez mais incerto.

A presente tese investiga o uso das soluções de controlo na origem como ferramenta para a gestão sustentável da água nas cidades e para a criação de 'water sensitive cities'; cidades com melhor capacidade de adaptação a riscos urbanos relacionados com a gestão da água, que providenciam recursos hídricos para pessoas e ecossistemas e que são desenhadas de forma adequada ao seu contexto geoclimático. A tese investiga as diferentes estratégias de soluções de controlo na origem, incluindo Best Management Practises (BMPs), Sustainable Drainage Systems (SuDS), Water Sensitive Urban Design (WSUD) e Nature-Based Solutions, sendo proposta uma abordagem que integra as várias estratégias. O caso de estudo é o vale de Alcântara em Lisboa, para o qual é desenvolvido uma análise dos factores históricos, ecológicos e antrópicos relevantes para a gestão de água, seguido de uma proposta para a gestão sustentável da água nesta bacia.

298 palavras

Palavras chave: 'Water sensitive cities'; cidades resilientes; soluções de controlo na origem; cheias e secas; Vale de Alcântara

RESUMO ALARGADO

Ao entrarmos no século XXI, mais de metade da humanidade vive em cidades e cerca de 200 mil pessoas migram para centros urbanos diariamente. Porém, esta realidade, impulsionada pela busca de transformação socioeconómica, geração de riqueza, prosperidade e desenvolvimento, tem resultado de igual forma num modelo de urbanização com práticas de produção e consumo desenfreadas, com consequências prejudiciais e insustentáveis para o meio ambiente, em particular no que diz respeito ao ciclo da água. Nas cidades, as superfícies impermeabilizadas e a reduzida quantidade de vegetação implicam uma menor taxa de infiltração e evapotranspiração, o que resulta num volume grande de escoamento superficial de baixa qualidade, o denominado *stormwater*, que pode causar cheias, poluição e erosão. A ameaça de desastres naturais de origem climática é também ampliada nas zonas urbanas, não só devido a estas alterações ao ciclo da água, mas também devido à densidade deste aglomerados, traduzindo-se num maior número de pessoas em risco. De facto, tem-se registado um aumento na incidência global de desastres naturais, bem como no número de pessoas afectadas por estes. Cerca de 70% dos desastres naturais são de origem climática (Tibaijuka, 2009), a maior parte dos quais relacionados com a água, sendo que a incidência de cheias e secas tem-se tornado maior em décadas recentes (Schneider, 2016).

De forma a abordar estas questões, foi desenvolvido e implementado em várias cidades ao longo do século XIX e XX um sistema de drenagem e abastecimento que providencia três serviços centrais: água potável, higiene urbana e proteção contra inundações. Esta infraestrutura tem sido eficaz na eliminação da maior parte dos problemas de água e saneamento das cidades, em particular nos países mais desenvolvidos. Contudo este sistema de gestão de água urbana tem sido sujeito a crítica devido a três factores principais, nomeadamente elevados custos de implementação e manutenção, um funcionamento dependente de elevadas quantidades de água, promovendo o desperdício de recursos e, finalmente, um dimensionamento estático que é feito para uma determinada população e um determinado volume de precipitação, calculado a partir de um período de retorno fixo. A natureza estática do dimensionamento desta infraestrutura limita a sua adaptabilidade a pressões externas, que incluem o aumento populacional, a urbanização e as alterações climáticas.

No que diz respeito ao aumento populacional e à urbanização, a população mundial continua a crescer e estima-se que atingirá 9,2 mil milhões até 2050, o que representa um aumento de 20% relativa à população atual de 7 mil milhões. A maior parte deste crescimento populacional concentrar-se-á em cidades de países em desenvolvimento, sendo 6,4 mil milhões o número global de habitantes urbanos projetado para 2050. A tipologia de cidade mais afectada será zonas urbanas de pequena a média dimensão, a maior parte das quais se encontram na Ásia e África (Smith, 2012, p. 32-35). Estimativas recentes apontam para a falta de planeamento em 95% do crescimento urbano nessas cidades (Gentleman, 2007). Este facto aponta para a forte possibilidade de que no futuro sejam ocupadas zonas menos favoráveis à urbanização, que acarretam maior susceptibilidade a riscos ecológicos (e.g. leitos de cheia).

No que diz respeito às alterações climáticas, sabe-se que o clima está a mudar devido ao aumento da concentração de gases com efeito de estufa e ao aumento global de temperaturas associado. Isto deve-se em grande medida à actividade humana, em particular o consumo de combustíveis fosseis e alterações à ocupação do solo. As presentes alterações climáticas apontam para a possibilidade de uma maior frequência de eventos climáticos extremos no futuro, em particular eventos relacionados com a água, uma vez que as alterações climáticas alteram os padrões de disponibilidade de água e intensificam o ciclo da água. Assim, antecipa-se um aumento de áreas propícias a seca e um aumento na frequência e intensidade de eventos de precipitação extrema (IPCC, 2013; Stern, 2006).

O aumento populacional, a urbanização e as alterações climáticas também agravam substancialmente as consequências dos desastres naturais. De acordo com White (2010, p.17), “podemos dizer de forma inequívoca que a humanidade tem sido progressivamente condicionada pela geografia e pelo clima através de um aumento no volume de pessoas sujeitas a situações de risco e de uma forma de estruturar a sociedade que se encontra dissociada da natureza; complexa, interligada e vulnerável.”

As soluções apresentadas face aos eventos climáticos extremos relacionados com a água nas cidades dos países desenvolvidos centram-se na abordagem tecnocêntrica descrita previamente e que aborda estes riscos a partir de um sistema de engenharia defensivo ou através de ferramentas económicas (e.g. seguros). Contudo, a maior incidência de exposição a desastres naturais tem vindo a expor as limitações desta abordagem à gestão de água urbana. A experiência demonstrou que as defesas projetadas, e mesmo as reservas de água, podem falhar, já que o risco nunca pode ser totalmente excluído de um sistema (White, 2010). Embora estas soluções de infraestrutura urbana sejam fundamentais no abastecimento de água potável, prevenção de cheias, drenagem e saneamento, carecem da flexibilidade necessária para responder a desafios futuros e têm frequentemente custos sociais, económicos e ambientais avultados. Assim, têm sido propostas soluções que se afastam de uma estratégia de defesa e se aproximam da acção e gestão proactiva dos recursos hídricos urbanos. Esta abordagem integraria infraestruturas centralizadas e estratégias descentralizadas de gestão de água pluvial (Gleick, 2003). O ordenamento do território representa uma ferramenta fundamental no desenvolvimento destas soluções, abordando a questão da exposição de pessoas e bens a riscos ambientais, tanto presentes como futuros, de forma prioritária.

As denominadas *water sensitive cities* representam uma forma urbana que proporciona uma gestão mais proactiva e sustentável dos recursos hídricos urbanos. Na *water sensitive city*, a gestão de água urbana dá resposta a necessidades humanas e ecológicas e a cidade é desenhada de uma forma apropriada ao seu contexto geográfico e climático. Esta abordagem visa restaurar o ciclo de água urbano a um estado mais resiliente através da promoção dos processos de controlo na origem, tratamento de águas pluviais e infiltração. Simultaneamente a água é valorizada como um recurso e é aproveitada para criar espaços verdes atraentes para as pessoas e habitats naturais para a flora e fauna selvagem, sustentando ainda a infraestrutura verde da cidade. A *water sensitive city* promove uma forma urbana resiliente que mais facilmente se adapta a futuros incertos. O termo *sustainable*

urban water management (soluções de controlo na origem) é utilizado para definir o conjunto de estratégias que promove o desenvolvimento das *water sensitive cities*.

O objectivo desta tese é examinar como as soluções de controlo na origem, em conjunto com estratégias de base ecológica de ordenamento do território, podem contribuir para o desenho de uma cidade mais sustentável no que diz respeito à gestão de água pluvial, tendo em vista a promoção das denominadas *water sensitive cities*.

A tese está organizada em duas partes, teórica e prática. Na parte teórica é abordada a questão da gestão de água nas cidades, expondo os principais desafios que actualmente se fazem sentir nesta área. A gestão da água é um tema complexo que não pode ser dissociado do seu contexto socioeconómico e que é afectado por processos políticos, objectivos urbanísticos, investimentos privados e pelas atitudes e comportamentos das pessoas. Desta forma, tanto medidas estruturais (e.g. ordenamento do território) como não estruturais (e.g. investimento na educação e sensibilização) podem ser importantes na gestão integrada da água. Neste sentido, as soluções de controlo na origem apresentam-se como medida estrutural e de planeamento que, associadas às estratégias tradicionais de drenagem da cidade, podem contribuir para essa gestão. Na parte teórica da tese são apresentadas as diferentes estratégias de soluções de controlo na origem, que incluem: Best Management Practises (BMPs), Sustainable Drainage Systems (SuDS), Water Sensitive Urban Design (WSUD) e Nature-Based Solutions. A estratégia proposta nesta tese representa uma visão integrativa das estratégias apresentadas, adoptando conceitos e medidas associados a cada uma delas.

Na parte prática da tese é apresentado um caso de estudo, o vale de Alcântara em Lisboa. É feita uma análise dos factores históricos, ecológicos e culturais que informam a gestão da água, seguida de uma proposta para a implementação de soluções de controlo na origem e para a gestão integrada do recurso água. Esta proposta tem por objectivo a criação de uma cidade mais resiliente, onde a água é vista como um recurso e não como um obstáculo que deve ser descartado o mais rapidamente possível. As soluções apresentadas procuram restituir o ciclo natural da água, através de medidas que procuram reduzir a área impermeabilizada, promover a infiltração e evapotranspiração e investir no tratamento da água pluvial com plantas macrófitas. A proposta visa igualmente a criação de espaços públicos de recreio e de lazer que melhorem a qualidade de vida das pessoas, promovam a biodiversidade e consolidem os corredores verdes da cidade.

1446 palavras

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LIST OF ABBREVIATIONS

BMPs	Best Management Practices
ETAR	Estação de Tratamento de Águas Residuais (Water Treatment Station)
LID	Low Impact Development
Ma	Million Years Ago
SuDS	Sustainable Drainage Systems
SUDS	Sustainable Urban Drainage Systems
SUWM	Sustainable Urban Water Management
TSS	Total suspended solids
UHIE	Urban heat island effect
WSUD	Water Sensitive Urban Design

CHAPTER 1

INTRODUCTION

Cities are the places where the majority of the global population is choosing to live. This is largely because they are vital for generating prosperity and improving standards of living, and have become a hub for physical, economic, social, political and cultural capital (White, 2010). Urban living provides many benefits by agglomerating people and resources, but it also brings about significant changes to the ecological functioning of the landscape, in particular with regards to the water cycle. The paved surfaces of cities and the reduced amount of vegetation means there is less infiltration and less evapotranspiration, which results in a large volume of low-quality surface runoff, known as stormwater, which can cause flooding, pollution and erosion. Cities also amplify the threats of climate-related natural hazards, not only because of these changes in the urban water cycle, but also because of the density of these settlements, meaning that more people can be at risk. Indeed, a rise in the global incidence of natural disasters has been recorded, as well as a rise in the number of people affected by these, suggesting increased exposure through settlement in at-risk areas. Around 70% of the disasters that affect people and the planet are climate related (Tibaijuka, 2009), and water based hazards are at the forefront of these, with the incidence of flooding and water scarcity events having become commonplace over recent decades (Schneider, 2016).

In an effort to deal with these issues, the 19th and 20th century saw the development and implementation of a drainage and supply system that provided three central services – water supply, public hygiene and protection against flooding – in many of the world's cities. This system has been largely successful in solving most of the water and hygiene-related problems of cities, in particular in more developed countries. However this system of urban water management has high investment and maintenance costs and relies on large quantities of water to work, resulting in an inefficient use of resources. It has also been incurring increasing economic, social and environmental costs as a consequence of pressures on the system, including an ageing infrastructure, a growing population, expanding cities, and climate change.

With regards to population growth and urbanisation, the world's total population is continuing to rise, and is estimated to reach 9.2 billion by 2050, representing a 20% increase from the current 7 billion. Most of this population growth will be concentrated in cities and in the developing world, with the global number of urbanites projected to reach 6.4 billion by 2050. The type of city that will be most affected by this growth is not existing mega cities, but the small to medium sized urban areas, most of which will be in Asia and Africa (Smith, 2012, p. 32-35). It is estimated that only 5% of building work that takes place in the world's expanding cities is planned (Gentleman, 2007), so it can be expected that in the future these cities will expand into areas that are less desirable for urbanisation, and in many cases, can be ecologically unfavourable, such as floodplains.

With regards to climate change, it is known that our climate is changing due to an increase in atmospheric concentrations of greenhouse gases and the resulting global increases in temperature. This is largely caused by human activities, in particular the burning of fossil fuels and land use changes. These changes to the Earth's climate can lead to changes in the likelihood of occurrence and/or in the strength of extreme weather events. Water based hazards are at the forefront of these extreme events, as climate change will alter patterns of water availability by intensifying the water cycle. As a result it is projected that there will be an increase in land areas exposed to drought and an increase in the frequency and intensity of heavy rainfall events (IPCC, 2013; Stern, 2006).

These three factors also critically aggravate the consequences of natural disasters. According to White (2010, p.17), "we can unequivocally say that humanity is becoming increasingly subject to the constraints of geography and climate via a rise in the volume of people exposed and a way of structuring society that is detached from nature; complex, interconnected and vulnerable."

Solutions to problems of water-related hazards in the urban areas of developed countries have traditionally focused on the technocentric approach described above, addressing these risks through the use of a defensive engineering approach or through the availability of economic tools such as insurance. However this approach to urban water management is being questioned in the face of the rising incidence of exposure to natural disasters. Experience has shown that engineered defences or even water supplies can fail, as risk cannot be completely designed out of a system (White, 2010). Although these structural "hard path" solutions have been fundamental in providing safe drinking water, flood protection, drainage and sanitation, they lack the flexibility required to cope with future challenges, and have often had substantial social, economic, and environmental costs. In light of this, a move away from defence towards proactive action and management of urban water resources has been proposed. This "soft path" solution could continue to rely on carefully planned and managed centralised infrastructure, but would also complement it with small-scale decentralised facilities (Gleick, 2003). Spatial planning can provide an important tool in moving towards this goal through the strategic planning of urban development, addressing the exposure of people and places to environmental risks, both present and future, as a priority concern.

The design of water sensitive cities has been proposed as a way of moving towards a more proactive and sustainable management of urban water resources. In a water sensitive city, urban water management supports both human and ecological needs, and the city is designed in a way that is appropriate to its geographic and climatic context. This approach aims to restore the urban water cycle to a more resilient state by promoting the processes of source control, stormwater treatment and infiltration. At the same time, water is viewed as a resource and used to create attractive spaces for people, habitats for wildlife, and is used to support the city's green infrastructure. The water sensitive city provides a more resilient urban form that can better adapt to uncertain futures.

The aim of this thesis is to examine how sustainable urban water management strategies, together with spatial planning strategies that incorporate ecological principles, can contribute to the design of a water sensitive city. A practical case study is developed for the city of Lisbon and part of Amadora and Odivelas, focussing on the largest watershed of the city, the Alcântara watershed. The structure of this thesis is organised as follows:

- In Chapter 2, the theoretical concepts behind sustainable urban water management are explored. First, the challenges inherent to the current urban water management paradigm are discussed. From here, the different sustainable urban water management strategies that have been developed around the world are introduced: Low Impact Development, Best Management Practises, Sustainable Drainage Systems, and Water Sensitive Urban Design. The guiding principles of these strategies are considered, followed by an analysis of the technical components that are available to move towards a water sensitive city. These techniques are selected from the different sustainable urban water management strategies, and a unique 'toolbox' that combines the most relevant techniques is proposed. Finally, three case studies are presented where sustainable urban water management has been successfully implemented.
- Chapter 3 consists of the development of a practical case study for the Alcântara watershed. First, the methodological foundation is discussed. This is followed by the presentation of a site assessment, which includes an analysis of the historical, ecological, and anthropic factors affecting the watershed. Finally, a watershed- and city-wide strategic plan is proposed with the goal of making Lisbon a more resilient city in terms of water management. This includes the identification of potential intervention sites and the development of a green infrastructure to complement and support these intervention sites.
- In Chapter 4 a proposal is outlined for these intervention sites, representing a vision for the city of Lisbon in moving towards a water sensitive city.

The emergence of cities as humanity's habitat of choice has appeared in current environmental debates as both a problem and a solution: although rapid and unplanned urbanisation can pose an environmental threat, as well as a risk to inhabitants, urban forms offer an efficient way of living, by agglomerating people and resources, that other forms of settlement do not (Tonkiss, 2013, p. 113). Although cities are unnatural and even 'parasitical landscapes' that consume resources and produce waste, they also have an inherent capacity to adapt given their "dynamic nature as centres for social and economic activity, the existence of networks, and the availability of all types of capital, governance institutions and knowledge" (White, 2010, p. 35). Cities are perceived as the primary mechanism for achieving an improved quality of life, and the vision is that economic growth or standards of living do not have to be sacrificed in order to pursue an environmentally sustainable agenda, which seeks to reduce the risk of water hazards in the city through careful spatial planning. With the use of technology and knowledge, cities can adapt to the challenges of our time, and continue to generate prosperity through a model that considers economic, social, and environmental costs, with a view to working towards humanity's long-term interests.

CHAPTER 2

WATER MANAGEMENT IN URBAN AREAS

2.1 THE NATURAL AND URBAN WATER CYCLES

2.1.1 The natural water cycle

The water cycle describes the continuous movement of water on Earth, whether it is in a liquid, solid (i.e. ice) or vapour state. The major reservoirs of water are oceans, ice masses and snow deposits, terrestrial waters, the atmosphere and the biosphere (Peixoto and Oort, 1992). Water moves between the different reservoirs by the processes of precipitation, infiltration, evaporation, condensation, surface runoff and subsurface flow (Figure 2.1).

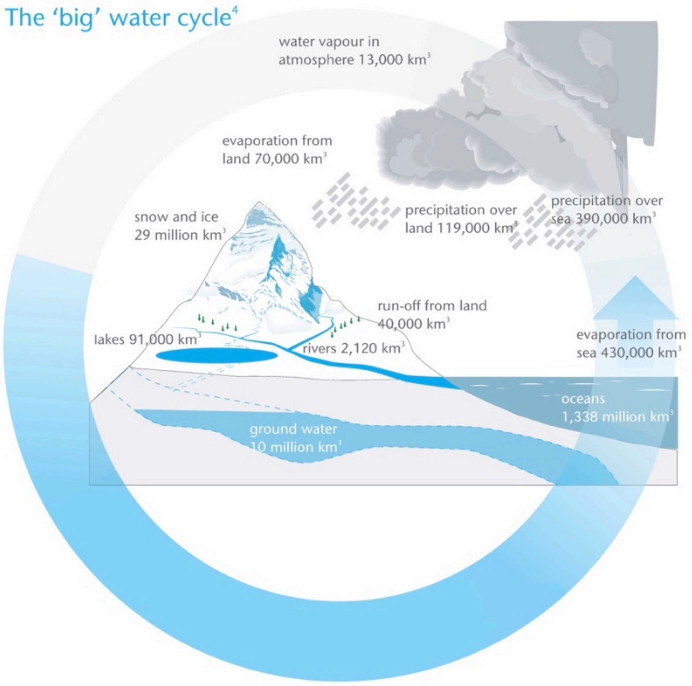

Figure 2.1 The water cycle (World Business Council for Sustainable Development, 2005)

Measuring where water is in the hydrological cycle is not an easy task. It is estimated that 97% of the world’s water is seawater or salty groundwater, and less than 3% is freshwater. Of this 3% of freshwater, over 2.5% is frozen, locked up in glaciers or in Antartica or the Arctic, and about 0.5% is available freshwater, held in aquifers, rainfall, natural lakes, reservoirs, and rivers (Figure 2.2) (Gleick et al., 1993). However, as water is a circulating resource, knowing the throughput or flux of water is just as important as knowing the absolute quantities held in the different reservoirs. For example, a drop of water moves down a natural river in a few days, whereas a drop of water that moves through a glacier, groundwater, or deep ocean current could take hundreds of thousands of years to complete its cycle. This is why rainfall and surface water, with their fast throughput, are so valuable to us, even though their storage capacity is so small. Also, it is these small storage capacities that make terrestrial life so vulnerable to the smallest variations in throughput, which are ultimately experienced as floods or droughts (Smith, 2012).

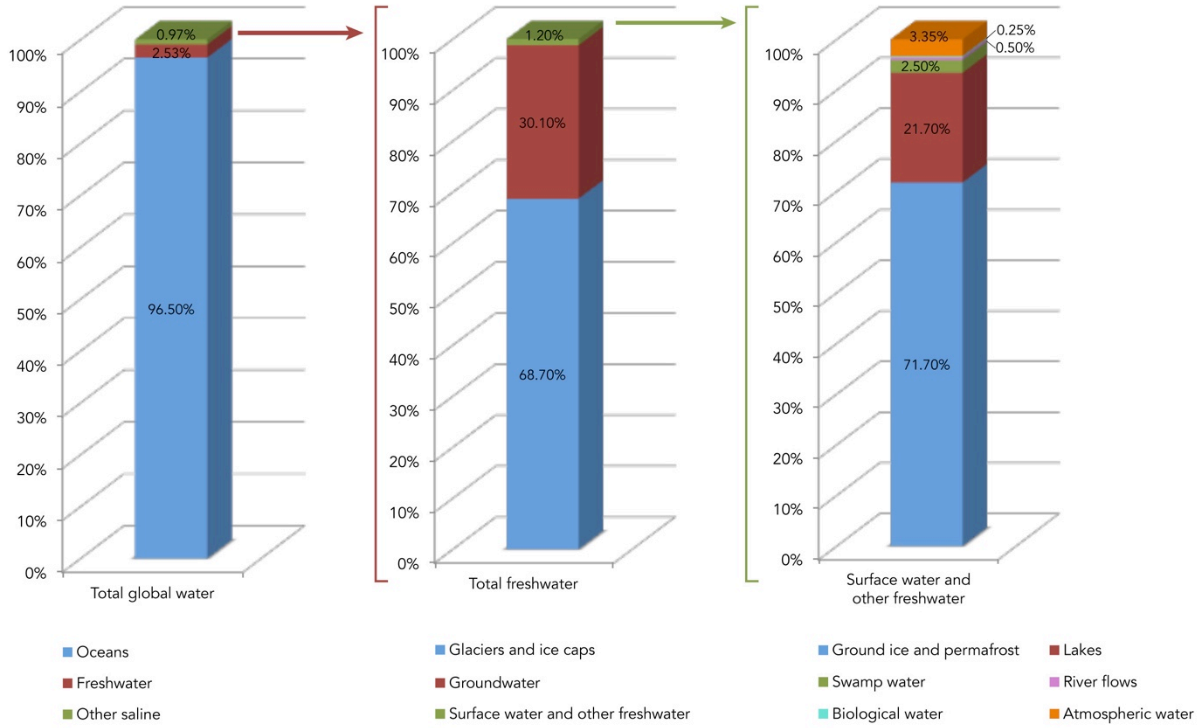

Figure 2.2 Distribution of Earth's water reserves (Adapted from Gleick et al., 1993, p. 13)

Another disparity related to the water cycle is the distribution of this fast-recycling freshwater around the planet, which in turn can be explained by the pattern of atmospheric circulation, one of the most powerful shapers of climate and ecosystems on Earth (Smith, 2012). Atmospheric circulation is the large-scale movement of air that, together with the ocean circulation system, allows thermal energy to be distributed on the surface of the Earth (Hartmann, 1994). The three-cell model of atmospheric circulation (Figure 2.3) is a simplified model that describes the redistribution of energy from areas of surplus (the tropics) to areas of deficit (the polar areas) through convection cells. The sun heats the equatorial regions more than the polar regions, causing warm air to rise at the equator and travel to around 30º latitude, where it cools and sinks, finally returning to the equatorial region. The rising and expanding air at the equator causes an area of low pressure, and the denser sinking air at 30º causes an area of high pressure. This convection cell is known as the Hadley cell, and is a thermally direct cell (BBC, 2016). The evaporation of huge quantities of water vapour over the equator makes this region very humid and is also responsible for triggering the Asian and African monsoons. Conversely, sinking air is usually dry and free of precipitation, which is why many desserts, such as the Sahara, Arabian, Australian, Kalahari, and Sonoran, are found around 30º North and South latitude (Smith, 2012). At the Poles, cold air sinks and travels to around 60º latitude, where it is warmed and rises; this convection cell is called the Polar cell and is also thermally direct. The Ferrel cell is powered by the Hadley and Polar cells, and is thermally indirect, as it transports energy from a cold area to a warm area (Hartmann, 1994).

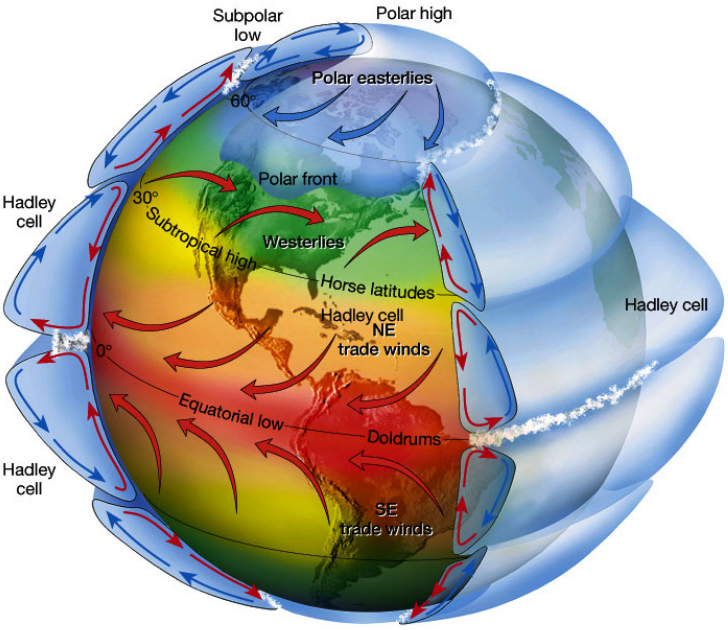

Figure 2.3 Idealised, three-cell atmospheric convection in a rotating Earth (Lutgens and Tarbuck, 2001)

Having seen that superficial freshwater, in the form of lakes, wetlands, and rivers, as well as the atmosphere's clouds, vapour and rain, make up a very small fraction of available freshwater, and that this water is unevenly distributed across the globe, it is important to note that our knowledge on the global dynamics of where, when or how much of this superficial freshwater water we have at any given moment is extremely poor (Smith, 2012). Satellite remote sensing provides a unique platform for providing this kind of information, however, monitoring and prediction systems for terrestrial hydrology have, until recently, been developed at resolutions (10-100 km) that do not adequately address critical water cycle science questions and applications. A new generation of satellite missions are being developed that will provide hydrological data on the storage, movement, and quality of water near the land surface with a much higher resolution, in the order of 100 m - 1 km, (Wood et al., 2011). One of these missions is the Surface Water and Ocean Topography (SWOT) mission, a collaboration between NASA and CNES, the French Space Agency, as well as other international partners, which is set to be launched in 2020. SWOT will provide high-resolution global measurements of water storage changes in all wetlands, lakes and reservoirs around the globe, as well as of ocean surface topography (Srinivasan, n.d.). These hydrological models will address emerging societal needs for information about water on a global scale, informing activities such as reservoir operations, irrigation scheduling, and flood and drought management. The data they will provide on ocean currents, which influence patterns of rainfall and temperature change, will be important in enabling improved weather and marine forecasts (Servir Global, 2015). The data provided by the SWOT mission will be particularly important in providing information on the discharge of water that feeds floods, especially for large river basins in developing countries, such as the Nile, Niger, Mekong, Indus, Ganges, Salween and Zambezi river basins, where there is insufficient ground data on water levels and where, when the data is available, it is not usually shared between countries (Servir Global, 2015; Wood et al., 2011). Additionally, these high-resolution hydrologic models will be important in providing improved data on urban hydrology, such as the effects of impervious areas on heat flows, infiltration, groundwater recharge, and flooding. A major challenge will be representing the geometry and functioning of the subterranean man-made infrastructure for drinking water, stormwater runoff and sewage, which affect water distribution both locally and far away from urban centres (Wood et al., 2011).

2.1.2 The urban water cycle

The urban water cycle differs fundamentally from the natural water cycle as a result of a higher proportion of impervious areas and a lower proportion of vegetation. This results in less groundwater infiltration and evapotranspiration, which contributes to increased and more rapid surface water runoff (Figure 2.4). This runoff, known as stormwater, is a product of urbanism, and can cause flooding, pollution and erosion (Susdrain, 2012; Woods Ballard et al., 2015).

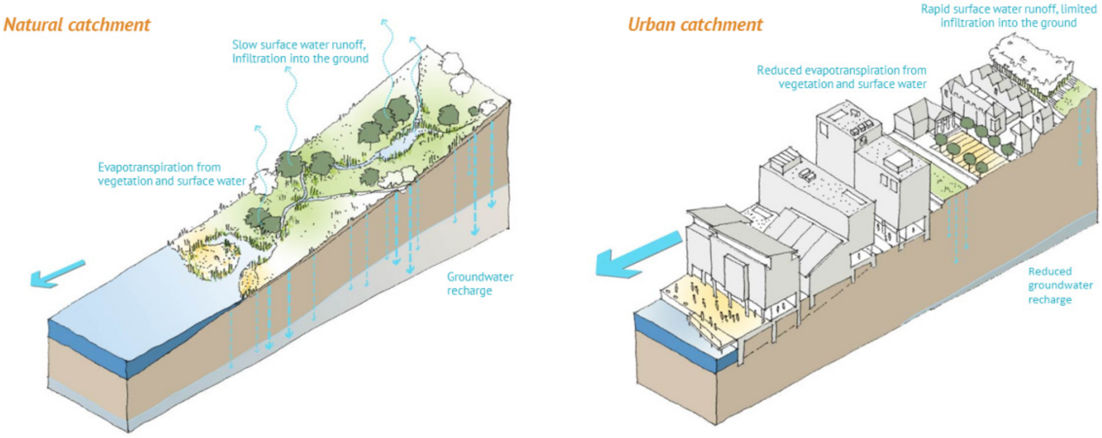

Figure 2.4 Schematic representation of a natural and urban water catchment (Susdrain, 2012)

The urban water cycle can be characterised by (a) water supply and distribution systems, (b) wastewater collection, and (c) stormwater drainage. The term *urban drainage* refers to both (b) wastewater collection and (c) stormwater drainage. Wastewater is water that “after use for life support, industrial processes or life enhancement must be collected and disposed of appropriately" and stormwater is runoff produced by precipitation (Burian and Edwards, 2002).

2.1.3 Urban drainage: from 3000 BC to today

Evidence of urban drainage dates back to around 3000 BC; ancient civilisations such as the Indus, Persians, the Mesopotamian Empire, Minoans, Etruscans, and Romans developed urban drainage systems to collect rainwater, prevent nuisance flooding, and convey wastes (Burian and Edwards, 2002). Following the fall of the Roman Empire, many cities in Europe and Asia shrank as people migrated away from the cities; urban drainage systems were not improved and were even neglected during the 'Dark Ages', most notably in Europe. During the nineteenth century, however, with scientific evidence linking sanitary waste and disease transmission, the public perspective of urban drainage shifted from "a neglected afterthought to a vital public works system" (Burian and Edwards, 2002). In 1843 William Lindley planned and designed the sewer system in Hamburg, Germany, becoming the first comprehensively planned sewerage system for a major city. This led the way for the design of other comprehensively planned sewerage systems in the second half of the nineteenth century in cities such as London, Chicago and Brooklyn (Burian and Edwards, 2002).

This period was a critical turning point in the history of urban drainage, as the concept of urban drainage was no longer limited to stormwater, but included sanitary wastewater. This change in approach resulted in the development of combined water and foul sewerage systems, known as 'combined sewers' (Faram et al., 2010). Another important shift at this time relates to the fact that sewerage systems began to be designed by engineers using numerical calculations, as opposed to through a trial-and-error process (Burian and Edwards, 2002).

More recently, in the mid-20th century, it has been regarded as 'more sustainable' to separate wastewater (foul sewage) and stormwater in two parallel drainage systems, even though this solution comes at great expense, as two drainage systems use more energy and resources (Chocat et al., 2007; Faram et al., 2010). This approach seeks to minimise the flows that are sent to the water treatment facilities, and sends the (presumably clean) stormwater directly to a watercourse (Chocat et al., 2007). Although these 'separate sewer systems' now represent the most common approach, being employed in many modern cities and in most post-1940s developments, it has been found to be too simplistic. On the one hand, stormwater is an important carrier of pollutants such as trace organics, heavy metals, nutrients (particularly phosphorus), contaminated sediments, complex organics and pathogens, and its direct discharge into watercourses is an important source of watercourse pollution (Chocat et al., 2007). On the other hand, it is not uncommon to have incorrect or cross connections between the two systems, leading to a surcharging of the foul system or to entry of foul sewage into the stormwater system, leading again to watercourse pollution (Faram et al., 2010). Also, the foul sewage system uses large amounts of (potable) water to convey the pollutants to the treatment facility.

Conventional urban drainage today continues to be largely focussed on the two main objectives of public hygiene and flood protection, albeit with environmental protection gaining increasing importance. Systems are designed to collect and convey stormwater runoff and wastewater away from urban areas as quickly and efficiently as possible (Chocat et al., 2007; Zhou, 2014). The impervious surfaces in urban areas (e.g. roads, driveways and roofs) lead to an increased volume of surface water runoff, with faster arriving flows and higher peak flows. Stormwater is drained as quickly as possible out of the urban area and into a receiving body of water, be it a river, lake, or the sea. Ultimately, the speed at which the water is transported means that flooding and erosion of the watercourse downstream is more likely to occur (Chocat et al., 2007). It also means that this runoff is transported at a faster rate to the sea, which, particularly in coastal cities, means the loss of a potential freshwater resource to a saltwater reservoir. Finally, it also results in lower groundwater levels, as natural infiltration rates are reduced.

As urban areas develop and expand, the pressure on these drainage systems increases; larger areas of impermeable surface cause increased volumes of stormwater, and the increase in population number and density results in higher volumes of wastewater. The quality of urban water systems is also impaired as changes in land use, such as removal of vegetation, use of impervious pavements, and clearance and filling of natural ponds and streams can increase the amounts of pollutants (Zhou, 2014). The response to these pressures has tended to be reactive, focussing on 'end-of-pipe' solutions that increase the size of sewers (Faram et al., 2010).

Climate change is also increasing the pressure on drainage infrastructure, as changes in frequency, intensity and spatial patterns of temperature, precipitation and other meteorological phenomena, such as wind and cloud cover, are expected to occur on a global scale. Although we know that global warming and the resulting climate change will have an effect on stormwater management in the future, it is difficult to quantify this effect precisely (Sieker et al., 2008). Nonetheless, it is possible to identify some of the key impacts of climate change on urban areas (Annex 1), bearing in mind the fact that the type of impact, their directionality and magnitude will differ around the globe (Dawson, 2007).

Indeed, it has been widely recognised that cities need to be more resilient to uncertain futures (Chocat et al., 2007; Faram et al., 2010; Gleick, 2003; Sieker et al., 2008); current thinking is more focussed on the concept of resilience than sustainability, as this concept is more likely to be realisable (Faram et al., 2010). Future approaches to urban drainage must be flexible, reversible, renewable, and abandonable where necessary, providing diversity within the system and allowing for uncertainty (Faram et al., 2010). It has been shown that conventional drainage systems, which are capital intensive, centralised infrastructural solutions, fail under these criteria, as they are inflexible, lack diversity, and are difficult to renew unless at a high cost (Faram et al., 2010). Apart from lacking flexibility, large-scale 'hard' infrastructure such as dams, aqueducts, pipelines, and complex centralised treatment plants have had serious and often unanticipated social, economical and ecological costs, such as the displacement of people, the threat of extinction of freshwater fauna populations, as well as reduced flows in many of the world's rivers, leading to nutrient depletion, loss of habitat and erosion (Gleick, 2003).

The need for flexibility in urban water management systems is corroborated by a recent study which states that stationarity, the idea that natural systems fluctuate within an unchanging envelope of variability, is no longer a valid concept for use in water resource management: “In view of the magnitude and ubiquity of the hydroclimatic change apparently now under way, (…) we assert that stationarity is dead and should no longer serve as a central, default assumption in water-resource risk assessment and planning” (Milly et al., 2008). Stationarity has been a foundational concept in water-resource engineering, informing the planning and building of critical infrastructure such as bridges, dams, and urban drainage systems, to name a few. It also makes the insurance industry work, and supports building codes in places prone to fires, flooding, hurricanes and earthquakes (Smith, 2012). There is a growing body of evidence showing that the core assumption that statistics of past behaviour will also apply in the future is starting to break down, mainly due to climate change, but also as a result of other factors such as urbanisation, changing agricultural practises, and climate oscillations such as El Niño (Smith, 2012). Taking into account the need to find alternative models to address uncertainty (Dawson, 2007; Evans et al., 2004), Milly and colleagues (2008) state “now is an opportune moment to update the analytic strategies used for planning such grand investments under an uncertain and changing climate”.

2.1.4 The future of urban drainage

In view of increasing water scarcity due to a growing world population, it has been noted that water must be regarded “not only as a fundamental human right, but also as a cornerstone for economic, health and food security” (Chocat et al., 2007). Indeed, Vörösmarty et al. (2000) show that, contrary to common perception, population growth and industrialisation represent an even bigger challenge to the global water supply than climate change. The authors carried out a study to quantify the contributions of climate change and development pressure on the degree of relative water demand in 2025, measured as the ratio of aggregate upstream water use relative to discharge. The results for three scenarios are shown in Figure 2.5, where red indicates an increase in water demand relative to today, blue indicates lower relative water demand, and green indicates little or no change in relative water demand (Smith, 2012).

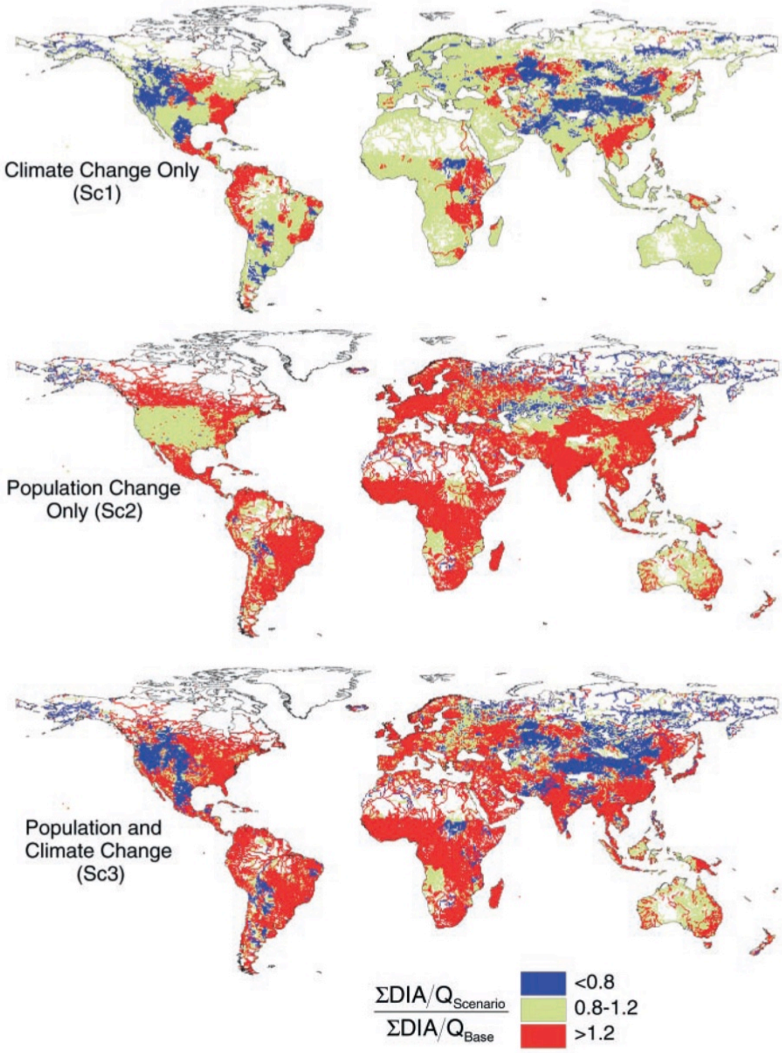

Figure 2.5 The projected effects of climate change (Sc1), population and economic development (Sc2), and the combined effects of climate change and population and economic development (Sc3) on relative water demand in 2025 (Vörösmarty et al., 2000)

The authors conclude that the major increases in relative water demand predicted by this study will present "substantial challenges to water infrastructure and associated water services" in much of the world, calling on the need for an integrated approach that brings together climate change, water resources, and socioeconomic communities as an essential step for future progress.

In light of these pressures on water resources, Chocat et al. (2007) develop a scenario for the optimal, yet realistic, future of urban water management. The authors begin by describing four possible scenarios for the future provision of urban drainage services (summarised in Annex 2) which all have significant limitations; the first three expose the limitations of over simplistic solutions or of radical change, and the fourth shows that the current path of urban drainage should not continue (Chocat et al., 2007). For the industrialised world, the authors state that an optimum scenario probably consists of a combination of the four scenarios described.

Importantly, the authors highlight the differences between industrialised nations, with fully functional water management systems, and developing and emerging countries, where this is not the case and where any interventions would have to start from an entirely different baseline. Currently, one in ten people globally do not have access to improved drinking water sources, and three in ten people are without improved sanitation facilities (UNICEF and World Health Organization, 2015). Lack of access to these resources is mostly felt in African and Asian regions. Accordingly, Figure 2.6 shows the regional distribution of the 9% of the global population that do not have access to improved drinking water, and the 32% of the global population that do not have access to improved sanitation (Annex 3 presents this data spatially and Annex 4 highlights the progress that has been made in this area between 1990 and 2015).

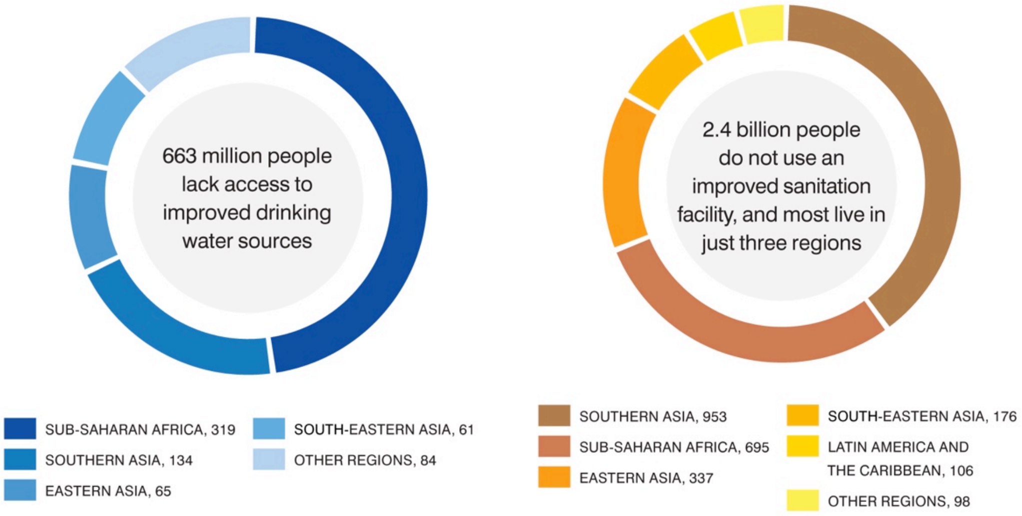

Figure 2.6 Population (in millions of people) without improved sources of drinking water and without improved sanitation in 2015, by region (UNICEF and World Health Organization, 2015)

Chocat et al. (2007) note that developed world technologies are unlikely to be installed in developing countries in the near future due to their high economic, human and resource cost, and that solutions in these regions will have to be adapted and take into account the characteristics of the individual situation in order to have the most success. Here, it will be important to provide easily repairable technologies, employment opportunities for local inhabitants, and basic education for installers and operators (Chocat et al., 2007).

In the industrialised world, the authors suggest that “the key feature of any optimum drainage solution (…) is the fusion of the existing traditional technology with recent technological achievements, taking due account of the individual and local community”. Decentralised stormwater treatment should form the foundation for a successful and realistic future vision, along with the utilisation of this treated water at the local level, wherever practicable, and the use of localised surface drainage networks. For this to be successful, however, it will require technological development and greater individual and community responsibility. The authors note that storm and sanitary wastewaters provide a resource opportunity, and so should be viewed as ‘opportunity’ water rather than as ‘waste’ water.

According to Chocat et al. (2007), flexible institutional arrangements and increased water awareness among all stakeholder groups are two important factors in bringing about water security, even more so than scientific and technological changes. This includes ensuring water professionals are competent and up-to-date, but also that residents try to minimise pollution in household effluent. Giving more responsibility to individuals and local communities is crucial to the success of decentralised water treatment solutions, albeit through the enforcement of an inspection and incentives system (Chocat et al., 2007).

2.2 SUSTAINABLE URBAN WATER MANAGEMENT

The term Sustainable Urban Water Management (SUWM) has been adopted in this thesis[1] to describe the cohort of water management strategies that have the common goal of activating natural water processes in the urban landscape. These strategies aim to promote the retention, infiltration and evaporation of stormwater, while simultaneously addressing water quality, biodiversity and visual amenity. They include Best Management Practises (BMP) or Low Impact Development (LID), developed in the USA, Sustainable (Urban) Drainage Systems (SuDS or SUDS), developed in the UK, Water Sensitive Urban Design (WSUD), developed in Australia, and nature-based solutions, a European Union Research and Innovation policy agenda. In this section each of these SUWM strategies are described, and their common guiding principles discussed. Each of these strategies comprises a number of technical components. Here, a new framework is presented that selects and integrates a number of these techniques. Finally, an analysis of the benefits and limitations of SUWM is presented.

2.2.1 International strategies

2.2.1.1 Low Impact Development and Best Management Practices

Low Impact Development (LID) is a site design strategy that aims to maintain or replicate the predevelopment hydrologic regime through integrated and distributed micro-scale stormwater retention areas, reduction of impervious surfaces, and the lengthening of flow paths and runoff time (US EPA, 2000). Allied to these strategies, LID also seeks to protect and preserve environmentally sensitive site features such as riparian buffers, wetlands, steep slopes, valuable trees, flood plains, woodlands and highly permeable soils (US EPA, 2000).

LID techniques designed to capture stormwater and reduce flow rate and volume are also used as stormwater best management practices (Palhegyi, 2010). The term Best Management Practices (BMPs) was coined in the 1980s to describe acceptable practises that could be implemented to protect water quality and promote soil conservation, and is currently used in stormwater management to describe control measures that seek to mitigate changes to the quantity and quality of urban runoff (North Carolina Forestry Service, 2016). BMPs can refer to a structural technique, such as a retention pond or green roof, or a non-structural technique, which refers to procedures such as modified landscaping practises.

LID uses decentralised micro-scale techniques to control stormwater at the source, and are categorised into runoff volume reduction functions and pollutant filtering functions. LID also seeks to incorporate the principles of conservation of natural features, minimisation of impervious surfaces, hydraulic disconnects, disbursements of runoff, and phytoremediation (US EPA, 2000). LID

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[1] The first reference to this term was found in Larsen & Gujer (1997)

techniques include bioretention facilities or rain gardens, grass swales and channels, vegetated rooftops, rain barrels, cisterns, vegetated filter strips, and permeable pavements.

2.2.1.2 Sustainable (Urban) Drainage Systems

Sustainable Drainage Systems (SuDS), or Sustainable Urban Drainage Systems (SUDS), mimic nature by managing rainfall when and where it falls, optimising the opportunities and benefits that can be obtained from surface water management (Woods Ballard et al., 2015). SuDS are a surface water management approach that address water quantity, water quality, biodiversity, and amenity (Figure 2.7), thus seeking long-term solutions in the water management process that address both environmental and social factors.

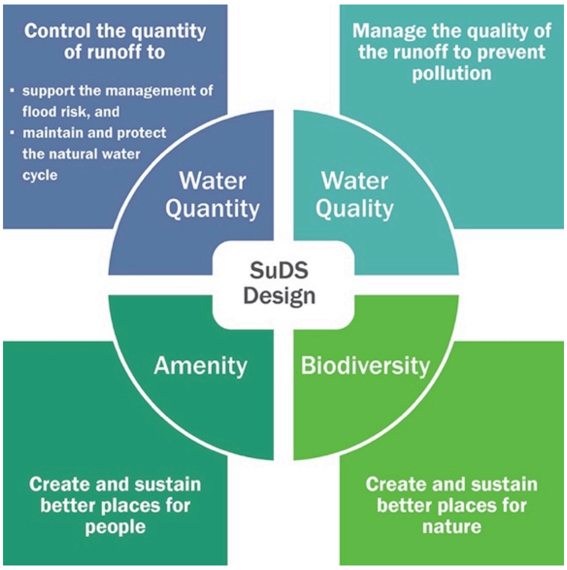

Figure 2.7 The four pillars of SuDS design

SuDS can be characterised as management practises, control structures, and strategies that aim to drain surface water in an efficient and sustainable way that will minimise pollution and avoid detrimental impacts on local biodiversity (Susdrain, 2012). SuDS can take many forms, but in general the most beneficial systems are designed to manage rainfall close to where it falls, on the surface, and incorporating vegetation (Woods Ballard et al., 2015). These solutions include managing runoff volumes and flow rates, protecting channel stability, developing ecosystem integrity and attractive habitats, recharging groundwater where appropriate, improving evapotranspiration, as well as creating better places for people to live, work and play (Medina et al., 2011; Susdrain, 2012).

SuDS techniques are described in a sequence of components known as the Management Train (Table 1). Collectively, these components control runoff frequencies, flow rates, and volume of runoff, and reduce concentrations of contaminants to acceptable levels (Woods Ballard et al., 2015).

Conveyance features also provide the opportunity to maximise the benefits to wildlife and people by serving as habitat corridors as well as by providing potential green spaces for recreational use.

Indeed, the design of SuDS should not be viewed as isolated features in the urban environment, but should be linked with existing or proposed habitat networks, creating or improving wildlife corridors.

Table 1 Stages in the SuDS Management Train

Management Train Stage	Function	Techniques
Prevention	Using design to prevent pollution from entering the system	Road sweeping Separating clean runoff (ex. roofs) from contaminated runoff (ex. car parks)
Source control	Ensures silt and pollution does not enter the management train and controls the flow and quality of water for use further downstream.	Green roofs Living walls Rain gardens Permeable surfaces Filter strips Bioretention areas
Site control	SuDS features within or at the edge of developments that provide secondary or tertiary treatment stage, as well as temporary storage for runoff.	Detention basins
Regional control	Manage large volumes of relatively clean runoff in temporary basins. Last water quality treatment before discharge into wider catchment.	Retention basins and associated wetlands
Conveyance features	Above-ground features that link components of the management train.	Swales and channels

As much as possible, SuDS design should rely on the following principles: using surface water as a resource; managing rainwater close to where it falls and on the surface; promoting infiltration and evapotranspiration; slowing and storing runoff to mimic natural runoff characteristics; reducing contamination of runoff; and treating runoff to reduce the risk of urban contaminants (Woods Ballard et al., 2015).

2.2.1.3 Water Sensitive Urban Design

Water Sensitive Urban Design (WSUD) is a term developed in Australia that proposes a catchment-wide approach to sustainably integrate water management into the urban environment (Figure 2.8). WSUD employs principles and practises borrowed from the natural environment in order to promote evapotranspiration, infiltration of rainfall, and conveyance of stormwater runoff. Surface systems incorporated within the urban environment enable the natural filtering and cleaning of water (Hoban and South East Queensland Healthy Waterways Partnership, 2007; Zhou, 2014).

WSUD is also committed to overtly communicating the resource value and life-sustaining qualities of water through building and landscape design, as well as reconnecting individuals and local communities with the management of their own water supplies, reducing reliance on imported water resources. (Hoban and South East Queensland Healthy Waterways Partnership, 2007).

Figure 2.8 The Water Sensitive Urban Design concept (Morgan, 2013)

WSUD acknowledges that urban planning and development have a profound effect on aquatic ecosystems, and that ageing water services infrastructure, as well as institutional arrangements, can cause inefficiency and vulnerability in the system (Hoban and South East Queensland Healthy Waterways Partnership, 2007). To address these issues, Brown et al. (2008) have proposed a framework for informing the development of long-term sustainable urban water management policy. This framework is intended as a benchmarking tool that will help build a clear vision regarding the attributes of a sustainable water city. It provides a typology of past and present hydro-social contracts in Australian cities, as well as proposing potential future visions based on sustainability principles, identifying six cumulative transition states in the development of sustainable urban water management (Figure 2.9). It is hoped that this framework will provide cities with the tools to assess progress towards sustainable urban water management, and thus help to understand the strategies that can most successfully be adapted and applied in different cities, each with their unique temporal, biophysical and institutional contexts (Brown et al., 2008).

As explained by Brown and colleagues (2008), institutions comprise three mutually reinforcing pillars that, collectively, shape patterns of practise. These are: (i) cognitive, referring to dominant knowledge and skills; (ii) normative, referring to values and leadership; and (iii) regulative, relating to administration, rules and systems. In order to bring about institutional change, all three of these pillars must be addressed in a mutually reinforcing fashion; for example, interventions focused on educating people about sustainable water management (cognitive pillar) which are not backed up by changes to how people value water (normative pillar) or to the rules they must follow (regulative pillar) will not be successful in bringing about institutional change. The ‘Cumulative Socio-Political Drivers’ in Figure 2.9 reflect changes in the normative and regulative dimensions of the hydro-social contract, and the ‘Service Delivery Functions’ refers to the cognitive response.

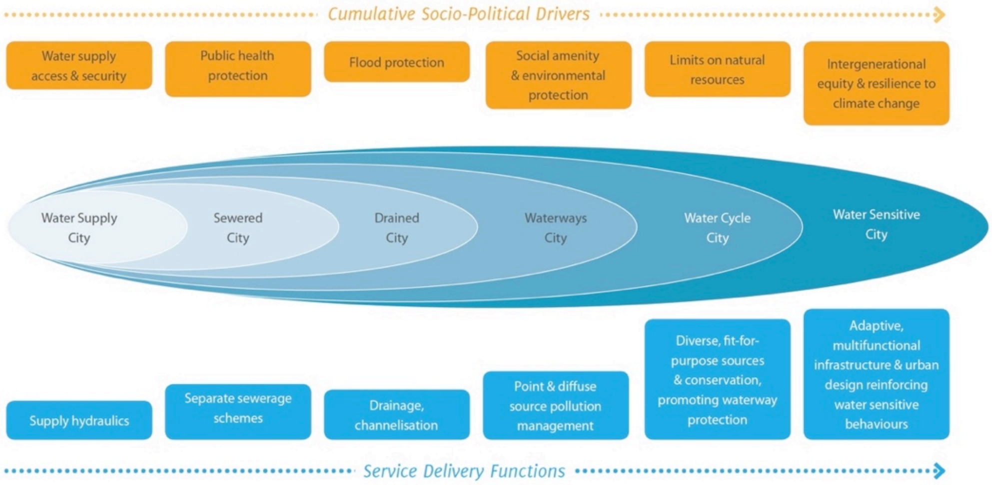

Figure 2.9 Key transitional stages to a Water Sensitive City (Hoban and South East Queensland Healthy Waterways Partnership, 2007)

The first three transition states were developed following a systemic review of historical scientific literature on the development of modern urban water systems in Australia since the 1800s (cognitive pillar), as well as an analysis of policy (regulatory pillar) and media documentation (normative pillar). The ‘Waterways City’ and part of the ‘Water Cycle City’ evolved from a second research phase which investigated the current barriers and drivers to advancing sustainable urban water management across Australian cities, and the remainder of the ‘Water Cycle City’ and the ‘Water Sensitive City’ transition states evolved from a projection of the future socio-technical factors that will be required for the institutionalisation of sustainable urban water management across Australia. Following the research phase, a number of large-scale stakeholder validation activities showed that the proposed transitions framework has potential applicability in the European context, given the historical and cultural commonalities in management practises between Europe and Australia (Brown et al., 2008).

The final stage in the transition continuum, the Water Sensitive City, should ensure environmental repair and protection, water supply security, public health and economic sustainability through water-sensitive urban design, enlightened social and institutional investment in water management, and diverse and sustainable technology choices (Hoban and South East Queensland Healthy Waterways Partnership, 2007). Although this transitions framework remains a hypothesis, it nonetheless is intended to inform the design of transitions policy and change management strategies (Brown et al., 2008).

As seen in Figure 2.8, the design objectives of WSUD include water conservation, wastewater minimisation, and stormwater management, and in order to achieve these goals, WSUD employs a range of best planning practises and best management practises.

Best Planning Practises (BPPs) relate to site assessment, planning, and design components, and provide advice on applying WSUD to (1) steep and undulating sites; (2) flat sites; (3) multiple use public open space; (4) street layout and streetscapes; (5) symbiotic land use clustering; and (6) industrial sites.

Best management practises (BMPs) refer to the "structural and non-structural elements of urban design that prevent, collect, treat, convey, store and re-use water within an integrated water management scheme" (Hoban and South East Queensland Healthy Waterways Partnership, 2007). These are outlined in Table 2 and can relate to one or more of the listed design objectives.

Table 2 List of Best Management Practises (BMPs) and how they relate to the three design objectives of WSUD (Source: Hoban and South East Queensland Healthy Waterways Partnership, 2007)

Best Management Practises (BMPs)	WSUD design objectives		
	Water conservation	Wastewater minimisation	Stormwater management
1. Demand Management	✔	✔	
2. Roofwater harvesting	✔		✔
3. Stormwater harvesting	✔		✔
4. Wastewater treatment for re-use	✔	✔	
5. Gross pollutant capture devices			✔
6. Sedimentation basins			✔
7. Grass or vegetated swales	✔		✔
8. Sand filters			✔
9. Bioretention systems	✔		✔
10. Constructed wetlands			✔
11. Porous pavements			✔
12. Infiltration measures	✔		✔

Stormwater management BMPs are usually used in combination in order to address a range of potential pollutants (Figure 2.10). This is known as a 'treatment train', and comprises the following categories:

1. Primary Treatment BMPs: these BMPs target litter and coarse sediment, and include gross pollutant capture devices (BMP 5) and sediment basins (BMP 6).
2. Secondary Treatment BMPs: these BMPs target sediments, partially removing heavy metals and bacteria. They address water quality and water quantity management, and include grass or vegetated swales (BMP 7) and sand filters (BMP 8).
3. Tertiary Treatment BMPs: these remove nutrients, bacteria, fine sediments, heavy metals, and include bioretention systems (BMP 9) and constructed wetlands (BMP 10).
4. Source control BMPs: these minimise the amount of stormwater entering the system, and include rainwater tanks (BMP 2), porous pavements (BMP 11), and infiltration systems (BMP 12).

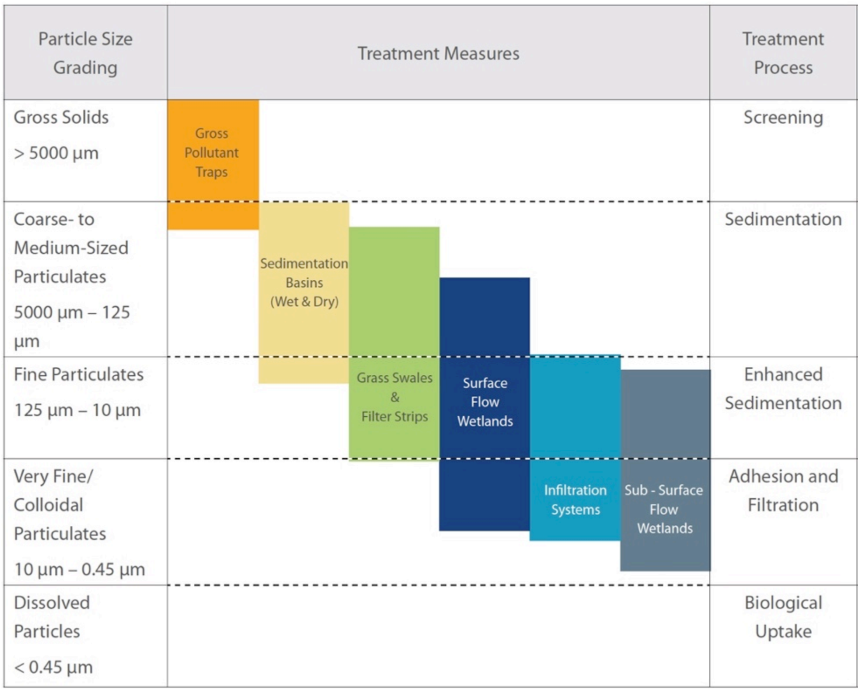

Figure 2.10 Range of pollutants that are addressed by BMP treatment measures (Source: Hoban and South East Queensland Healthy Waterways Partnership, 2007)

2.2.1.4 Nature-based solutions

'Nature-based solutions and re-naturing cities' is a European Union Research and Innovation policy agenda that aims to create more sustainable and resilient societies. They address environmental, social and economic challenges through solutions that are cost-effective and supported by nature, providing locally adapted, resource-efficient and systemic interventions (European Commission, 2016). The four main goals that are addressed by nature-based solutions include: enhancing sustainable urbanisation, restoring degraded ecosystems, developing climate change adaptation and mitigation, and improving risk management and resilience. These goals will be addressed through seven priority actions: urban regeneration, improved well-being in urban areas, establishing coastal resilience, watershed management and ecosystem restoration, increasing the sustainable use of matter and energy, using ecosystems as insurance value, and increasing carbon sequestration.

Many of these priority actions are relevant to the goals of SUWM, such as urban regeneration and improved well-being for urban residents, but the most relevant action relates to watershed management and ecosystem restoration. This priority action aims to reduce the risks of floods and droughts, as well as to improve water quality and manage water quantity. It also seeks to restore floodplains, grasslands, arable land and forests, peatlands, and former industrial and brownfield sites in order to improve water quality and carbon sequestration, and to provide species and habitat conservation and attractive landscapes (European Commission and Directorate-General for Research and Innovation, 2015).

2.2.2 Guiding principles

The different approaches to SUWM discussed above all embody the common principle of 'source control' (Faram et al., 2010), seeking to restore the urban water cycle to a more resilient state, where surface run-off is reduced and evapotranspiration, infiltration, and stormwater treatment is promoted (Figure 2.11).

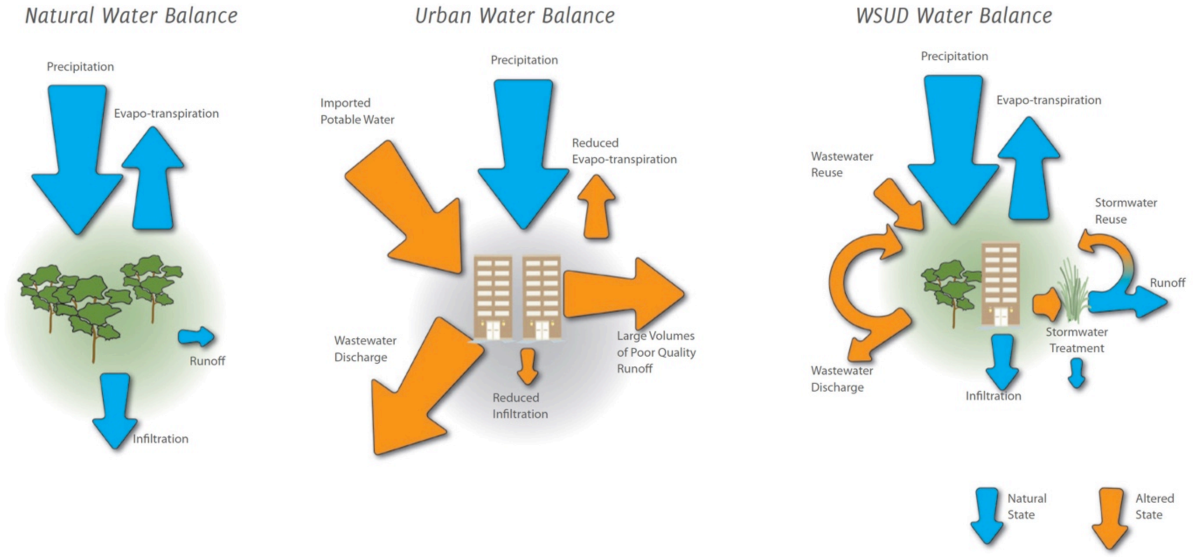

Figure 2.11 Schematic representation of the natural water cycle, the traditional urban water cycle, and the urban water cycle considering the implementation of water sensitive urban design (Hoban and Wong, 2006)

In promoting the pre-development state of the hydrological cycle, SUWM strategies must address water quality through the design of systems that filter out contaminants and pollutants that are picked up in the urban environment. When rain falls in urban areas, the surface water runoff mobilises sediment, litter and pollutants such as oils, grits, metals, fertilisers, pesticides, animal wastes, salts and pathogens. Silt is one of the most important components of this run-off, as pollutants adhere to it and are thus transported downstream. This pollution is known as 'diffuse pollution' because of its widespread nature, coming from different locations, and also because at individual source sites the pollution may not be significant, but as it moves further downstream it begins to pose a significant threat to groundwater and surface water, increasingly degrading water quality (Graham et al., 2012; Woods Ballard et al., 2015). This is why a focus on water quality is so central to all SUWM strategies. Figure 2.12 describes the different treatment processes that address pollutants, by particle size and type. SUWM strategies all employ a range of technical components that cover the different treatment processes described in Figure 2.12. These technical components use plants, soil and water to trap pollutants and work together to break down hazardous substances through a process known as bioremediation (Graham et al., 2012).

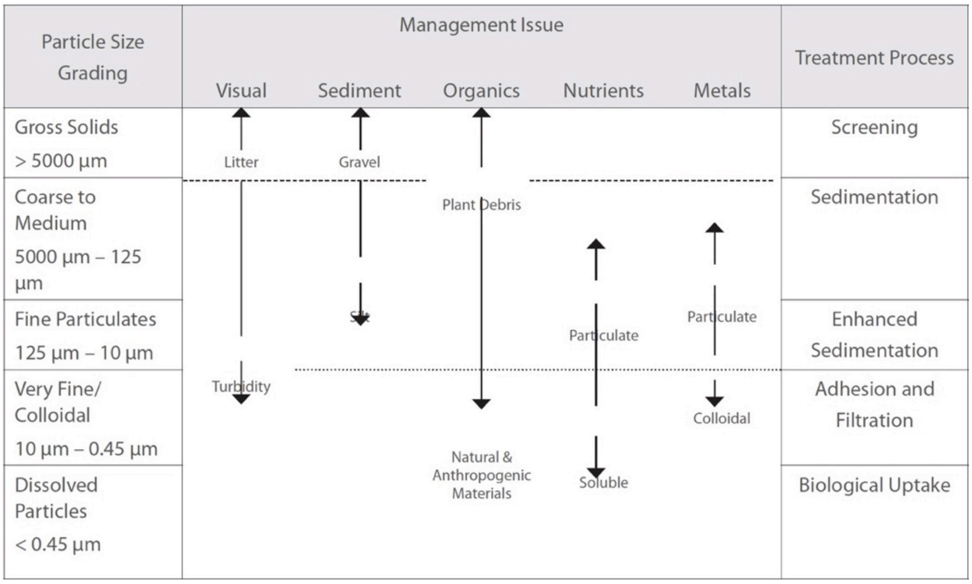

Figure 2.12 Range of pollutants and associated stormwater management issues and treatment processes (Source: Hoban and South East Queensland Healthy Waterways Partnership, 2007)

SUWM strategies also focus on creating a functionally equivalent hydrologic landscape by managing runoff volumes and flow rates. Traditional stormwater control measures can negatively affect the natural hydrology of a catchment by causing inadequate base flow, thermal fluxes or flashy hydrology, and this can have a detrimental effect on the ecosystem, independently of water quality control. In this way, SUWM components are also designed to reduce the amount of impervious areas and contribute to stormwater infiltration, thus lengthening flow paths and runoff times while also contributing to the recharging of groundwater (US EPA, 2000).

As the promotion of stormwater infiltration is inseparable from the treatment of stormwater pollutants, these two goals of addressing water quantity and water quality form the foundational guiding principles of all SUWM strategies.

Another important guiding principles of SUWM strategies is to deliver multiple benefits, such as using surface water to enhance biodiversity, beauty, tranquillity, and the natural aesthetics of buildings, places, and landscapes, as well as helping the city become more resilient to climate change (Woods Ballard et al., 2015). However, only by ensuring that water quantity and quality are controlled, can SUWM begin to consider other benefits, such as amenity and biodiversity, in greater detail.

Promoting the development of resilient cities in a time of uncertainty is another important objective of all SUWM strategies. The uncertainty regarding future climate change impacts calls for flexible solutions that can be adapted, extended, and even abandoned over time if necessary (Faram et al., 2010). The characteristics of a resilient water management system, as outlined by Faram et al. (2010), are:

(a) renewability of the system (ability to change)
(b) diversity within the system (a repertoire of alternative options)
(c) redundancy or headroom in the system (allowing for uncertainty)

Several studies discuss the importance of resilience and flexibility in SUWM design. As part of the EU-funded SWITCH project, and using the town of Kupferzell, Germany as an example, Sieker et al. (2008) show that small-scale decentralised solutions such as stormwater infiltration tend to be more flexible than conventional drainage systems. Hamilton (2009) describes SUDS as a method of increasing resilience related to flood protection, by reducing the rates and concentration of urban rainfall runoff into piped urban drainage systems through the use of infiltration and water-slowing features such as swales and ponds.

De Graaf (2009) argues that urban areas are vulnerable by nature as they are very dependent on external resources, and that climate change, resource scarcity, and urbanisation increase this vulnerability. Using local water and energy resources in addition to external resources provides an adaptive strategy to make cities more self-supporting and flexible, providing a diversity of water sources and thereby reducing the vulnerability of urban areas to flooding, droughts and energy scarcity. It is shown that decentralised solutions are more flexible and adaptable than large-scale centralised infrastructure, which has a “low capacity to adapt to uncertain future developments due to sunk costs, vested interests and social and technical lock in patterns”. The author explores the trade-offs between having “an efficient, centralised system that is vulnerable to rarely occurring, large scale disruptions, and a local, less efficient system that has a lower overall vulnerability”. The authors also describe how innovative urban water management strategies, such as rainwater harvesting, using local urban water systems as an energy source, and using surface water for floating urbanisation, can help reduce the vulnerability of cities.

A model has been proposed by White (2008) for an ‘absorbent city’, which addresses the issue of flood risk management and which could constitute an important guiding principle in SUWM design. The absorbent city is founded on three principles: (i) reflexivity: learning from the past and creating knowledge from self-inquiry, as well as identifying gaps in knowledge; (ii) knowledge generation and dissemination; and (iii) the ability to adapt: planning for the multi-functional use of space and for allocating land to its most sustainable use, compensating for losses elsewhere. The absorbent city uses spatial planning to create more resilient cities by planning according to hydrologically sensitive principles rather than purely socio-economic principles, as has been the case in the past. It advocates the use of fewer traditional hard engineering solutions and a more interventionist approach in influencing urban form and function.

When proposing changes to urban water management and the adoption of SUWM, it is also important to address the social dimension of this change. The ‘hydro-social contract’ is a term that has been employed to describe the pervading values and often-implicit agreements on how water should be managed. It is shaped by culture and history, expressed through regulations, and physically represented by water systems infrastructure. When moving between different management paradigms, it is important to be aware of the temporal, ideological and technological context of the city, as well as its history, ecology, geography and socio-political dynamics. As mentioned before, addressing the values and existing knowledge of a society is a fundamental step towards achieving institutional change (Brown et al., 2008). Although regulation usually holds the most formal institutional power, changes to thinking and values usually precede regulatory changes.

Finally, with regards to European regulation, SUWM supports the delivery of requirements and strategies related to flood risk management, water resource management, climate change resilience, green infrastructure, wetland creation, biodiversity and wildlife, and carbon reduction (Woods Ballard et al., 2015).

2.2.3 Technical components

The technical components of SUWM can be classified in numerous ways, namely: position in the urban water catchment (e.g. upstream or downstream), function (e.g. water quality or water quantity control), stage of water treatment they provide (e.g. primary, secondary or tertiary), and type of structural component (e.g. 'hard' components such as infrastructural or engineering interventions or 'soft' components such as interventions that incorporate vegetation). Most of the SUWM strategies described above use similar techniques in their approach to stormwater management, however, categorisation systems can be quite different. In this thesis a new framework is proposed that selects and integrates techniques from the strategies presented in section 2.2.1. The term 'treatment train' is adopted from the WSUD literature to describe the sequence of stormwater treatment devices that collectively address all stormwater pollutants (see Fig. 2.12). This resulted in the development of the following categorisation system and technical components, summarised in Figure 2.13:

1. Non-structural measures. These focus on human action and attitudes and include demand management and wastewater treatment for re-use.
2. Structural measures.
    1. Source control techniques, which seek to minimise the amount of rainwater entering a system. These include rainwater harvesting, green roofs, pervious pavements, and attenuation storage tanks and detention basins.
    2. Primary treatment techniques. These target litter and coarse sediments and include gross pollutant capture devices and sedimentation basins.
    3. Secondary treatment techniques. These target sediments, partially removing heavy metals and bacteria, and provide management for both water quantity and quality. Techniques include vegetated swales and sand filters.
    4. Tertiary treatment techniques. These remove nutrients, bacteria, fine sediments, and heavy metals, and include bioretention systems and constructed wetlands.
    5. Infiltration measures provide a final step in the urban water cycle by allowing for the infiltration of treated water. These include infiltration systems (leaky wells, infiltration trenches, soak-aways, infiltration basins) and aquifer storage and recovery systems.

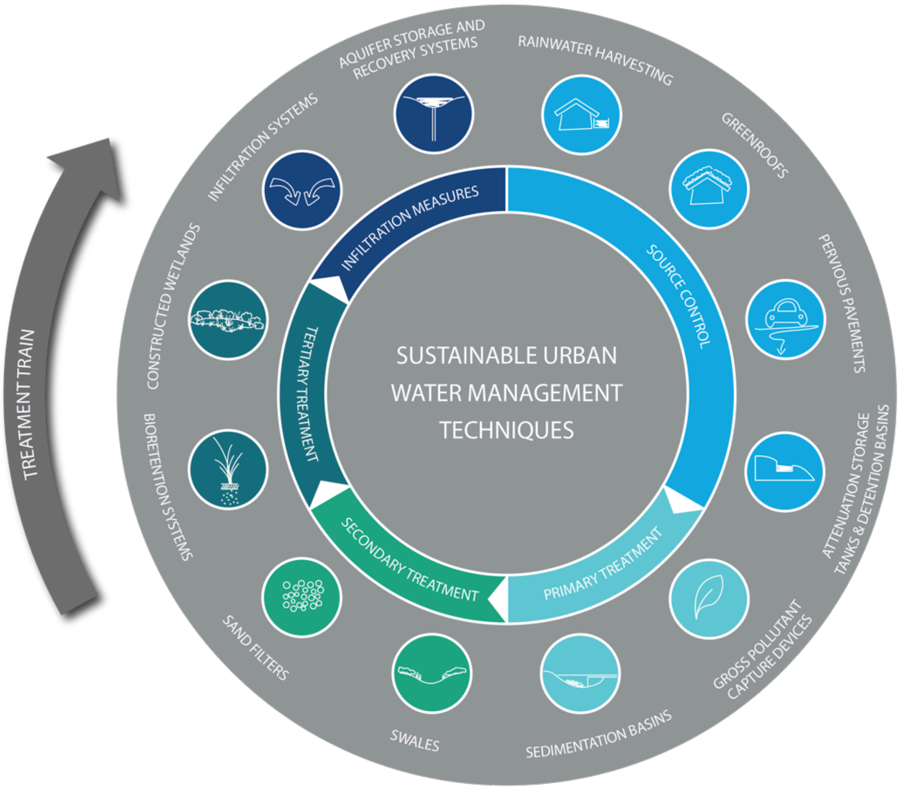

Figure 2.13 Structural measures of the SUWM strategies represented in a treatment train (diagram by the author)

2.2.3.1 Non-structural measures

Demand management refers to measures that reduce water use in the urban environment. These can be behavioural measures, which seek to enhance social awareness and influence water use patterns, ultimately reducing overall demand, or structural measures, which contemplate the use of more water-efficient appliances within buildings[2], as well as the design of more water-efficient urban landscapes, through changes to soil characteristics as well as to the choice of plants.

Wastewater treatment for re-use contemplates the recycling of wastewater in appropriate ways, following treatment to 'fit-for-purpose' standards. Wastewater includes blackwater, which is wastewater from toilets and kitchen sinks, and greywater, which is water from non-toilet plumbing fixtures such as showers, basins, washing machines and taps. Re-use applications include industrial uses, agricultural uses, non-potable domestic uses, and urban open space irrigation. Wastewater treatment and re-use schemes should consider important factors such as community acceptance, public health risk management, and sensitivity of local ecosystems for irrigation by treated wastewater (Hoban and South East Queensland Healthy Waterways Partnership, 2007).

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[2] Such as low water use taps, dual flush toilets, waterless urinals and composting toilets

2.2.3.2 Structural measures

2.2.3.2.1 Source control

Rainwater harvesting involves collecting rainwater from roofs and storing it above or below the ground. This water can be used directly, without treatment, for different non-potable uses such as toilet flushing, washing machines, car washing or irrigation, but is rarely used to provide potable water for consumption or bathing. Typically, rainwater harvesting systems have a back up secure water source, because of the irregular nature of rainfall and the variable patterns of end use demand. Roofwater can also be a useful supply alternative to dams, reservoirs and weirs, as a large amount of rainfall can be collected before a runoff threshold is attained. Re-use of harvested roofwater provides a source control measure that addresses water quantity, reducing the volume of stormwater in downstream urban areas as well as associated pollutant loads (Hoban and South East Queensland Healthy Waterways Partnership, 2007; Woods Ballard et al., 2015).

Green roofs have vegetation installed on the top of buildings, and provide retention and treatment of rainwater, as well as promoting evapotranspiration (Samant, 2015). Other benefits provided by green roofs include visual benefits, improved thermal performance of the building (evapotranspiration cools the roof during summer months), opposing the urban heat island effect, and contributing to improved air quality by trapping dust particles.

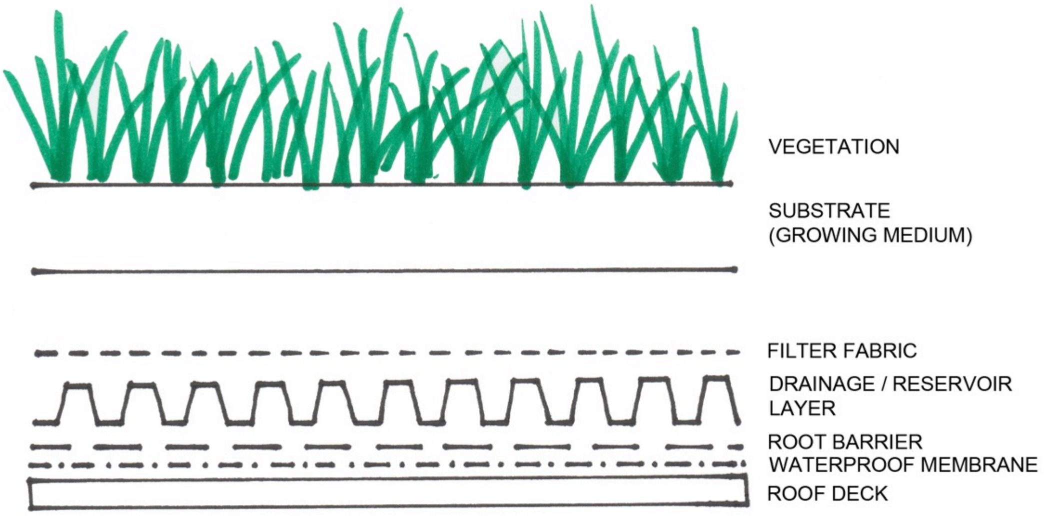

Figure 2.14 Typical components for an extensive green roof (Adapted from Woods Ballard et al., 2015)

These roofs are generally more expensive to construct and maintain than conventional roofs, and consist of several layers of material (Figure 2.14) that allow for the establishment of a vegetative cover and for an adequate drainage. Green roofs can be divided into extensive green roofs, which have low substrate depths, simple planting, low maintenance, and are usually inaccessible, and intensive green roofs, which have deeper substrates, support a variety of planting, involve higher maintenance, and are usually accessible (Woods Ballard et al., 2015).

Pervious pavements provide an alternative to traditional impermeable pavements as they allow infiltration of rainwater through their surface to the underlying structural and foundation layers. They can consist either of modular blocks that allow water to infiltrate through the void spaces (known as permeable pavements), or of pavements that allow infiltration across their entire surface (known as porous pavements). Water then infiltrates through an underlying sand or gravel media layer, which provides some removal of sediments and attached pollutants. However, the main purpose of pervious pavements is to manage surface water runoff close to its source, reducing the volume and frequency of runoff and reducing flow velocities. For this reason they should be designed so that the stormwater receives further treatment downstream to ensure adequate water quality standards.

Attenuation storage tanks and detention basins provide temporary storage for water, either below ground or as landscaped depressions that only store water following rainfall events, respectively. They can be used at the start of a treatment train, storing water before it enters the treatment system, or at the end of a treatment train, prior to the water's infiltration to the surrounding soil or to its reuse (Woods Ballard et al., 2015).

2.2.3.2.2 Primary treatment techniques

Gross pollutant capture devices (GPCD) target coarse litter and sediments, and can either be implemented as dry traps, such as a simple net over a pipe, or wet well traps, where the trapping device is submerged, potentially resulting in the trapping of much smaller particles. GPCD should be used in areas with high man-made litter and low organic loads, such as shopping centres and commercial precincts, but not residential catchments, where organic loads are usually high. This is because if captured in wet well traps, organic loads such as grass clippings would decompose quickly, releasing nutrients that would then have to be treated further downstream. When GPCD are used in isolation without further treatment stages downstream, it is preferable to use a dry trap instead of a wet well trap to capture the organic loads, in order to reduce the risk of nutrient and toxin release. When used in conjunction with other treatment devices further downstream, the aim of GPCD is to target litter and coarse sediments in order to reduce the risk of other treatment devices further downstream becoming overloaded and reducing their performance (Hoban and South East Queensland Healthy Waterways Partnership, 2007).

Sedimentation basins are designed to remove coarse to medium sized sediments by settling them from the water column. They are usually simple excavated pools that reduce flow velocities and provide temporary storage, thus allowing sediments to settle. Permanent sedimentation basins, known as 'wet' basins, are formed by an inlet structure, a settling pond, an outlet structure, and an overflow structure (Figure 2.15). Temporary sedimentation basins, known as 'dry' basins, are only used during construction and building phases, and are not discussed here. Sedimentation basins are integrated into a treatment train, and as they are typically one of the first elements in the sequence, they are likely to present turbid water.

Planting dense macrophyte vegetation at the edge of sedimentation basins helps restrict public access, maintain aerobic conditions, reduce erosion of the banks, and deter floating vegetation from becoming established, which would negatively impact the basin's sedimentation performance. Selection of plant species should consider the water level regime and the soil type of the site, as well as the plant's life histories, physiological and structural characteristics, natural distribution and community groups. Plants should be selected to establish to a depth of 0.2 m (shallow marsh zone) and to 0.2 m above water level (ephemeral marsh zone), avoiding species that may spread to deeper water.

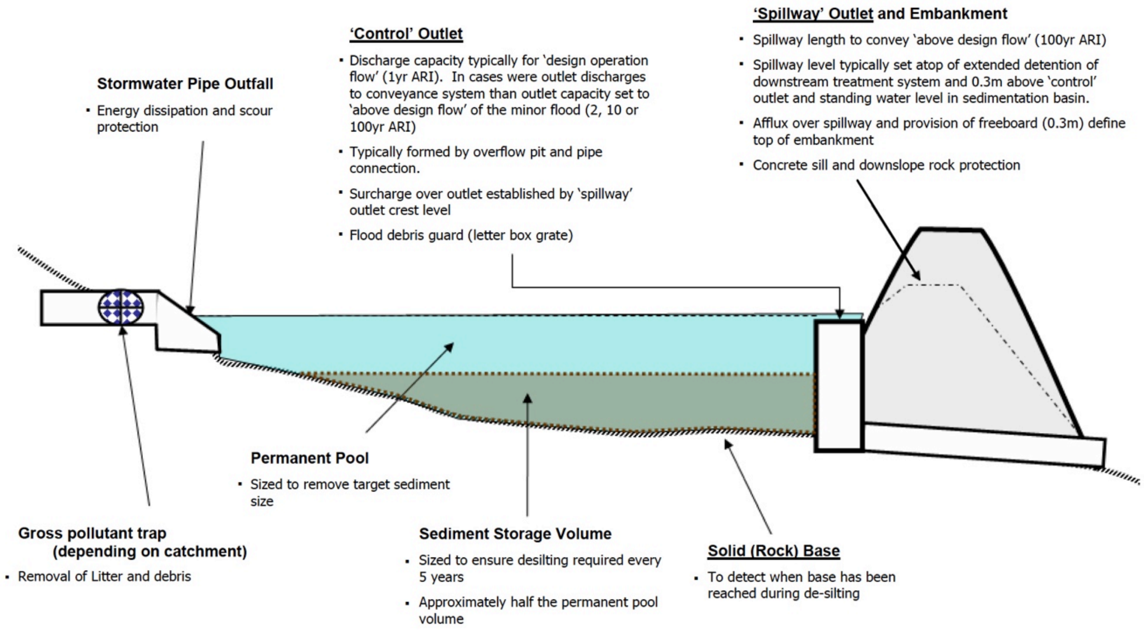

Figure 2.15 Conceptual layout and key elements of a sediment basin (Water by Design, 2006)

The most important design requirement of a sedimentation basin is selecting a target sediment size, which is generally 125 μm or larger. This is because it has been shown that 50-80% of suspended solids conveyed in stormwater are of this dimension. The settling velocity of this target sediment size is then matched with a design flow in order to calculate the required size of the sedimentation basin. If the basin is undersized, large sediments will deposit in downstream components and risk clogging them up, and if the basin is oversized, fine sediments with heavy metals and nutrients attached to them will be captured, but will not be effectively treated, as treatment of these kinds of pollutants requires dense wetland vegetation. Thus, the treatment systems downstream of sedimentation basins are usually the macrophyte zone of a constructed wetland or a bioretention basin. When a sedimentation basin precedes a constructed wetland, the outlet structure is usually an overflow pit located within the sedimentation basin, which is connected via one or more pipes to an open water area upstream of the wetland's macrophyte vegetation zone. When a sedimentation basin precedes a bioretention basin, the outlet structure is usually a weir that keeps stormwater flows at the surface, so that it can then flow on to the surface of the bioretention filter media. Outlet structures consist of a 'control' outlet structure, which delivers flows up to the design conditions, and 'spillway' outlet structures, which are designed to convey any excess flows that are ‘above design’ around the downstream treatment systems, thus bypassing and protecting downstream vegetation from damaging high flows.

Regular maintenance is crucial to the proper functioning of the basin, and consists of draining the water and desilting, or removing accumulated sediments, when the sediment level has reached half the basin depth. The settling pond is composed of a permanent pool settling zone and the sediment storage zone (Figure 2.15), which should be designed for a desilting frequency of once every five years. If regular maintenance is not ensured it can lead to damaging weed growth throughout the system. Importantly, the design of the sedimentation basin should consider access to the site by the appropriate maintenance machinery, such as an excavator, as well as how to ensure minimal disturbance to the edge vegetation during this process. Generally sedimentation basins are not implemented in dense urban settings due to the large area they require.

Sedimentation basins can also form important landscape features where community education can take place, as they are large and visible, and usually provide a transition between an urbanised stream and a natural wetland. In the past, poorly designed or managed water bodies have lead to the formation of swamps and lagoons. Given the generally unattractive nature of stale water bodies and the possible health and safety risks, such as the amplification of disease vectors (e.g. mosquito populations), this may have contributed to a legitimate negative perception of these kinds of permanent water bodies. As one of the first sites for water treatment in an urban water catchment, sedimentation basins provide an opportunity to change this negative perception as well as to educate the community on the processes being carried out by this technical component as well as by the entire SUWM system. Sedimentation basins provide many potential benefits, such as interesting views (due to the fact they are often sited at the highest point of a constructed wetland), a dynamic interface between fast flowing, shallow water and slow, deep water, and an opportunity to observe wildlife adapted to these lagoon-like environments. This technical feature thus provides an opportunity for successful landscape design that enhances visual amenity, environment, habitat, community safety, and stormwater quality (Hoban and South East Queensland Healthy Waterways Partnership, 2007; Water by Design, 2006).

2.2.3.2.3 Secondary treatment techniques

Vegetated swales convey stormwater slowly downstream instead of, or with, underground pipe drainage systems, while providing removal of coarse and medium sediments. Pollution settlement and retention is facilitated by the interaction between stormwater flow and vegetation, even when vegetation is relatively low, such as with grass swales. Swales are effective at removing coarse sediment, and should be followed in the treatment train by a tertiary treatment system in order to provide adequate water quality standards. For swales to be effective, flows must be well distributed across the full width of the swale, and the longitudinal slope is usually between 1% and 4% in order to ensure slow flow conditions. If a steeper slope than 4% is required, check banks such as small rock walls (typically 10 cm rock weirs) can be implemented across the base of the swale to help distribute flows evenly and reduce flow velocities. Flow velocities should be kept at < 0.5 m/s for minor flood events and ≤ 2 m/s for major flood events. Swales should be designed to convey frequent storm flows, which typically involve storm flows up to the 3-month Average Recurrence Interval (ARI). In order to conserve the swale's long-term water quality improvement function, these should only be used in catchments up to 1-2 ha, so as to ensure the flow depths and velocities do not compromise the swale's performance and endurance.

Vegetation should cover the entire width of the swale, and can include turf, sedges and tufted grass. It should also be capable of withstanding design flows and provide enough density to prevent preferred flow paths. Turf swales require consistent mowing in order to operate effectively, whereas densely vegetated swales require less maintenance once they are established, and can become features of the urban landscape. It should be noted, though, that densely vegetated swales require a larger area and/or more frequent use of swale field inlet pits, given that the flow in these swales has a higher hydraulic roughness. Swales should not be located with significant shading from trees or other overhead structures, as this could limit the growth of the vegetation in the swale (Hoban and South East Queensland Healthy Waterways Partnership, 2007; Water by Design, 2006; Woods Ballard et al., 2015).

Sand filters are used to percolate stormwater and filter out sediments and some nutrients and heavy metals, as well as to delay runoff peaks by providing retention capacity and reduced flow velocities. They provide a similar function to bioretention systems, except that the stormwater filter is composed of an inert medium, usually sand, with no vegetation growing on its surface. This means that the stormwater treatment performance is not as effective as with bioretention systems, where the biologically active soil layer around the vegetation's root zone provides improved treatment performance, but has the advantage of being able to be implemented in areas where the urban environment is already highly developed, with stormwater treatment being carried out underground. Plant growth would not possible under these conditions as such a filter medium does not retain enough moisture and as there would be inadequate amounts of light to support plant growth. In this way, sand filters should only be used where bioretention systems or constructed wetlands cannot be implemented due to limited land area or where the treatment needs to be provided underground. Sand filters should always be preceded by primary treatment components that remove large sediments in order to avoid clogging and thus ensure the system's treatment performance.

Sand filters require more routine maintenance than bioretention systems, as they have no vegetation to break up the filter surface. Removal of accumulated sediments from the filter medium, which can form a 'crust' on the surface of the sand, is critical to ensuring the sand filter remains porous and can sustain its treatment performance. Maintenance involves removing the top 25-50 mm of fine sediments from the filter media.

A sand filter is typically composed of three chambers (Figure 2.16). The inlet chamber (A) allows larger sediments in the stormwater to settle before the water then flows via a weir into the sand filter chamber (B). Here the water percolates through the sand filtration media, which is typically 400-600 mm deep. It is important to note that the lifespan of the filter media is limited as the sand filter is unable to convert or dispose of the nutrients, fine particulates and accompanying pollutants such as heavy metals. The frequency for replacing the sand depends on the catchment, but a typical timeframe is between 2-5 years. The sand filtration chamber should be sized to trap sediments larger than 125 μm, with a capture efficiency of 70%. The chamber is composed of two layers; a top layer consisting of the sand filter media with a saturated hydraulic conductivity of 360-3600 mm/h; and a drainage layer (minimum 200mm thick) composed of washed river sand, with a saturated hydraulic conductivity of 4000 mm/h, which encases the perforated under-drain pipes. These pipes collect the treated water and convey it downstream, and should be designed to drain freely so as not to cause blockages in the system[3]. Finally, a high flow bypass chamber (C) allows very high flows to be diverted around the sand filter media when water levels in the two previous chambers exceed the depth of extended detention. These excess flows are then conveyed to a downstream drainage system, where appropriate treatment should be ensured.

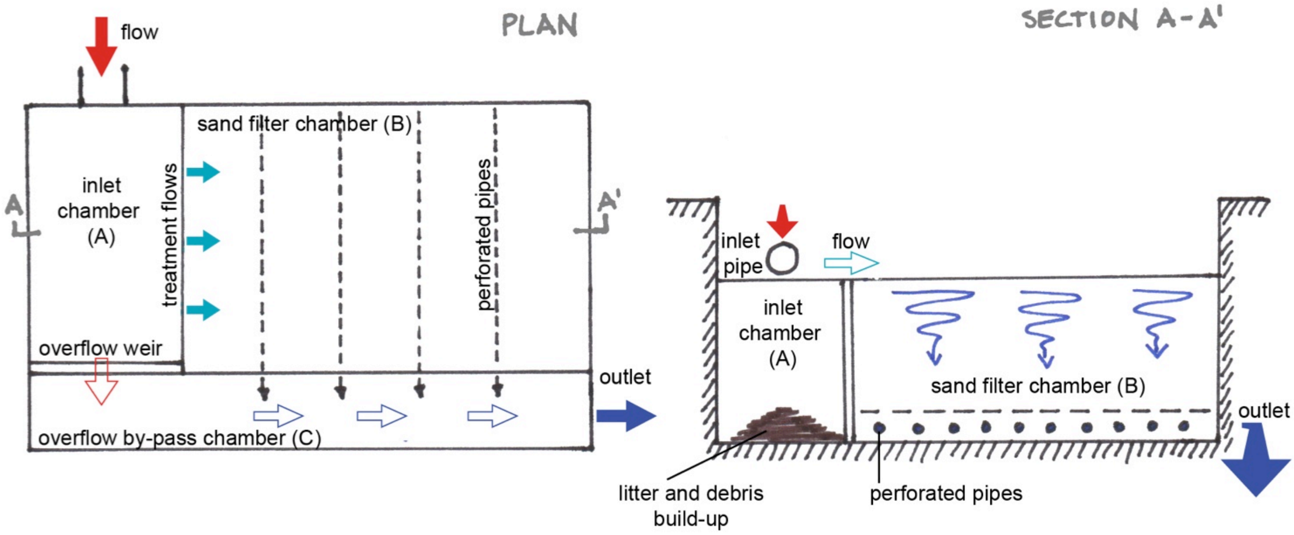

Figure 2.16 Configuration of a typical sand filter in operation (Adapted from Water by Design, 2006)

An important design consideration is whether the sedimentation chamber will be drained of water during dry periods or not. With a permanent body there can be disadvantages related to stagnant water and potentially high organic loads that could lead to anaerobic conditions, which causes the release of soluble pollutants and generates odorous gases. The sand filter media is less effective in retaining and processing soluble pollutants, and the discharge of these pollutants downstream could lead to water quality issues such as algal blooms. Also with regards to maintenance, the cost of removing wet material from the sedimentation chamber is higher than for drained material. On the other hand, drained sedimentation chambers must be designed so that the weep holes that drain the water do not block with accumulated sediments. It is important to note that the water that is drained has not undergone treatment, and so provisions must be made to either link the drained water back to

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[3] In order to drain freely, the capacity of the under-drains needs to be greater than the maximum infiltration rate

the sand filter or to convey it to another downstream treatment device. It is also important to design the sedimentation chamber so that at the start of a rainfall event stormwater inflow does not cause re-suspension of accumulated material. In order to prevent re-suspension of material, a baffle arrangement or other structure can be constructed across the inlet flow path to minimise turbulence as water enters the sedimentation chamber.

One of the most important considerations with sand filters is their maintenance; without regular maintenance, the system may become obstructed, leading to inadequate water treatment as well as the formation of a stagnant water body. In this way, any sand filter proposal should be supported by formal guidance for scheduled maintenance (Hoban and South East Queensland Healthy Waterways Partnership, 2007; Water by Design, 2006).

2.2.3.2.4 Tertiary treatment techniques

Bioretention systems are shallow depressions in the urban landscape that allow stormwater runoff to pond temporarily on the surface before filtering through densely planted surface vegetation and then percolating through a biologically active sand and loam filter media. This system targets a range of stormwater pollutants, including anthropogenic and organic litter, fine sediment, phosphorus, nitrogen, metals, and hydrocarbons. These are captured by fine filtration, adsorption and biological processing by microbes and plants. Particulates such as organic matter are captured on the surface of the system, and dissolved pollutants are removed by adsorption onto fine particles when then the water percolates through the filter media. The filter media layer is typically 500-1000 mm deep, and is followed by a transition layer, which is at least 100 mm deep, and is composed of coarse sand that prevents the washing of finer filter media particles into to the layer below. The drainage layer, which is below the transition layer and usually at least 100 mm deep, is composed of fine aggregate and perforated pipes and allows the filtered water to be collected and conveyed to downstream drainage systems, or alternatively be discharged directly to groundwater (Figure 2.17).

Bioretention systems also delay the release of stormwater, both by capturing runoff from small rainfall events and reducing the time of concentration, as well as by promoting evapotranspiration and infiltration into the surrounding soil. The extended detention, which provides temporary storage of stormwater before it infiltrates, thereby allowing a larger volume of stormwater to be treated, is typically 100-300 mm deep.

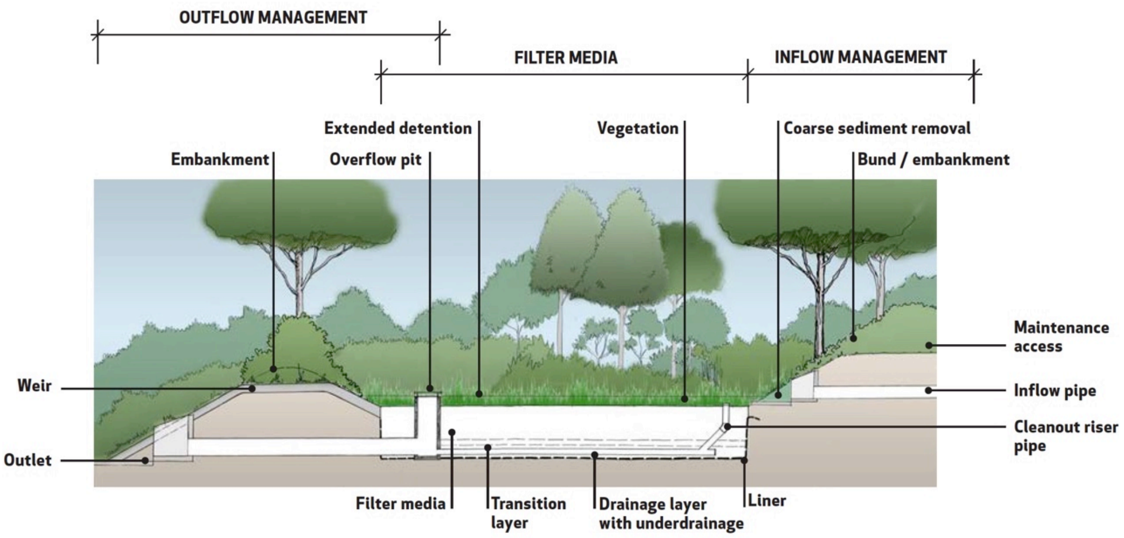

Figure 2.17 Typical components of a bioretention system (Water by Design, 2014)

Bioretention systems can use a range of different drainage profiles, as described in Figure 2.18. In the first type, the saturated zone bioretention systems, an impermeable liner at the base of the system ensures the layers below the filter media are saturated, providing water storage and allowing the vegetation to access water during dry periods. The sealed bioretention system (type 2) also has an impermeable liner at its base but water drains through the under-drainage pipes and so the system does not have a saturated zone. Conventional bioretention systems (type 3) also have perforated pipes at the base of the system but do not have an impermeable linin, such that infiltration into the surrounding soils is encouraged and frequent stormwater flows are managed. The fourth type, the pipeless bioretention systems, do not have under-drainage pipes and so allow the treated stormwater to infiltrate into the surrounding soils.

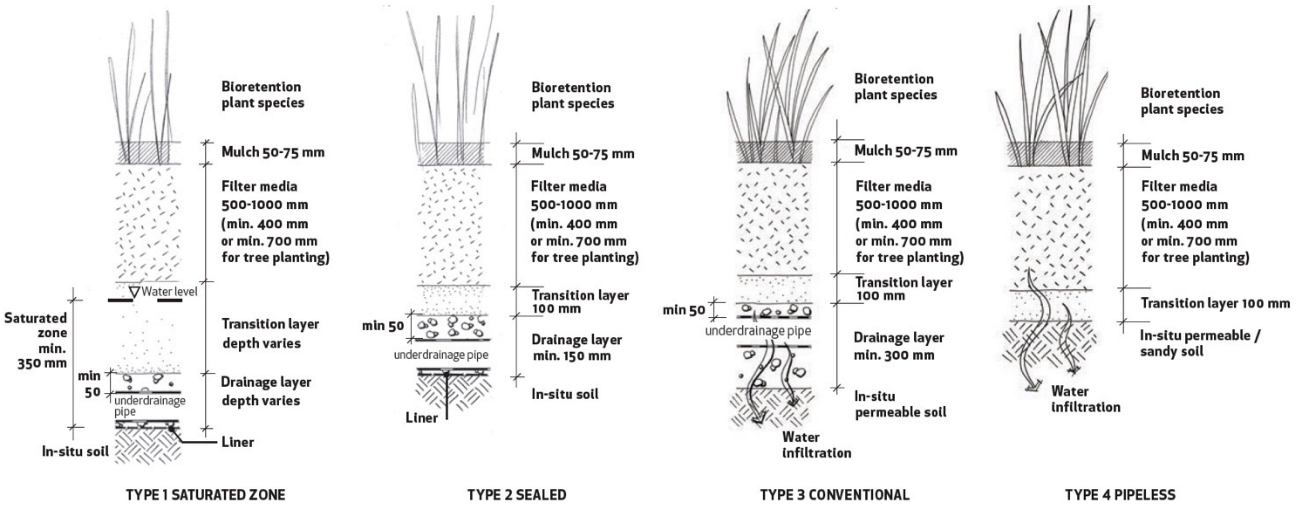

Figure 2.18 Drainage profiles used in bioretention systems (Adapted from Water by Design, 2014)

The design of the system is quite flexible and can take many different forms, such as rain gardens, bioretention swales, and tree systems. Table 3 outlines four main bioretention system configurations that can be readily integrated into a range of landscapes, including individual development sites, allotments, streetscapes, civic spaces, parklands, and adjacent to riparian corridors or other natural areas.

Bioretention systems are permanent and should therefore be designed considering the suitability of the site regarding function, aesthetics, constructability and maintenance requirements. As seen above, bioretention systems can be successfully applied to treat pollutants as well as to manage urban hydrology, particularly frequent stormwater flows, and can be incorporated into a range of landscapes, from hard urban spaces to softer natural areas. The required treatment area for bioretention systems is 1-2% of the contributing catchment, and so these can usually be implemented in smaller, more constrained spaces. On the other hand, they can also be used to manage runoff from larger catchments, provided the design solutions are tailored to this situation. If carefully designed, bioretention systems can be implemented in relatively steep topography, as well as on flat topography such as streetscapes. Bioretention systems can also be used for stormwater harvesting, as water can be treated to acceptable levels for some forms of re-use.

Table 3 Bioretention system configurations

Bioretention configuration	Description
Bioretention basin	End-of-pipe system; 100-800 m^2 of filter media surface area; often located adjacent to parkland/natural areas, and selected vegetation must be compatible with pre-existing vegetation
Bioretention swale	Treats and conveys stormwater; bioretention system components are located at the base of the swale and is typically 600-2000 mm wide; surface of the filter media follows the longitudinal slope of the swale, which is generally between 0.5% and 2%.
Biopods	At-source system; typically 50 m^2; receives water from surface run-off from impermeable areas; commonly planted with shrubs, grasses, and sedges.
Bioretention street trees	At-source system; typically 2-4 m^2; typically receives water from surface run-off from impermeable areas

Bioretention systems are not suitable to be implemented in sites with insufficient elevation from the surface of the system to the receiving drainage system, as this would not allow proper drainage. They should also not be used on sites with tidal influence, as the saline water would compromise the system's biological function. Sites with continuous inflow are inappropriate, as moss or algae can form thick films in continuously wetted areas, thereby reducing infiltration to the filter media layer. Swales with high-flow velocities (> 1 m/s) do not provide adequate conditions for installing bioretention systems, as high-velocity flows would scour the surface. Bioretention systems should not be used on sites subject to toxic runoff, as this would compromise the biological functioning of the system. Sites with limited accessibility are also inappropriate, considering periodic maintenance is critical to ensuring optimal function.

The choice of vegetation is very important as it influences the performance of the system, prevents erosion of the surface soil layers, and has a strong influence on the amenity and biodiversity value of the system. Although vegetation selection for bioretention systems is site specific, Annex 5 provides a guideline for vegetation specifications (Hoban and South East Queensland Healthy Waterways Partnership, 2007; Water by Design, 2006; Woods Ballard et al., 2015).

Constructed wetland systems are shallow water bodies that are extensively vegetated, allowing settlement of suspended solids, fine filtration and biological removal of pollutants. Wetlands generally consist of an inlet zone (preceded by a sedimentation basin; see section 2.2.3.3), a macrophyte zone, and a high flow bypass channel that protects the macrophyte zone from scour when flows exceed the extended detention depth, which should be 0.5 m - 0.75 m (Figure 2.19).

The macrophyte zone should be designed to include a sequence of ephemeral marsh, shallow marsh, marsh, and deep marsh zones, as well as open water zones. To create these four marsh zones the bathymetry must range gradually from 0.2 m above the permanent pool level to a maximum of 0.5 m below the permanent pool level. This range of habitats will support a variety of species and ecological niches, thus providing a range of treatment processes. The marsh zones should be connected to deeper open water zones, thus allowing mosquito predators to seek refuge in this deep sump of permanent water during dry weather. The depth of the open water zones should be at least 1m below the permanent pool level and no more than 1.5 m. This is to avoid colonisation by emergent macrophytes and to allow for colonisation by submerged macrophytes respectively.

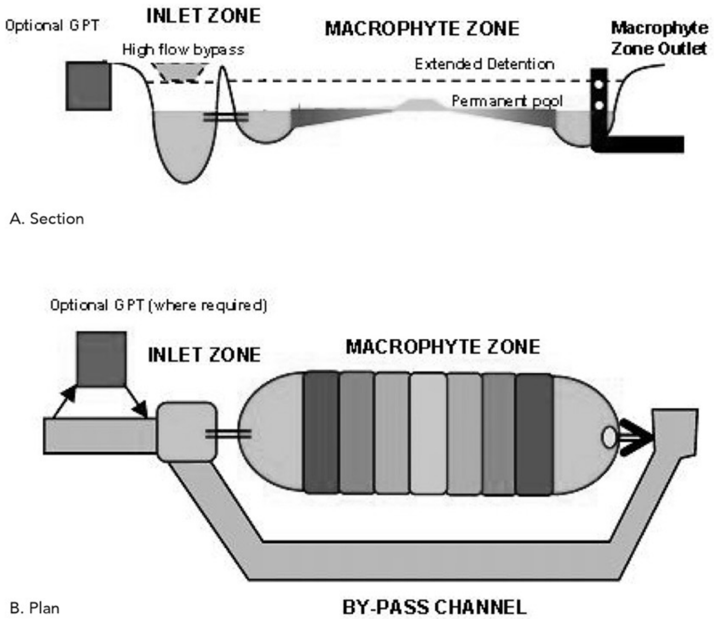

Figure 2.19 Schematic layout of a constructed wetland system (Water by Design, 2006)

The wetland should be designed so that the distribution of flow velocity is uniform, eliminating short-circuit flow paths and poorly mixed zones, which would otherwise lead to stagnant areas where litter could accumulate or where mosquito breeding might become an issue. One way to do this is to adopt a high length to width ratio for the macrophyte zone, typically ≥ 5:1. Wetland zones should be arranged perpendicular to the flow path (Figure 2.19) with an even plant distribution in order to ensure uniform hydraulic conveyance. The outlet structure of the macrophyte zone should be designed to allow a notional detention time of 48-72 hours, which is the time taken for water to travel through the macrophyte zone assuming 'plug' flow conditions.

Other design considerations are the inundation depth, wetness gradient, and frequency of inundation, which should take into account the hydrology and size of the catchment draining into the wetland (Hoban and South East Queensland Healthy Waterways Partnership, 2007; Water by Design, 2006; Woods Ballard et al., 2015).

2.2.3.2.5 Infiltration Measures

Infiltration systems are designed to promote the infiltration of treated water into the surrounding soils and underlying groundwater. They consist of a 'detention volume', which detains a certain volume of runoff that will subsequently be infiltrated, and an 'infiltration area', which is the interface between the detention volume and the surrounding soils. They should only be located after a tertiary level treatment system. The four basic types of infiltration systems are leaky wells, infiltration trenches or soak-aways, and infiltration basins.

A leaky well is a vertical concrete or PVC perforated pipe that is set in the ground and covered in non-woven geotextile and surrounding by a ring of 5-10 mm diameter gravel. Pre-treated water enters via an inlet pipe and allows water to seep through the 8.5 mm diameter perforations into the surrounding soils as well as through the bottom of the pipe, which is covered in geotextile (Figure 2.20). These systems are usually used in small-scale residential settings.

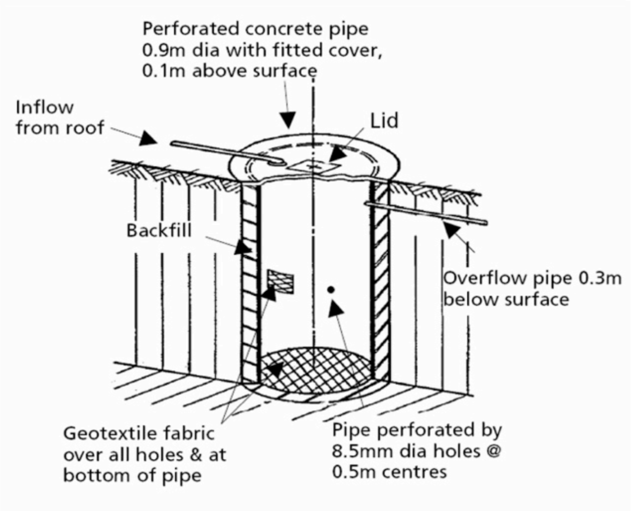

Figure 2.20 Schematic representation of a leaky well (Water by Design, 2006)

Infiltration trenches are linear soak-aways that are usually 0.5-1.5 m deep and filled with gravel or modular plastic cells lined with non-woven geotextile. With gravel-filled trenches, a perforated pipe is usually included to help distribute water along the trench. The advantage of this system is that it helps distribute the infiltrate area, so that in the case of less permeable areas of soil, the impact will be less pronounced. Infiltration soak-aways typically have a larger plan area and are shallower than infiltration trenches (Figure 2.21).

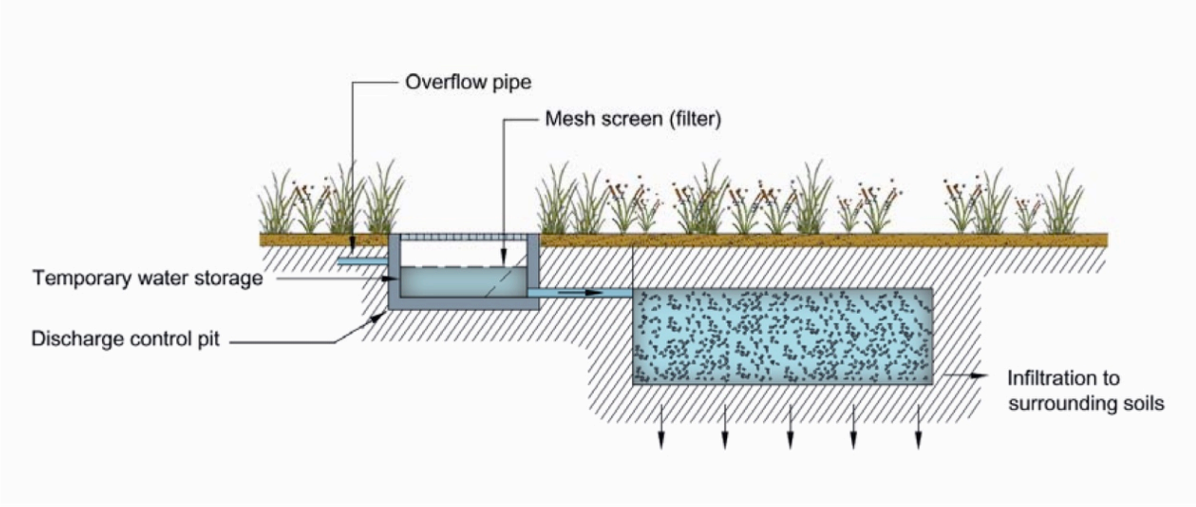

Figure 2.21 Schematic representation of an infiltration soak-away (Water by Design, 2006)

Infiltration basins are natural or constructed depressions that store pre-treated stormwater before allowing it to infiltrate into the soils. They are best suited to areas with sandy or sandy-clay soils, and can be used on a large scale in areas where space is not a constraint.

Aquifer storage and recovery (ASR) systems allow recycled water with appropriate water quality levels to be introduced into groundwater aquifers. This can provide a low cost water storage alternative to surface storages and is dependent on local hydrology, geology, and the presence and nature of aquifers (Hoban and South East Queensland Healthy Waterways Partnership, 2007; Water by Design, 2006; Woods Ballard et al., 2015).

2.2.4 Benefits and limitations

It has been shown that SUWM is an approach to urban water management that uses a series of techniques that work together to provide multiple benefits, as illustrated in Figure 2.21. This is a very different way of managing water, treating it is as an asset and a resource, rather than forcing it to leave the city as quickly as possible through pipes and conduits (Charlesworth, 2010).

Figure 2.22 Benefits of water sensitive urban design (Morgan, 2013)

First of all, SUWM manages the quantity of water as well as the quality of water in the urban environment. With regards to water quantity, SUWM techniques work in concert to reduce peak runoff rates and runoff volumes (i.e. the speed and volume of runoff that is discharged from the site), thus reducing the risk of flooding, as well as the risk of riverbank erosion. Figure 2.22 shows the reduction in peak runoff rate for developed sites where there has been flow attenuation through the slowing and storing of runoff on site and controlled discharge to the receiving watercourse. In this way, SUWM avoids the detrimental impacts of urban surface water runoff on people, property and the environment. However, SUWM techniques are most effective at reducing flood risk for high intensity, short and medium duration rainfall events, and tend to have less impact on large watercourses that are more sensitive to long duration rainfall events. Indeed, stormwater management focuses on the more frequent, everyday stormwater runoff, which is most affected by urbanisation and has the greatest impact on aquatic ecosystems' health. The objective is to capture the initial portion of runoff from impervious areas and to replenish the runoff capture capacity within 24 hours of the runoff event (Hoban and South East Queensland Healthy Waterways Partnership, 2007; Woods Ballard et al., 2015).

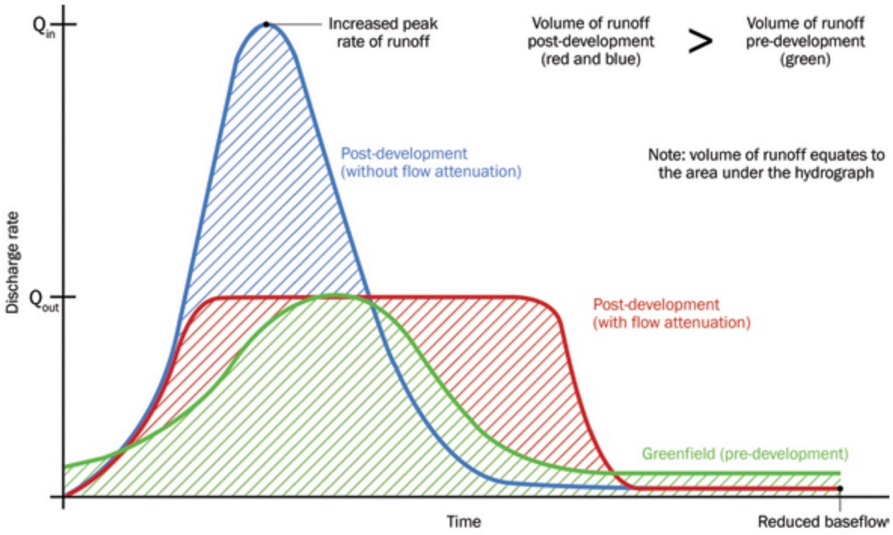

Figure 2.23 Example of a runoff hydrograph showing peak runoff rates for post-development, post-development with flow attenuation, and pre-development situations (Woods Ballard et al., 2015)

In line with this idea, Medina et al. (2011) investigate the assumption that SUWM measures are most effective at controlling small storms, and tend to have less impact on extreme events with a higher return period, which are the events that usually result in flooding. The authors conclude that, although the basic tenet of SUWM techniques is to control small storms (which typically comprise around 80% of the annual average rainfall), when implemented on a watershed-wide basis they can still provide substantial long-term benefits by reducing average economic losses associated with flooding.

The authors show that SUWM techniques such as bioretention filters, pervious pavements, green roofs and cisterns (referred to in the article as Green Infrastructure – GI) are ultimately designed to capture a volume of water that corresponds to a threshold rainfall depth; for example, to capture 80-85% of the annual rainfall in the mid-Atlantic United States, the threshold is around 25mm; to capture 80-85% of the annual rainfall in semi-arid climates, the threshold is around 12mm. Given that extreme storms have depths of much higher orders of magnitude (for example, the 100-year storm event for Columbia, South Carolina, USA, is 213mm), capturing volumes of up to 25mm may not have a significant effect. Indeed, the study showed that the effect of SUWM techniques on the 100-year event is negligible, however, their findings indicate that there is a noticeable reduction in the inundated area for storms with a 2-year return period.

The study also analysed the effect of SUWM techniques on the total economic costs associated with floods, showing that watershed-wide implementation of SUWM techniques clearly reduces flood damages, with up to 40% savings. Another focus of the study was to analyse the cost-effectiveness of implementing SUWM techniques. Costs for retrofitting these systems in the mid-Atlantic USA are estimated at \$100 000 per acre of impervious land (roughly \$25 per m^2), whereas costs for implementing them in new developments are substantially less. The study shows that, for the case study watershed, the damages avoided as a result of implementing SUWM techniques can total up to 20% of the implementation costs.

With regards to water quality, SUWM techniques are devised as part of a treatment train that addresses a range of pollutants (see Figure 2.12) through a variety of treatment processes. At the final stage of treatment, the objective is to achieve a minimum of 80% reduction in total suspended solids (TSS), 60% reduction in total phosphorus, 45% reduction in total nitrogen, and 90% reduction in gross pollutants, when compared to untreated urban stormwater runoff (Hoban and South East Queensland Healthy Waterways Partnership, 2007).

However, SUWM goes far beyond simply mitigating flooding and water quality concerns. It supports local natural habitats and associated ecosystems by encouraging biodiversity and by linking habitats. It also aims to create attractive places where people want to live, work and play, connecting people to water and nature, thus improving their wellbeing as well as their appreciation for the place. This in turn will improve people's understanding of this approach to water management, helping to educate communities on the benefits of these sustainable approaches. Alongside these biodiversity, amenity, and education benefits, SUWM also seeks to make cities more resilient to climate change, while delivering cost-effective infrastructure with a lower carbon footprint than conventional drainage solutions. By greening and cooling urban areas, SUWM techniques will help reduce the urban heat island effect (UHIE), improve air quality, and contribute to carbon reduction and sequestration. Techniques such as green roofs, green walls or trees also help to regulate building temperature, reducing the need for air conditioning and the associated energy costs and greenhouse emissions, as well reducing outside surface temperatures through evapotranspiration. Gill et al. (2007) have shown that adding 10% green cover can reduce maximum surface temperatures by 2.4 to 2.5 ºC.

Alongside these benefits, SUWM can have other associated benefits that include crime reduction, economic growth stimulation, tourism promotion, and the provision of traffic calming measures. Kuo and Sullivan (2001) show that vegetation can inhibit crime by increasing informal surveillance as well as mitigating some of the psychological precursors to violence, such as mental fatigue; indeed, contact with nature has been linked with enhanced cognitive functioning and so may aid in the recovery from mental fatigue. By using water as a resource to create a sense of place and identity, SUWM can stimulate economic growth through a variety of ways: increased consumer spending, enhanced attractiveness of an area to new businesses, creation of jobs associated with technical maintenance of SUWM devices, and improved productivity of workers. The enhanced attractiveness of an area and the use of local resources in a creative way can also promote visitors to the area and tourism. SUWM can also contribute directly or indirectly to traffic calming measures when incorporated in the urban streetscape (Charlesworth, 2010; Susdrain, 2012; Woods Ballard et al., 2015).

In this way, SUWM should be integrated with traditional drainage solutions where appropriate, in order to provide the best possible urban water management solution. As stated by Faram et al. (2010), because each city, river, and wetland is unique, "the challenge is to interpret local needs, opportunities and constraints, combining the most appropriate technical solutions to provide the best outcome". The objective is to deliver robust and sustainable drainage, with the portfolio of options including the use of piped systems whenever these prove to be an effective solution (Faram et al., 2010; Graham et al., 2012; Hoban and South East Queensland Healthy Waterways Partnership, 2007). In this scenario, the established traditional drainage system provides relief from rare and infrequent rainfall events, while the decentralised, sustainable drainage approach manages the more frequent runoff and provides a more flexible and adaptable solution to urban water management, simultaneously using water as a resource to provide new recreational uses and place-making opportunities, as well as improving biodiversity and providing climatic benefits.

One of the main barriers to implementing SUWM measures is concern over long-term performance and maintenance costs. Heal and colleagues (2008) describe the medium-term performance and maintenance of SUDS implemented in Hopwood Park Motorway Service Area (MSA), central England, with regards to flow attenuation, water and sediment quality, ecology, management and maintenance, through different assessment studies conducted between 2000 and 2008. The SUDS were designed to attenuate the 1 in 25 year storm runoff, provide a greenfield runoff rate of 5 L/s/ha, and treat the first 10 mm of storm runoff. The study showed the benefits of using a 'SUDS management train' as opposed to individual SUDS measures as peak flows, pond sediment depth and contaminant concentrations in sediment and water were found to be reduced throughout the management train. This also meant that the cost and frequency of sediment removal was much lower than what was initially projected. Finally, maintenance costs were found to be substantially lower for SUDS (£ 2500 per year) than for conventional drainage structures (£ 4000 per year).

Cities are complex environments, and the big challenge is to implement SUWM within the constraints of a pre-existing urban area. Also, the fragmented nature of these decentralised systems will require greater stakeholder engagement and community participation, especially as many interventions may be applicable at the level of individual property owners. An open-minded attitude towards new ideas will be required, making the challenge as much sociological as it is technological (Faram et al., 2010).

2.2.5 Case studies

2.2.5.1 The Woodlands ecologically planned community, Texas, USA, 1976

The Woodlands was one of the first communities in the USA to implement innovative methods to minimise the impact of stormwater runoff on receiving waters. This new town development of nearly 11700 ha followed Ian McHarg's ecological planning approach, with a focus on stormwater management. A unique water management plan was designed to avoid the adverse water quality and hydrologic effects from urbanisation as well as to preserve the forest environment. As such, the main strategies were to: (1) preserve land with highly permeable soils, (2) maintain forest preserve land and (3) use open surface drainage.

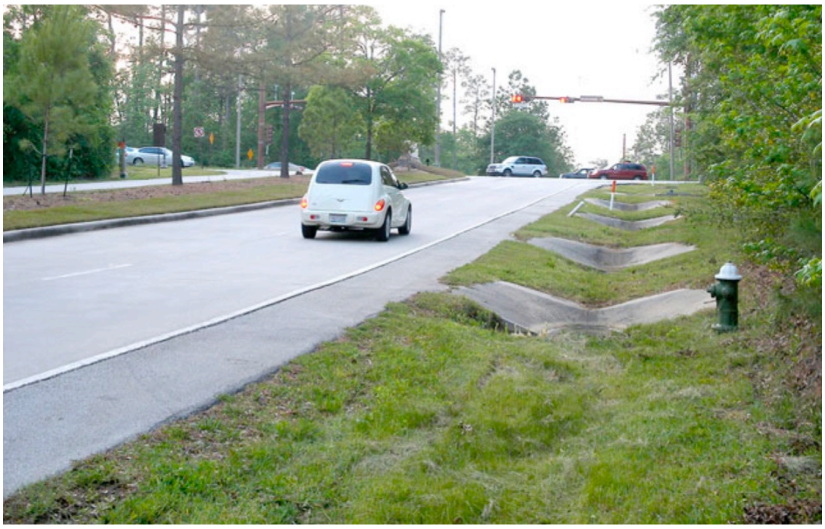

Figure 2.24 Open surface drainage at The Woodlands with check dams to retard runoff and promote infiltration where soils present good permeability (Yang et al., 2015)

This was important as about one-third of the site lies within the 100-year floodplains, with areas of poorly draining soils and flat topography. The area also suffered seasonal hurricane events, which often lead to widespread flooding. This strategy allowed The Woodlands to survive a 100-year storm in 1979 and a 500-year storm in 1994 with limited property damage. However, following a management ownership change in 1997, after which McHarg's planning approach was largely abandoned, floods were reported in 2000, 2008 and 2009 (US EPA, 1979; Yang et al., 2015). It was shown that McHarg's approach generated much less stormwater runoff and lower peak discharges (Yang and Li, 2010). McHarg's open drainage design allowed for remarkable construction savings of $14 million (construction price was $4.2 million, compared to conventional drainage that would have cost $18.7 million), as well as savings when increased erosion, runoff and flooding hazards were avoided (Yang et al., 2015).

McHarg's planning approach is a unique case which has to date never been replicated at a similar scale. It was possible due to the commitment and financial support of the developer George Mitchell, a

US Department of Housing and Urban Development loan of $50 million, and the flexible planning system in the US in the 1970s. However it has been noted that some of the strategies used in The Woodlands, such as open surface drainage channels, can be seen in contemporary practices, such as the rain gardens and stormwater planters seen in Portland, Seattle, Philadelphia, and Kansas City, amongst others (Yang et al., 2015).

2.2.5.2 Victoria Park inner city urban redevelopment, Sydney, Australia, 2002

Victoria Park is a 24 ha mixed-use development with housing, commercial and retail facilities for a population of 5000. The site was originally part of a large wetland and lagoon ecological system and was first developed as a racecourse in the 1800s. It was later used for heavy industry, having become an abandoned and degraded brownfield site until its redevelopment in 2002. This inner city urban redevelopment project was designed with an innovative site-wide water management system that was successfully integrated with the urban design concept, leading it to become a benchmark project in water sensitive urban design.

The design concept embodied four key principles: site-wide environmental strategy, interpretation of the natural wetland systems, site connectivity and community development. The east-west streets, which are wider and have better solar access, feature bioretention swales or wetlands, while the north-south streets are traditional avenues. This provides a consistency and legibility to the design of the public domain. The planting of indigenous wetland species also provides a unifying theme in the design, along with public artworks that express and celebrate improved water quality achievements (Hassell Studio, 2017; Hoban and South East Queensland Healthy Waterways Partnership, 2007).

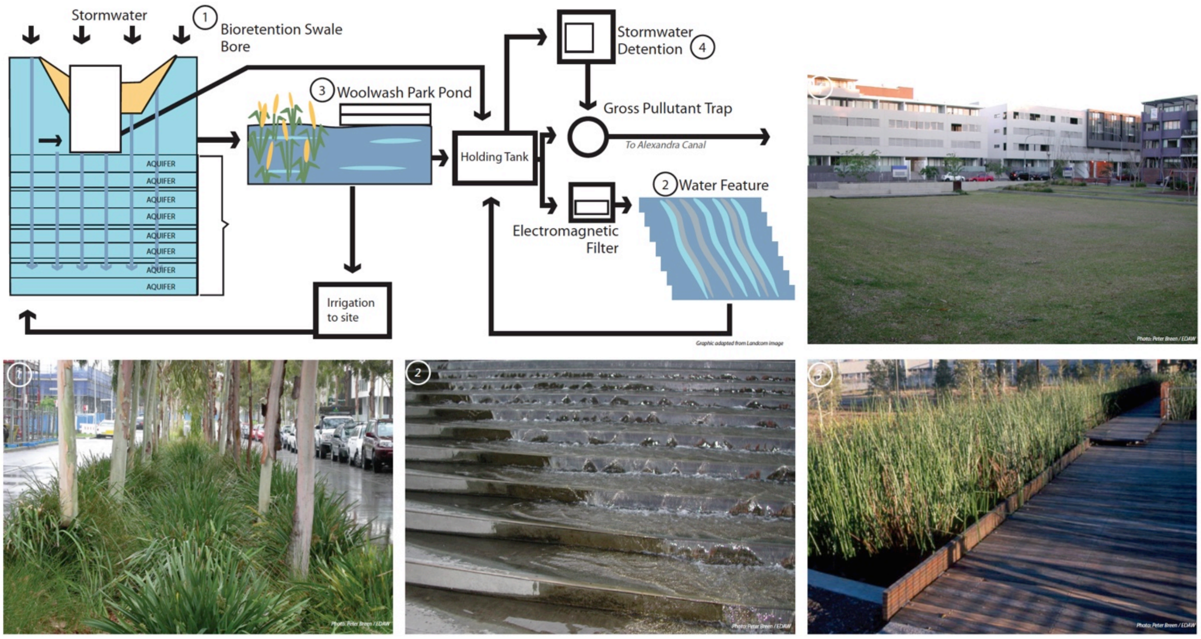

Figure 2.25 Schematic description and illustrative photographs of the water management system in Victoria Park (Hoban and South East Queensland Healthy Waterways Partnership, 2007, p. 95)

The park provides a variety of settings to be enjoyed by the community including plazas, playgrounds, public artworks, water features, large open spaces and amphitheatres. As described by the designers, “Victoria Park provided proof that natural systems, or constructed ecologies can work in urban environments (…), redefines the role of natural systems, and exposes the shortcomings in the ideas of landscape as ornament” (Hassell Studio, 2017).

2.2.5.3 Hans Tavsens Park and Korsgade, Nørrebro, Copenhagen, Denmark, 2016

SLA, a Danish based group of urban quality experts from the fields of urban space, city planning and landscape architecture, have established and practised a new model for city development for the last twenty years, termed the Nordic Model. This model is based on co-creation, dialogue, and humanistic nature-based solutions, and addresses physical, social, and cultural challenges within the city. SLA’s project ‘The Soul of Nørrebro’ addresses these issues for the Nørrebro district of Copenhagen, through the design of a climate adaptation and renewal project for the Hans Tavsens Park and Korsgade street. The project aims to redirect rainwater from cloudbursts and recycle stormwater while simultaneously providing attractive and liveable urban spaces. Hans Tavsens Park will simulate a natural water catchment and will be able to handle up to 18000 m^3 of water at one time, with excess water being conveyed through Korsgade street to the Copenhagen lakes, while it is simultaneously treated by biological purification. The system will also pump water from the lakes in dry periods so there is a continuously visible water feature in the city. This will simultaneously help to purify the lake water, which is filled with phosphorus, as it is then conveyed back through the biotopes on Korsgade street in a self-cleansing circuit (SLA, 2016).

Figure 2.26 Render of the Hans Tavsens Park in ‘The Soul of Nørrebro’ project, showing the Park’s temporary function as a rainwater retention basin (www.sla.dk/en/projects/hanstavsenspark)

CHAPTER 3

SITE ASSESSMENT AND STRATEGIC PLANNING

3.1 METHODOLOGICAL FOUNDATION

In this chapter a practical case study is discussed to implement the theoretical concepts in sustainable urban water management outlined in chapter 2. The case study is the Alcântara watershed, located in the city of Lisbon, Portugal. The Alcântara watershed is the largest watershed intersecting the city of Lisbon, with an area of 3673 ha and spanning three municipalities: Lisbon, Amadora and Odivelas. Figure 3.1 shows the administrative borders of the watershed (Direcção Geral do Território, 2015).

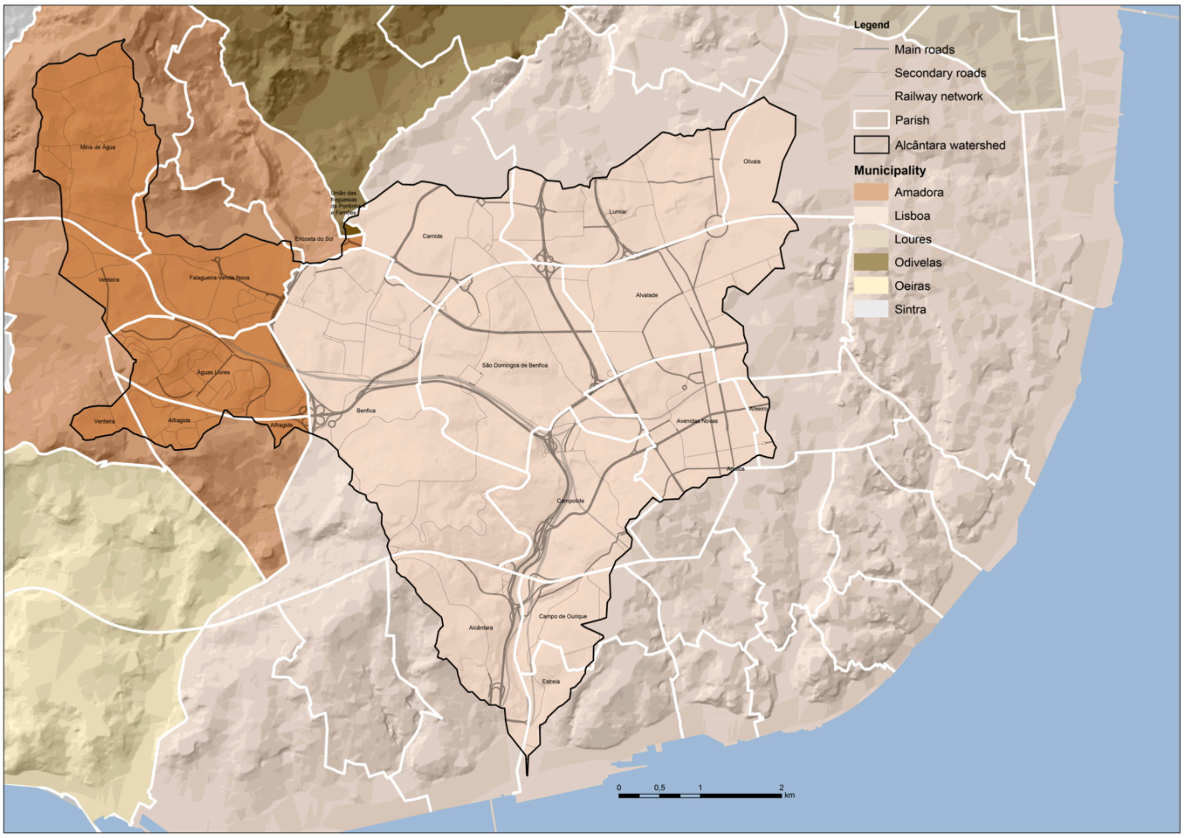

Figure 3.1 Administrative borders (municipalities and parishes) within the Alcântara watershed (Direcção Geral do Território, 2015)

The first section of this chapter provides a site assessment of the case study watershed and the second section proposes a water management planning strategy to move towards the development of a more resilient city. The concept of a resilient city is discussed, providing a methodological foundation for the case study's site assessment and strategic planning.

As outlined in the Introduction, the predominantly technocentric approach to water management in cities has been unable to consistently protect society from water-related risks, such as flooding and water scarcity events. Population growth, urbanisation and climate change are three of the most important drivers that magnify the risk of water-related hazards to people, property and the environment (White, 2010, p. 94). The development of more resilient cities, "where urban form and function are connected to the natural environment in a manner complementary and appropriate to their geographical context", has been proposed as a conceptual framework to manage these risks (White, 2010, p. 34).

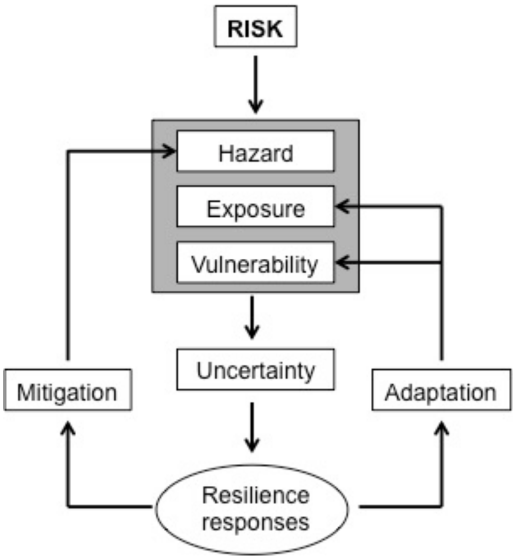

Figure 3.2 Resilience responses as a framework to address risk (White, 2010, p. 110)

Risk can be understood as the result of three interrelated elements: hazard, exposure and vulnerability. A resilient city is able to more successfully target how and why urban hazard, exposure or vulnerability are driven and take remedial action. According to White (2010, p. 126), "strategies to manage risk by proactively reducing hazard, vulnerability and exposure have the potential to increase resilience in the medium and long term". As shown in Figure 3.2, resilience responses can include mitigating the strength of the hazard by reducing its driving forces, while adapting to exposure and vulnerability by changing to a new normality. These two types of resilience responses reflect the dual definition of the resilience concept, which can be understood either as a restoration of equilibrium or as an adaptation to differing circumstances. The differences between adaptation and mitigation strategies can be temporal (adaptation strategies usually have a faster effect than mitigation strategies) and spatial (adaptation strategies have a stronger local impact whereas mitigation strategies can affect much larger scales). Nonetheless, it is important to note that these strategies can be complementary and should not be viewed as operating independently (White, 2010, p. 107-110).

With regards to water-related hazards in the city, although their origin is natural, their effect is manufactured, representing a socially and culturally constructed risk. In this way, water-based hazards can be both naturally driven, such as by climate, and anthropogenically driven, such as by urbanisation. Given that anthropic drivers are generally more easily controlled than natural drivers, strategies to reduce these hazards are mainly concerned with how we use land, and in particular with the interaction between precipitation and the surface of the urban area. The main strategies are concerned with the control of runoff and with capturing and storing water for consumption, which can be delivered through the use of SUWM strategies as well as through the appropriate design of green infrastructure (White, 2010, p. 126-138).

Adaptation strategies to reduce exposure to flooding are mainly concerned with a more strategic consideration of land use, where development is located according to hydro-geographical principles rather than driven by socio-economics. This could involve altering the location of buildings, defending the land, or increasing the capacity to store and transport water. With regards to water scarcity, adaptation strategies are mainly concerned with increasing supply, such as promoting groundwater infiltration, and decreasing demand, by influencing usage within three main sectors, agriculture, industry, and household (White, 2010, p. 147-153).

As shown above, strategies to reduce hazards and exposure are mainly concerned with spatial planning and address *how* and *where* protection can occur. On the other hand, strategies to reduce vulnerability are more concerned with the operation of society as a whole, and address *what* and *who* should be protected, focussing on the function of places and on people and communities. This can involve reducing the level of critical infrastructure at risk, identifying and engaging with vulnerable groups of people, addressing social inequalities, and so on. Although the application of strategies to reduce vulnerability present real challenges due to their interdisciplinary nature, it is important to acknowledge the city's broader social context and the operation of its institutions, as well as the important role these may have in influencing resilience (White, 2010, p. 160-171).

Finally, it is important to note that the foundation of any water resilient city is knowledge, which provides a logical mechanism to reduce uncertainty. Historically, our understanding of most water risks has been highly uncertain, and the largely accepted view that societies should act where consequences and uncertainty are high, has been largely unsuccessful with regards to water risks. Thus, the best approach is to expand knowledge and science related to water in the city in order to be able to make strategic and informed land use decisions based on a robust evidence base. The necessary knowledge requirements for informing intervention are outlined in Figure 3.3 (White, 2010, p. 111-116).

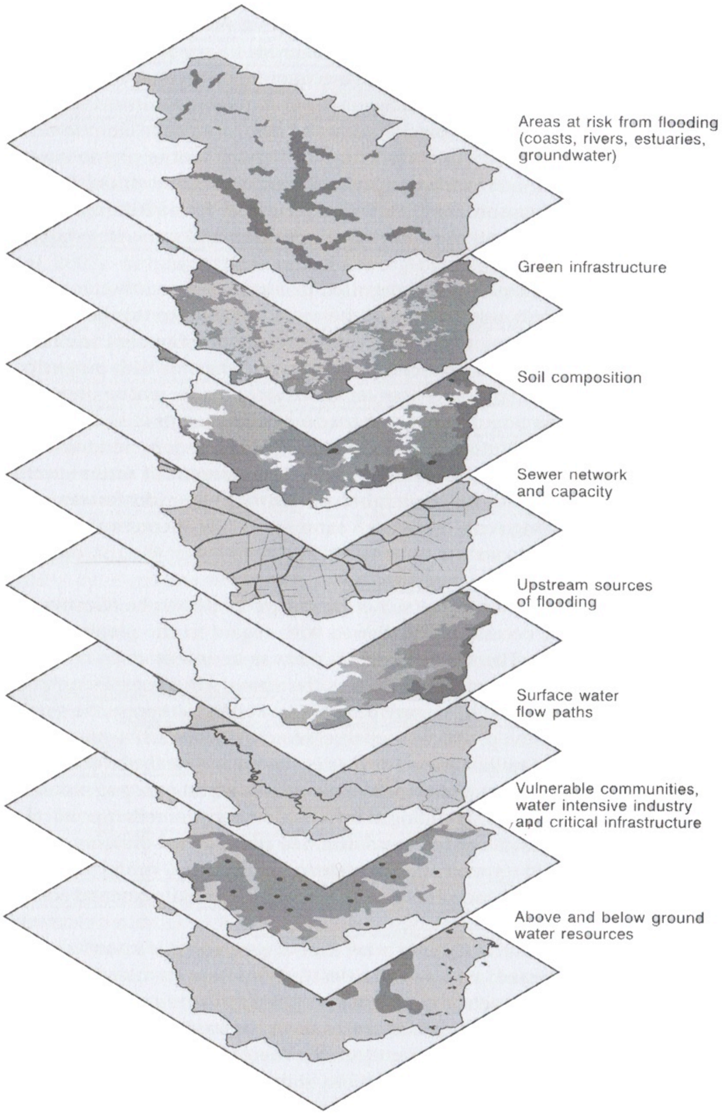

Figure 3.3 The layers of knowledge required for moving towards a water resilient city (White, 2010, p. 116)

In conclusion, resilience provides an important framework to address risk because of the ability to address uncertainty, the potential to adapt to minimise impacts, and facilitating the capacity to respond (White, 2010, p. 102).

The site assessment section of this chapter aims to contribute to the knowledge base of the case study watershed, although in the scope of this thesis it is not be possible to provide all the knowledge layers outlined in Figure 3.3. Nonetheless the data collected aims to contribute to a more informed platform for decision-making in the strategic planning section of this chapter. The collected data is divided into ecological and anthropic factors that affect the watershed at a regional planning scale (1:35.000). The ecological factors include geology, soils, infiltration potential, landform, aspect, hydrology and slope, flood risk, and green infrastructure, and the anthropic factors include built and permeable areas, land use, and the existing and proposed drainage network.

In the strategic planning section two overview maps are presented, one for the ecological factors and another for the anthropic factors, providing a multi-layered view of the most relevant assessment factors that can inform the sustainable urban water management of the Alcântara watershed. These overview maps, along with the identification of the void spaces in the watershed, provide an important tool in the selection of sites where SUWM strategies may be implemented. Finally, a system of corridors is proposed, which defines areas where SUWM strategies, as well as a broader green infrastructure strategy, can be implemented.

The limit of the case study area was determined in ArcGIS using the *Watershed* function, for which the original input was a digital terrain model with a resolution of 10 m, generated from a contour map with an equidistance of 10 m (Instituto Geográfico do Exército, 2008). Figure 3.4 shows the case study watershed in the context of the surrounding watersheds of the Lisbon area.

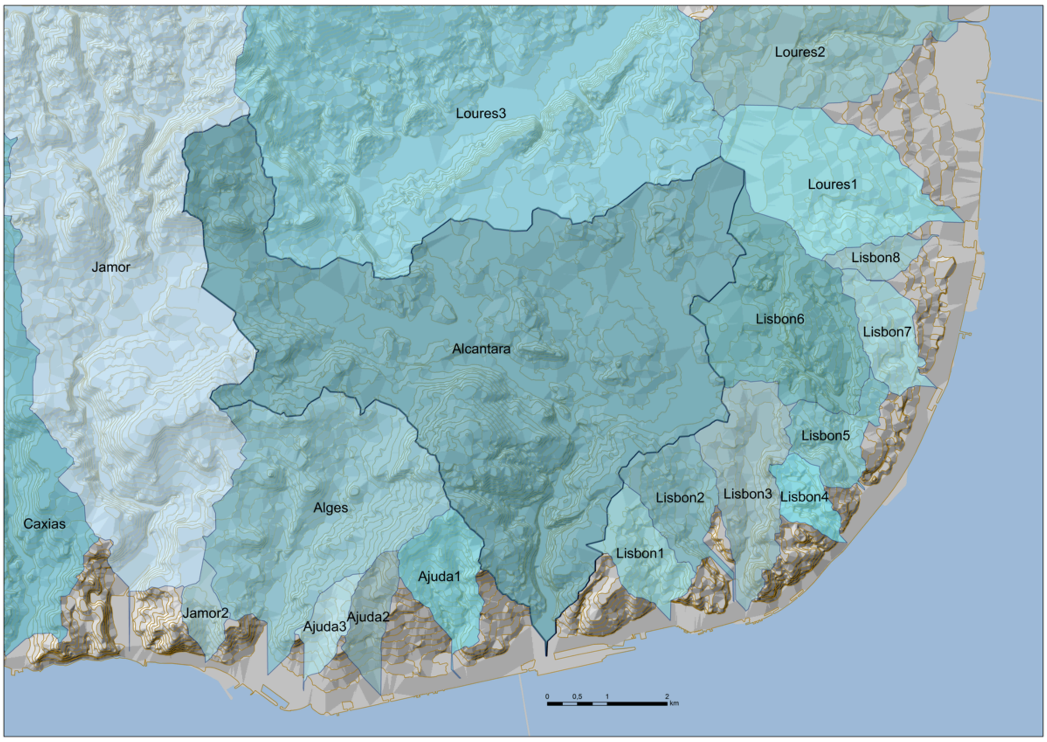

Figure 3.4 Watersheds in and around the city of Lisbon

3.2 SITE ASSESSMENT FOR THE ALCÂNTARA WATERSHED

3.2.1 Historical analysis

Water has had an important role in the development of the city of Lisbon, as historically the availability of potable water has always been limited. The city of Lisbon was established on the hill of the St George Castle, and grew under Roman influence from 195 BC onwards, from its establishment as a 'citadel' to its classification as a Roman 'municipality' (Câmara Municipal de Lisboa, 2017a). Under Moorish rule from 700 AD, Lisbon remained confined to the hill of the St. George Castle and Alfama (*Cerca Moura*, Fig. 3.5), the only area of the city with a potable water supply, which was sourced from wells and cisterns, as well as rainwater. By the 14th century the city had grown beyond the medieval walls, and was confined by the *Cerca Fernandina* (Fig. 3.5). During this time, most of the water supply came from springs that were outside the city walls. This led to the renovation of several fountains inside the city gates, known as *chafarizes*, in the 15th century (Arquivo Municipal de Lisboa, 2014).

Figure 3.5 Lisbon's historic city walls; the *Cerca Moura* under Moorish rule from the 8th century and the *Cerca Fernandina* under King Ferdinand from the 14th century (Boaventura, 2016)

In the 16th century, the economic prosperity that resulted from the Portuguese maritime explorations led to a population expansion beyond the *Cerca Fernandina*, prompting a more rational urban design for new developments such as Bairro Alto, as well as the constructions of new *chafarizes* in these areas of the city with no local water supply. After 60 years of Spanish rule, which ended in 1640, King John IV delineated a new urban perimeter, which extended from Santa Apolónia in the east to Alcântara in the west. In the 18th century, under King John V, construction works to improve and enlarge the city were undertaken. This included construction works in Alcântara, such as the enlargement and restoration in 1743 of the bridge over the Alcântara River, which historically had always been an important entry point to the city of Lisbon. It also included the construction of the *Águas Livres* Aqueduct in response to the problems of water scarcity in the city, which continued to intensify. Construction of the Aqueduct, to bring water from Belas to the city of Lisbon, began in 1731, and included a network of canals that spread out 58 km away from the city, collecting water from 58 springs. Upon reaching the city of Lisbon, the water entered the Aqueduct, crossing the 941 m stretch over the Alcântara valley towards the water reservoir on the east side of the valley known as the *Mãe d'Água*. The construction of the Aqueduct was completed in 1744, and by 1748 this engineering feat was supplying water to the city of Lisbon. For over 200 years it supplied the city with 1300 m^3 of water per day, until its deactivation in 1967 (Câmara Municipal de Lisboa, 2017a; Marques, 2009).

After the 1755 earthquake, the King's Prime Minister, the Marquis of Pombal, was in charge of the reconstruction of the city. His plan encompassed not only the reconstruction of the destroyed downtown city, following an innovative system based on symmetry and aligned streets, but also presented an integrated and global vision for the city's expansion. This included new urban areas (such as Amoreiras, Lapa and São Bento) which followed the same design rules as downtown Lisbon, a plan to improve the Port of Lisbon, and a 'Public Promenade' (*Passeio Público*), one of the first public green spaces of the city, which was built to the north of the Rossio square, marking the future direction of the city's expansion (Câmara Municipal de Lisboa, 2017a; Marques, 2009).

The reconstruction of the city led to an increased demand for raw materials, many of which came from the quicklime ovens and limestone quarries located in the Alcântara valley. The need for water as a source of energy led to the establishment of an increasing number of industries along the Alcântara valley, which was well positioned and in close proximity to the city (Marques, 2009).

A period of political instability in the late 18th century marked the end of the city's major reconstructions, and was followed in the beginning of the 19th century by a period of industrialisation, which greatly affected the Alcântara valley. Most of the factories that were established in the Alcântara valley at this time were linked to the textile industry. New neighbourhoods were constructed to house workers, such as the Calvário neighbourhood in 1877, establishing Alcântara and its valley as a suburb of Lisbon rather than merely as a limit of the city (Marques, 2009).

The construction of two railway lines in the 1880s that linked Alcântara to Sintra in the west and to northern Lisbon had an important effect on the development of Alcântara, stimulating population growth in this area. The few plans that existed for the construction of new housing did not provide an effective response to the growing population's needs, leading to the development of several shantytowns on the outskirts of Lisbon. One example is the *Casal Ventoso* neighbourhood, located on the steep left bank of the valley, which for many years housed much of the population working in Alcântara. Many other areas of shanty housing sprung up throughout the Alcântara valley, around the urban perimeter of the city of Lisbon.

Between 1944 and 1957, Avenida de Ceuta was constructed along the main watercourse of the Alcântara valley in order to link Alcântara to the growing urban areas of northern Lisbon. This required much of the Alcântara River to be piped, as shown in Figure 3.6, a landmark event in the history of the watershed. The construction of the bridge over the Tagus River, the *Ponte 25 de Abril*, in the 1960s also had a significant impact on Alcântara, leading to its fragmentation and to a deterioration in its inhabitants' quality of life. The construction of the bridge, which involved the expropriation of land by the state and the demolition of housing in Alcântara, led many of the industries to relocate to other peripheral areas of the city.

These new constructions, including the railways, Avenida de Ceuta, the Tagus bridge, and the reclaimed land for the Port of Lisbon, firmly established Alcântara as an infrastructure channel and a gate to the city on both a local and a regional level (Marques, 2009).

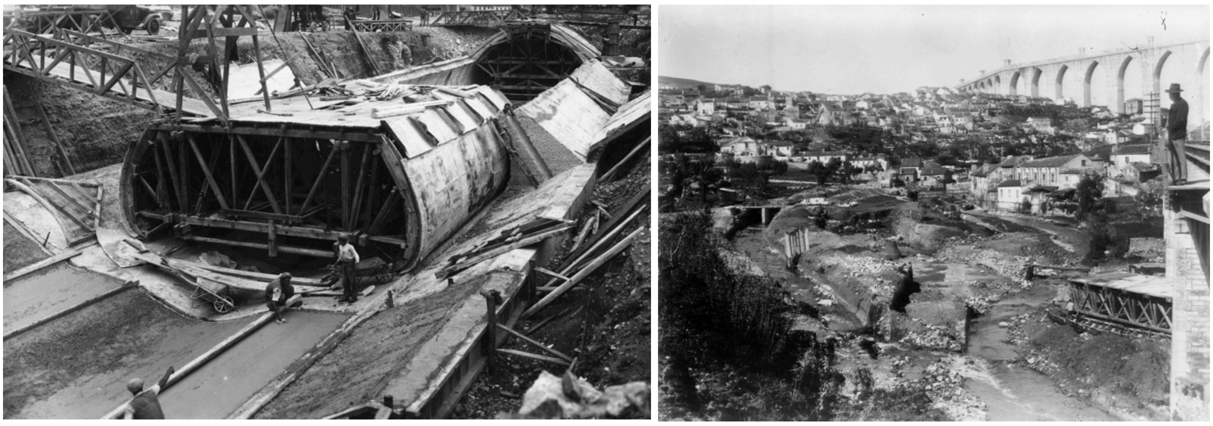

Figure 3.6 Construction works to pipe the Alcântara River (Portugal, 1947, 1945)

Since the second half of the 20th century the downstream areas of the watershed, which include the town of Alcântara, as well as some of the flatter upstream areas such as Benfica, Sete Rios, and Praça de Espanha, have historically been prone to flooding. Flooding in these areas has largely been exacerbated by an unplanned and haphazard urban development, the piping of the Alcântara River, and a failure to clean the pluvial drainage system of debris at the start of the rainy season, all of which have a significant effect on surface water flow.

The most dramatic of these floods occurred on the night of the 25th November 1967, and affected all the major water basins around the greater Lisbon area, leading to over 700 deaths. Heavy rainfall fell in a very short amount of time, with 159 mm of rainfall registered in 24 h (roughly 1/5 of the total mean annual rainfall), 129 mm of which was registered in 5 hours, and a return period for the event which was calculated at 500 years (Ramos and Reis, 2001). The cause of the abnormally heavy rainfall was the convergence of a cold front from the northwest with an advection of warm air from the southwest, brought by the subtropical jet, resulting in a huge development of cumulo-nimbus clouds and the movement of the depression to the northeast, in the direction of Lisbon (O Século Ilustrado, 1967; Ramos and Reis, 2001). Nonetheless, this flood had especially catastrophic effects as it occurred around the periphery of Lisbon, an area that at the time had a high population density, where many poor people lived in shanty houses, many of which were located in flood plains (Figure 3.7). The intensive urbanisation that occurred throughout the second half of the twentieth century also aggravated the flood's effects, creating higher volumes of surface water run-off, intensifying the effects of the floods. Additionally, buildings that had been legally constructed on riverbed banks were destroyed when the banks collapsed. Although this rainfall event was exceptional, its consequences were greatly exacerbated by a lack of land use planning, as well as a failure to comply with basic rules of hydraulic planning and even a failure to comply with the law (Ramos and Reis, 2001).

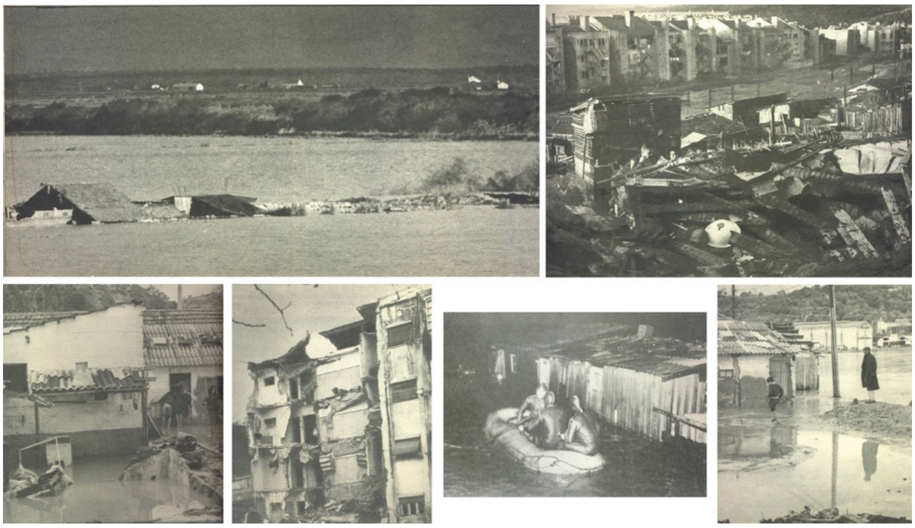

Figure 3.7 Effects of the 1967 floods on the greater Lisbon area (Source: O Século Ilustrado, 1967)

In the face of this accelerated urban growth and the accompanying social changes, the Lisbon Municipality questioned the planning methods used throughout the 1940s to the 1970s, and by 1992 had elaborated a Master Plan for Lisbon (*Plano Diretor Municipal*) that sought to define the guiding principles for the planning process, as well as priority objectives for the city (Câmara Municipal de Lisboa, 2017b). The Master Plan that is currently in force was updated in 2012 and aims to stimulate urban rehabilitation, improve the quality of public spaces, promote sustainable mobility and increase environmental efficiency, as well as attract more inhabitants, businesses and jobs (Lisbon City Hall, 2013). This Master Plan was submitted as a project entitled 'Lisbon Atlantic Capital of Europe' to the International Society of City and Regional Planners Conference in 2013, and was distinguished with an award for excellency (ISOCARP, 2017).

These planning strategies appear to have been effective in controlling flooding, as shown in Figure 3.8 by the decrease in the number of flood events in the Lisbon municipality despite the increase in precipitation levels. The period analysed (1918/19 to 1993/94) can be sub-divided into three groups based on the frequency of flood occurrences, the first from 1918/19 to 1934/35, the second from 1935/36 to 1969/70, with a clear increase in the number of flood events, which corresponds to the period of unplanned urban development in Lisbon, and the third from 1970/71 to 1997/98, where the frequency of flood events decreased. According to Oliveira (2005), this decrease in flood event frequency from 1970/71 to 1997/98 reflects the different interventions that were carried out on the city's drainage system, as well as a greater efficacy in collecting litter and debris that frequently obstructed the drainage system. These interventions greatly improved the flow capacity of the city's drainage system, but did not completely resolve the flooding issue, as shown by recent flooding events in 2011 and 2014. These events affected not only the city's lowland riverfront, where the tides can have an aggravating effect on flood events (SIC Noticias, 2011), but also the flatter upland areas of the Alcântara watershed, such as Damaia, Benfica, and Praça de Espanha (SIC Noticias, 2014; TVI, 2011).

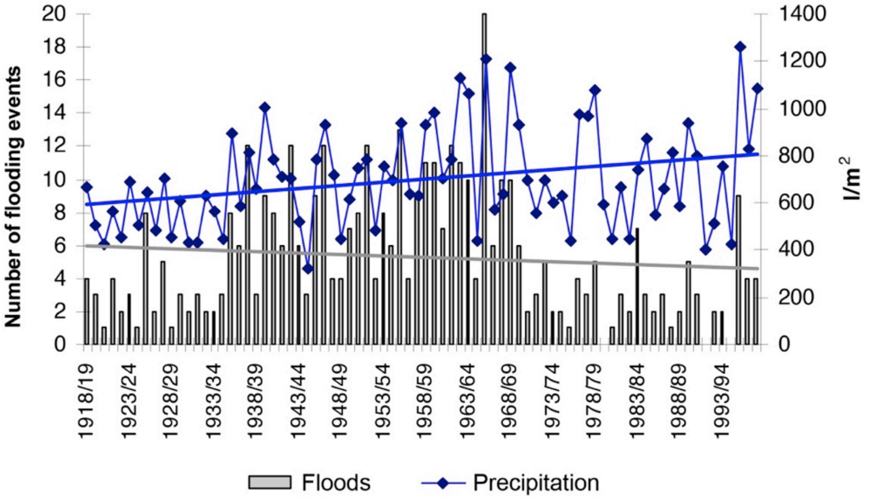

Figure 3.8 Number of flooding events and amount of precipitation in L/m^2 (or mm) in the Lisbon municipality from 1918/19 to 1993/94 (Adapted from Oliveira, 2005)

Most recently, the Lisbon Municipality's General Drainage Plan has outlined the strategies to be adopted between 2016 and 2030 in order to control the risk of flooding and water pollution in a rational, transparent, and sustainable way, taking into account economic, social and environmental costs. The Plan advocates for an advanced system management as seen in other European cities, which associates structural solutions with decentralised source control solutions such as BMP's or SUDS, and promotes the use of flow control equipment and real-time modelling and management in order to direct water flows to water treatment stations (known as *Estação de Tratamento de Águas Residuais*, or *ETAR*) and reduce flooding and water pollution (Leboeuf et al., 2015, p. 19-20). Annex 6 outlines the Plan's main criteria for the implementation of source control solutions, which relate primarily to rainwater quality and soil characteristics. The Plan discusses three macro alternatives to address flood events in the Alcântara basin and adapt to the drainage challenges brought on by climate change: (A) attenuate peak flows by building two underground attenuation storage tanks in upland areas (total storage volume of 51 500 m^3) and disconnect pipes that lead to the lower Alcântara area; (B) attenuate peak flows by building five possible underground attenuation storage tanks in upland areas (total storage volume of 170 000 m^3) and divert flows from the Alcântara watershed towards Av. Liberdade and Av. Almirante Reis; (C) construction of a 5 km underground tunnel that crosses several important watersheds and diverts flows from the main pipe of the old Alcântara River towards Santa Apolónia (Figure 3.9). This tunnel would allow for flows with a return period of over 20 years, considering climate change. Along with other smaller-scale above-ground interventions, the construction of the tunnel (alternative C) was considered to be the most technically favourable solution, as well as the one with the lowest social and environmental impact and the lowest investment costs. Although the Plan focuses largely on structural solutions, it recognises that complementary interventions, including decentralised source control solutions, are a fundamental measure to adopt (Leboeuf et al., 2015, p. 171). For the Alcântara basin, these include infiltration and detention measures, such as pervious pavements, infiltration trenches, and detention/infiltration basins. The Plan observes that the urban tissue in the eastern section of the Alcântara watershed is largely consolidated, with few open areas, concluding that source control solutions should be encouraged in open areas, such as the Monsanto Park, or in new developments (Leboeuf et al., 2015, p. 245). The Plan discusses the ability for these solutions to minimise peak flows, but does not discuss measures that address water quality, biodiversity, or amenity, which are fundamental tenets of this approach.

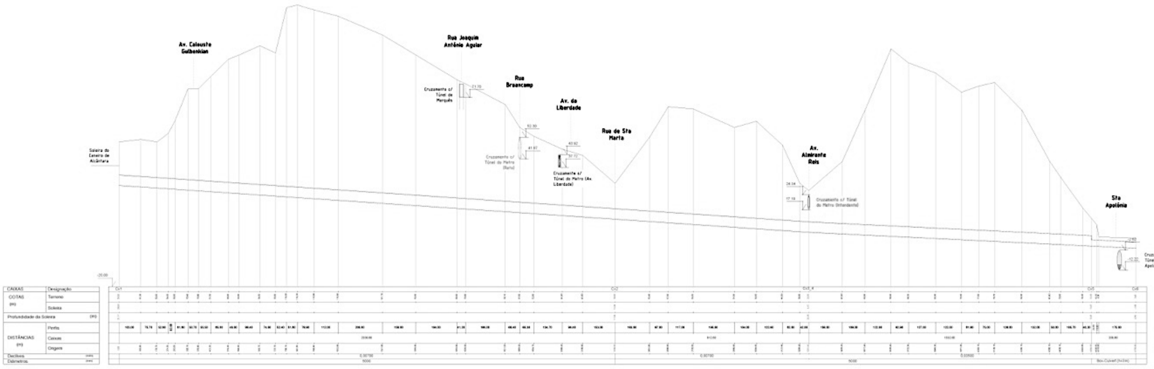

Figure 3.9 Cross-section of the 5km tunnel proposed by the General Drainage Plan for Lisbon to divert flows from the Alcântara watershed towards the Tagus River (Leboeuf et al., 2015, p. 150)

On the 28th September 2016 the Lisbon Municipality launched its green corridor project for the Alcântara valley, which covers an area of 13 ha over a 3 km corridor. The ecological goals of the project, which include regulating surface water flows, increasing the amount of vegetation, and designing a green corridor which provides ecological continuity with other green spaces in the city, is allied to social concerns related to citizen's mobility and quality of life. The complex road and rail connections between Sete Rios and Alcântara currently make it impossible for pedestrians or cyclists to access much of the area. In view of this, a pedestrian bridge and tunnel (Figure 3.10) have been planned near the *Águas Livres* Aqueduct. The project aims to provide pedestrian and cycle paths with better links to the rest of the city, improved lighting, additional green spaces with the introduction of over 700 new trees, a watering system that uses recycled water, and public infrastructure. According to the project description, "by increasing the amount of green spaces with trees and optimising the water cycle, this corridor will play a vital role in the city's climate change adaptation process" (Câmara Municipal de Lisboa, 2017c).

Figure 3.10 Render of the public spaces provided by the Lisbon municipality's green corridor project for the Alcântara valley (Câmara Municipal de Lisboa, 2017c)

3.2.2 Ecological factors

3.2.2.1 Geology

The Portuguese territory is made up of three main geomorphic provinces (Figure 3.11); the Iberian Massif, which consists of rocks from the Palaeozoic Era formed around 300 Ma by the Variscan Orogeny; the Meso-cenozoic sedimentary basins (the Algarve and Lusitanean basins), which formed between 200 and 70 Ma during the sedimentary phase of the Alpine Orogeny; and the Tagus-Sado sedimentary basin, which formed around 70 Ma between the Mesozoic and Cenozoic Eras as a result of the opening of the North Atlantic, and which began to be filled with sedimentary deposits during the early-middle Eocene (Medeiros et al., 2005; Pais, 2012). The study area is located within the Tagus-Sado basin, the most recent geomorphic province in the Portuguese territory.

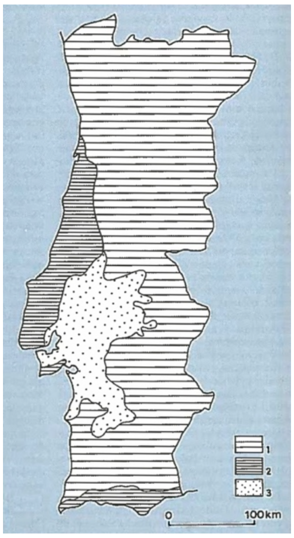

Figure 3.11 Geomorphic provinces of the Portuguese territory; 1 – Iberian or Hesperic Massif, 2 – Mesocenozoic sedimentary basins, 3 – Tagus-Sado Cenozoic sedimentary basin

The geological outcrops of the Alcântara basin (Drawing Annex 01) date back at least 100 million years, to the Albian Age of the Mesozoic Era. Apart from the alluvial deposits that delimit the hydrological network, and the marine terrace deposits, the most recent outcrops are from the Neogene period of the Cenozoic, dating back at least 11 million years. Annex 7.1 shows the geological time scale of the formations present in the Alcântara watershed.

Figure 3.12 provides a cross-section of the geological formations in and around the Alcântara watershed (Drawing Annex 01), showing their relative depths. These can be broadly divided into three categories; igneous rocks, which includes the basaltic formations of the Lisbon Volcanic Complex; sedimentary rocks, which include different formations of limestone, sand and clay; and unconsolidated sediments, such as the alluvial deposits found in the river valleys and the marine terrace deposits. Annex 7.2 describes the geological formations of the Alcântara basin in greater detail.

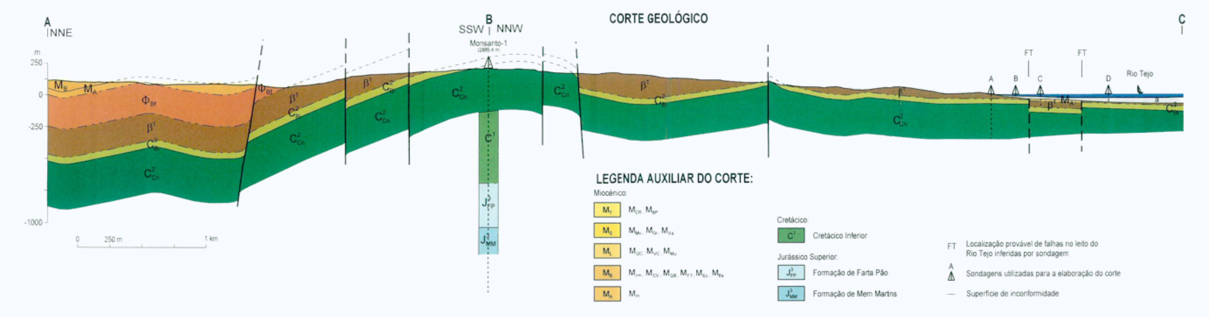

Figure 3.12 Cross-section of the geological formations in and around the Alcântara watershed

The Early Cretaceous Aquifer that underlies Lisbon is a multi-layered aquifer made up of sandstone and clay from the lower Albanian – upper Barremian. It is semi-confined by the Early Cretaceous volcanic deposits, namely the Lisbon Volcanic Complex, which has a low permeability, and the Paleogenic Marlstone formation (Benfica complex). These Albian and Cenomanian limestone formations (C^2C_n and C^2B_i in Drawing Annex 01) present interesting hydro-geological properties, especially when fractured and karstified (Pais et al., 2006). These properties include a transmissivity[4] of up to 400 m^2/day, 15-25% effective porosity, flows of up to 180 m^3/h and temperatures of 50 ºC at a depth of 1500 m. This data was obtained between 1987 and 2001 from a borehole exploration at a depth of 1495 m in Lumiar (Hospital da Força Aérea), which is located on the northern border of the Alcântara watershed. Studies so far suggest that this aquifer has a low rate of groundwater recharge and considerable compartmentalisation due to the faults, folds and dyke or sill intrusions of the Lisbon Volcanic Complex. It has also been shown that from 1987 to 2001 the salinity of the water has been increasing, suggesting either the intrusion of seawater or the release of evaporite, a water-soluble mineral sediment, from the geological formations above or below (Diaz et al., 2013). These features could limit its geothermal exploitation, but they also suggest that the artificial recharge of the aquifer may be limited, due to the low permeability of the rocks above the aquifer (Lisbon Volcanic Complex) as well as the apparent contamination of the aquifer with saltwater.

In the areas of Alfragide and Carnide, where the Lisbon Volcanic Complex predominates (central and western areas of the Alcântara watershed), the presence of water resources depend on the extent of rock weathering and on the existence of faults caused by tectonic movements. In Alfragide, faults of 80-117 m have been documented, as well as a flow of 0,6-3 L/s and a water table depth of 60-80 m (Pais et al., 2006). Another borehole exploration at a depth of 70 m near the Lisbon Airport, in the northeast area of the Alcântara watershed, indicated the presence of an aquifer from the Burdigalian Age, with a flow of 2,4 L/s and a water table depth of 31 m. This data indicates the possibility of groundwater recharge in these more recent geological formations.

In the Alcântara watershed's more urbanised areas, the alluvial deposits do not present an opportunity for groundwater recharge, as urban expansion in these areas has altered the nature of these deposits, reducing their permeability and their capacity for groundwater recharge.

3.2.2.2 Soil

The soil map for the Alcântara watershed uses the Portuguese Soil Classification System (Leitão et al., 2013; SROA/CNROA, 1969). Equivalent terms between this classification system and the World Reference Base for Soils (WRB) are established for the purpose of this thesis. The soil maps also indicates the ecological value of the soil, a parameter which is based on the characteristics of the soil and which indicates its relative scale of importance, considering productive and ecological potential. It

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[4] The transmissivity is a measure of how much water can be transmitted horizontally through the vertical cross-section of an aquifer, expressed in square metres per day.

considers five ecological value classes, which range from very high, five, to very low, one (Leitão et al., 2013).

The soil map for the Alcântara watershed (Drawing Annex 02) describes a large area classified as *Área social* (socially-influenced area). This term is used for areas that were not considered for soil identification given the extent of urbanisation and the resulting disturbance of the soil.

The central-western area of the watershed has a large area of *Barros*, which is equivalent to Vertisols in the WRB. These typically derive from basaltic rocks, such as those of the Lisbon Volcanic Complex, and have a high proportion of expansive clays (montmorillonite) that allows for the contraction and expansion of the soil in dry and wet weather, respectively. The soil’s contraction can lead to the development of large cracks, where organic matter tends to accumulate. When the soil then expands, this organic matter is incorporated in to the soil’s profile. These soils have a high ecological value as they have a high capacity to retain water and cations due to their mineral composition and as a result of isomorphic substitutions, which occur during clay formation processes. These soils have a low permeability as when it rains they soak up water, and when saturated they are almost impermeable. The natural vegetation for vertisols are grassland or savanna, with tree species being generally less successful as the roots can be damaged by the cracking of the soil (IUSS Working Group WRB, 2015).

The map describes small areas of *Solos argiluviados pouco insaturados (solos mediterrânicos)*, which can correspond to Luvisols, Lixisols, Alisols or Acrisols in the WRB, depending on the proportions of high or low activity clays and of high or low base saturations. Given the climatic characteristics of this region, the most likely corresponding classification would be Luvisols, which have high-activity clays (cation exchange capacity > 24 cmol/kg), with a high capacity to retain and supply nutrients, and a high base saturation. These soils derive from a variety of unconsolidated material including alluvial and colluvial deposits, and so are described as having an intermediate ecological value (IUSS Working Group WRB, 2015).

The western area of the watershed also presents soils derived from limestone (*Solos calcários*), which is abundant in the area (see Drawing Annex 01). According to the Portuguese classification, limestone-derived soils are defined as soils that contain calcium carbonate, but do not necessarily present an accumulation of calcium carbonate. Therefore these soils can be described in the WRB classification as Leptosols, Cambisols, Regosols, or Calcisols. They are described as having an intermediate ecological value, as the first three have a low ecological value and calcisols have a higher ecological value due to the substantial accumulation of secondary carbonates within the first 100 cm of soil (IUSS Working Group WRB, 2015). These soils generally present good permeability, depending on the proportion of clays they present (i.e. marl).

Interspersed with these limestone-derived soils are the *Solos de baixa (coluviossolos)*, which can correspond to Regosols or Fluvisols in the WRB. As Regosols are weakly developed soils in unconsolidated parent material, the most likely corresponding classification would be Fluvisols, which are generally young soils in fluvial, lacustrine or marine deposits. Fluvisols may have a weak horizon differentiation but a distinct topsoil horizon (IUSS Working Group WRB, 2015). These soils are considered to have a high ecological value.

Finally, a small area of *Solos litólicos não húmicos* is present, which can correspond to Cambisols, Leptosols, or Regosols. Generally these soils correspond to Regosols, which are weakly developed mineral soils derived from non-consolidated parent material, which are not rich in coarse fragments, not sandy and not with fluvic materials. These soils have a low moisture holding capacity and so have a low ecological value, yet a relatively high permeability (IUSS Working Group WRB, 2015).

3.2.2.3 Potential permeability

The soil and subsoil's potential permeability (Drawing Annex 03; adapted from Franco, 2011) was obtained from a qualitative assessment of the soil's water infiltration capacity, considering the influence of the geological substrate, soil, land morphology and slope (Pena et al., 2016). In this model, five permeability classes are considered: (1) low; (2) low to moderate; (3) moderate; (4) moderate to high; and (5) high. These values are attributed to the geological substratum based on rock type, structure, texture, and weathering degree, and to the soils according to soil type, thickness and texture. Permeability values for soil and geology are crossed, resulting in a combined infiltration value, which is adjusted taking into account slope. The resulting permeability values are considered potential as they do not consider the land use parameter, vegetation or climatic conditions (Pena et al., 2016; Pena and Abreu, 2013).

3.2.2.4 Landform

The landform analysis map (Drawing Annex 04) was generated in ArcGIS from 10 m equidistant contour lines and describes the elevations of the Alcântara watershed (Adapted from Instituto Geográfico do Exército, 2008). Two main high areas are apparent from this analysis, one in the northwest corner in Moinhos da Funcheira (260 m) and another in the western side in Monsanto (220 m). The map also shows a flatter area in the northern section of the watershed in the 75-100 m altimetric range, which leads to an abrupt and steep valley where the Alcântara River, which is now piped, used to flow. The only area of the watershed where natural streams can still be found are in the northwest corner, which is the least urbanised area of the watershed.

3.2.2.5 Aspect

The aspect map (Drawing Annex 05) was generated from the Digital Elevation Model (Adapted from Instituto Geográfico do Exército, 2008), and can be important in identifying areas of higher or lower human bioclimatic comfort. This information can be used for selecting the most appropriate sites for an intervention project, nevertheless keeping in mind potential differences in scale between the aspect map (1:50.000) and an intervention project (usually larger than 1:2.000). It can also be used as a tool for informing the selection of appropriate vegetation for a given area.

3.2.2.6 Hydrology and gradient analysis

The hydrology and gradient analysis map (Drawing Annex 06; adapted from Instituto Geográfico do Exército, 2008) identifies the areas of the Alcântara watershed with steep slopes, considering gradients above or equal to 20%, and flat slopes, considering gradients below or equal to 4%. A distinction was made between flat valleys and flat hilltops, which according to the Magalhães (2007) methodology, are known as the 'humid system' and 'dry system' respectively. The map also identifies the hydrological and ridge systems. This hydrology and gradient analysis allows us to extrapolate information as to where water may tend to infiltrate, due to lower gradients, and where it may tend to run off, due to steeper slopes, and is complementary to the landform and the potential permeability maps.

3.2.2.7 Flood risk

The flood risk data for the Lisbon Municipality, presented in Drawing Annex 07, was obtained from the Master Plan of Lisbon, the *Plano Diretor Municipal* (Câmara Municipal de Lisboa, 2012). Flood risk for the Amadora Municipality, also shown in Drawing Annex 07, was extrapolated from the landform and the hydrology and gradient analysis data, whereby flat valleys (areas with < 4% slope that intersect stream lines) were attributed a 'moderate' flood risk.

3.2.2.8 Vegetation types

The vegetation map presented in Drawing Annex 08 is adapted from the Land Use map (Instituto Geográfico Português, 2007). It describes a large area of coniferous and mixed coniferous-deciduous forest in the Monsanto Forest Park, a municipal protected forest with around 900 ha, which was extensively reforested from 1938 onwards (Câmara Municipal de Lisboa, 2017d). The parks and gardens that can be found within the watershed are also identified, as well as areas of more natural, spontaneous vegetation, including schlerophyll, herbaceous and shrub vegetation. Two small areas of eucalyptus (5,3 ha) and chestnut-deciduous forest (1,3 ha) are described, the first in the north-east corner near the airport, and the second in the north-west corner. The city of Lisbon is in the process of expanding its green corridor system, which began in the late 1970s with the development of the Parque Eduardo VII – Monsanto corridor, and has now expanded to include several green corridors.

3.2.3 Anthropic Factors

3.2.3.1 Urban fabric

Drawing Annex 09 describes the urban fabric within the watershed, and includes the identification of built areas, semi-permeable areas, and permeable areas, as well as the road and the cycle-path networks (CicloviasLX, 2017; Instituto Geográfico Português, 2007). This map provides an idea of where surface run-off will be promoted (i.e. built areas) and where infiltration may be facilitated (permeable and semi-permeable areas). The identification of the cycle-path network is important as it shows us where these linear recreation and/or transportation systems are already present, providing guidance of where these systems could be coupled with a linear SUWM technique, such as a swale, at the intervention stage.

3.2.3.2 Land use

Drawing Annex 10 shows the land use map for the Alcântara watershed, which was adapted from Instituto Geográfico Português (2007). The land use categories include a simplified urban fabric, industry, commerce, parking, cemiteries, vegetation types and agricultural areas, construction sites or abandoned sites, and sports facilities. The categories also include public and private facilities, which includes hospitals, universities, schools, etc., and cultural facilities and historical sites. Notable industrial areas are present in Amadora, near Venda Nova and Damaia, and in Lisbon, near the airport. The identification of parking areas is important as these are potential sites for unsealing of hard surface in order to promote infiltration and limit runoff. Other possible areas for unsealing are urban squares or areas with low public usage (White, 2010, p. 150).

3.2.3.3 Existing drainage network

Drawing Annex 11 shows the drainage network map that was obtained from the Municipality's Land Use Planning Study (Câmara Municipal de Lisboa, 2012). This map does not contain information for the sections of the Alcântara watershed that belong to the Amadora and Odivelas municipalities.

3.3 STRATEGIC PLANNING TOWARDS A RESILIENT CITY

3.3.1 Overview study of ecological and anthropic factors

Figure 3.13 A (Drawing Annex 12) presents the fundamental ecological network that can inform the sustainable urban water management of the Alcântara watershed. This network includes the hydrological and ridge systems, areas with moderate to high or high permeability, flat valleys and flat hilltops, soils with a very high ecological value, and areas with flood risk.

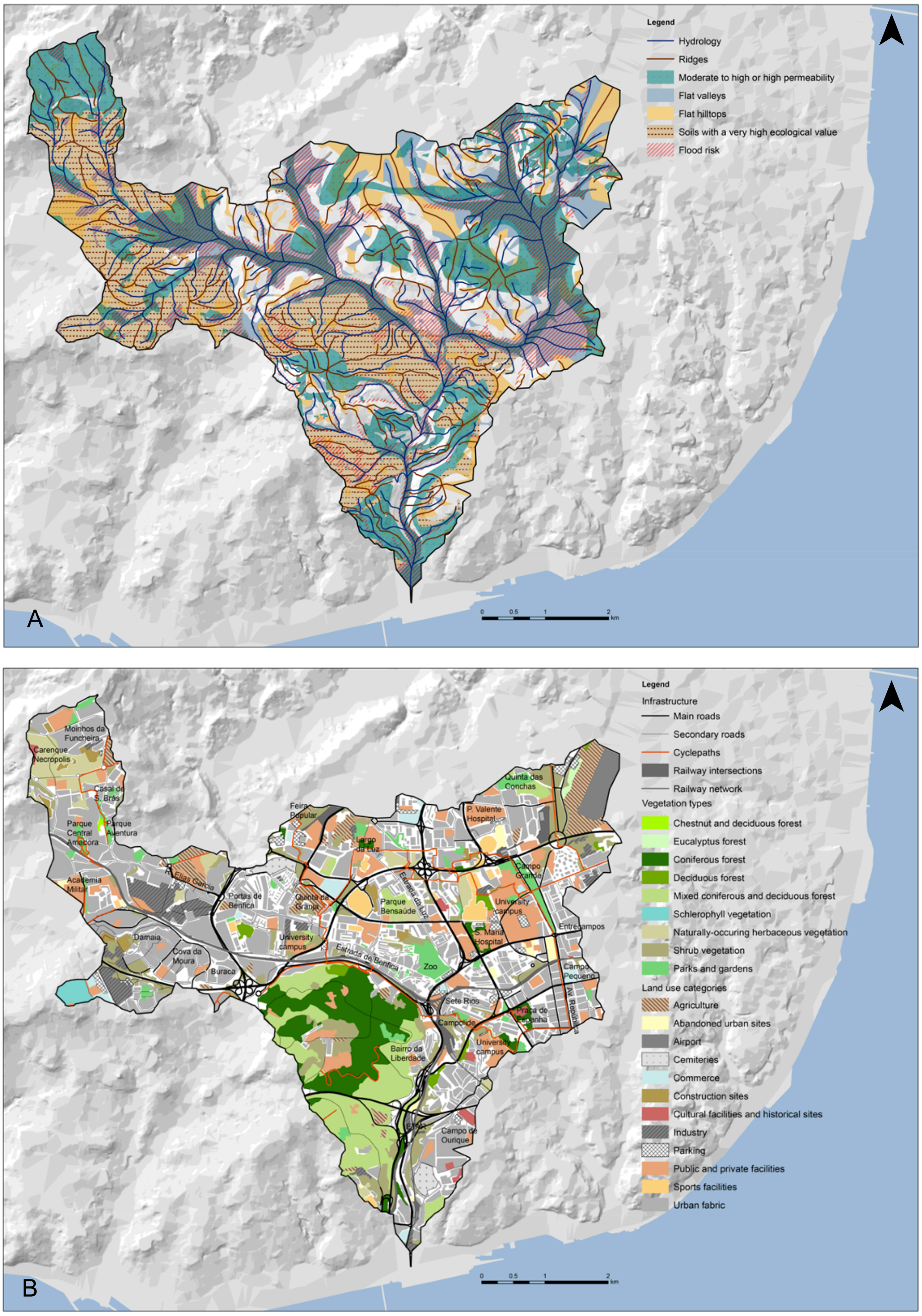

Figure 3.13 Fundamental ecological network (A) and anthropic and land use factors (B)

Figure 3.13 B (Drawing Annex 13) presents a summary of the anthropic and land use factors that provide relevant information for the implementation of sustainable urban water management measures in the Alcântara watershed. These include the infrastructure network (road, rail and cycle paths), the urban fabric and land use types. The identification of these ecological and anthropic factors is an important tool to aid in the selection of intervention sites.

3.3.2 Identification of urban voids and intervention corridors

Figure 3.14 (Drawing Annex 14) presents the urban voids within the watershed that can be identified at a fixed scale of 1:5.000. These urban voids represent sites where there is a potential for sustainable urban water management to be implemented, and have been categorised by the existing land use.

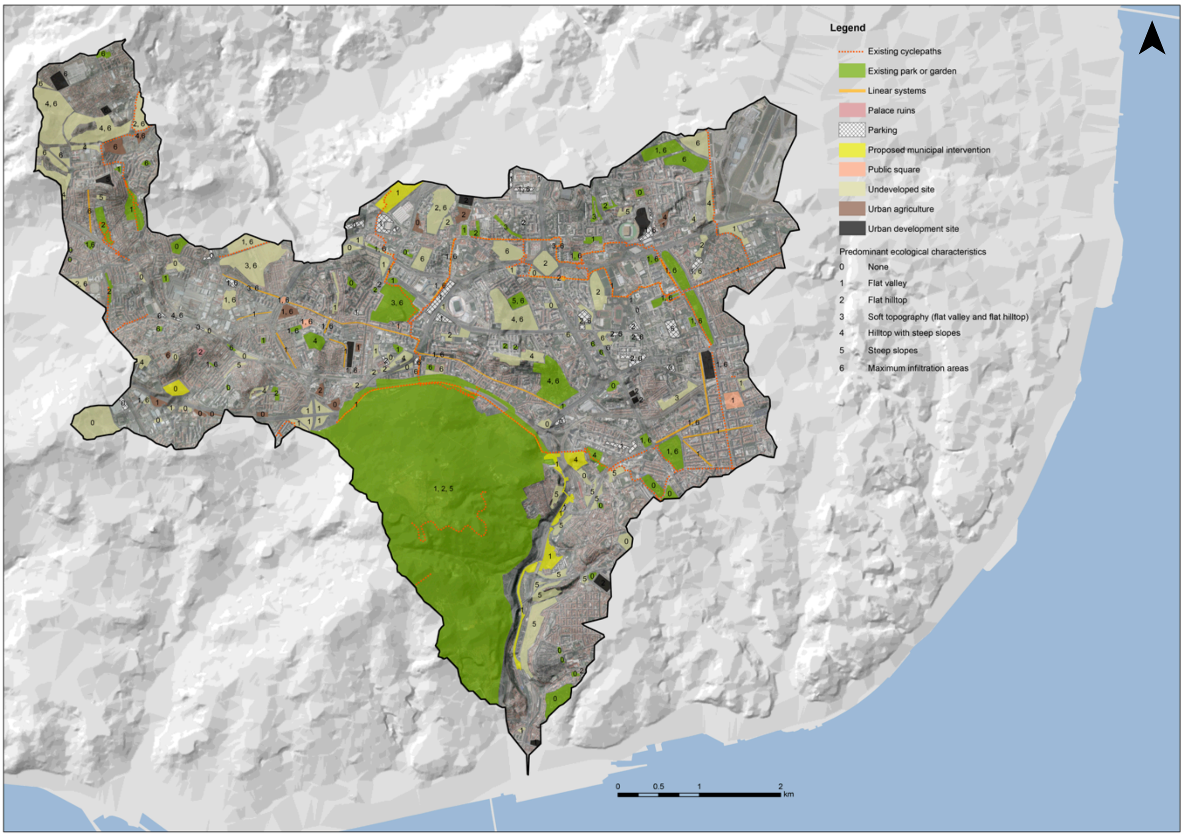

Figure 3.14 Identification of urban voids with intervention potential

The land use types identified were: existing parks or gardens, linear systems (this includes streets with existing cycle paths, streets with trees along an axis, or streets which are wide enough to support an axis of trees and/or SUWM techniques such as swales or bioretention systems[5]), parking lots, public squares, undeveloped sites, urban agriculture, proposed municipal intervention sites, and sites that

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[5] In this case, biopods or bioretention street trees; see table 3, page 34.

are likely to be destined for urban development. The land use categories with the highest potential for intervention are the undeveloped sites, the linear systems, parking lots, and public squares, as these sites are where retrofit design solutions are more likely to be successfully implemented. Conversely, in the remaining types of urban voids (agriculture sites, proposed municipal intervention sites, urban development sites and existing parks or gardens), it may be possible to incorporate sustainable urban water management measures, but these will have to take into account any pre-existing plans for those sites. The predominant ecological characteristics of each urban void are also presented in this map, supporting the decision-making on the type of SUWM technique that can be implemented for each urban void.

Figure 3.15 (Drawing Annex 15) studies how these urban voids with a potential for intervention can be connected in a system of corridors, known as green infrastructure. Green infrastructure is defined as the interconnected network of green spaces that conserve natural ecosystem values and functions and also benefit human populations (Benedict and McMahon, 2006, p. 1; White, 2010, p. 114). The map presents the Lisbon Municipality's green corridor system (which includes the municipality's existing and proposed corridors), as well as a proposed green corridor system that links the watershed's urban voids. This green corridor system forms the backbone for the implementation of the SUWM strategies discussed in the following chapter.

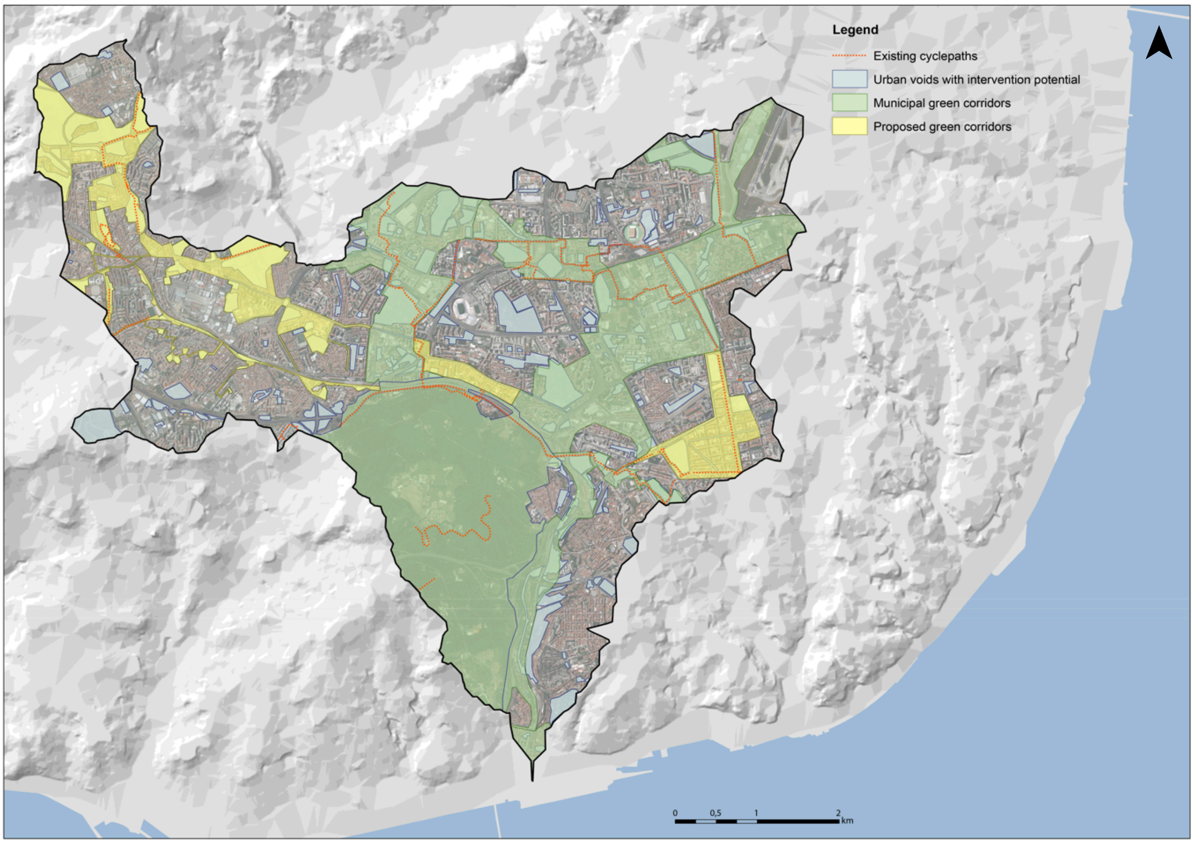

Figure 3.15 Proposed intervention corridors

3.3.3 Strategic planning vision

Figure 3.16 (Drawing Annex 16) shows a strategic planning vision for the Alcântara watershed, taking into account ecological and anthropic factors, as well as types of urban development (adapted from White, 2008). Preferential areas for upstream storage are identified, and consist of higher altitude areas. Existing green spaces are identified as being in areas of maximum infiltration or low infiltration; this information can help in creating a hierarchy of SUWM interventions for the area's existing green spaces. The different types of urban development are identified, including low-density residential areas, where new development should be restricted and where maintaining or increasing the permeability of the area should be favoured; densification areas, which form the urban core of the city and provide opportunities for well-planned, incisive retrofit resilient design; and unplanned developments, which are areas of informal housing that may be ear-marked for demolition, and where potential new uses may be considered. The housing in some of these areas is already ear-marked for demolition, but without a definite timeline, and some houses have already been demolished (Henriques and Silva, 2017). This makes for a bleak scenario of a degraded neighbourhood, with an urgent need for a requalification project, however given the uncertain future of these housing areas, any distinct realistic future plans are not possible at the moment. Finally, a schematic representation of the proposed and existing green infrastructure corridors is shown.

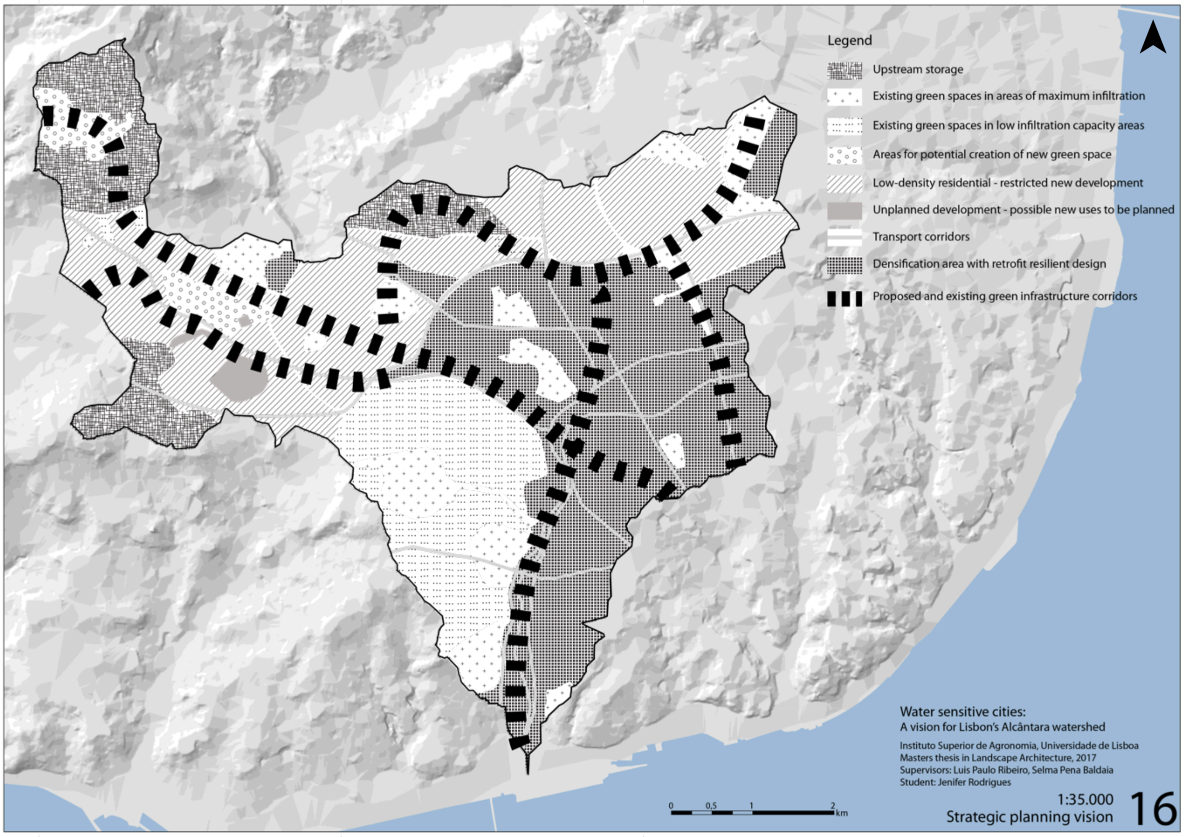

Figure 3.16 Strategic planning vision for the Alcântara basin

CHAPTER

4

PROPOSAL

In this chapter, a proposal for the implementation of a sustainable urban water management (SUWM) strategy is delineated at the watershed level. The aim of the proposal is to contribute to the design of a more resilient city through the appropriate use of SUWM techniques, linking urban form and function to the natural environment and to its geographical context. The proposal takes into account the theoretical foundations from chapter 2 and the site assessment and strategic planning described in chapter 3. It draws on relevant SUWM strategies, as well as complementary strategies such as the protection of hilltops through the planting of trees or the use of hedges (Abhijith et al., 2017) as important components of a city-wide green infrastructure. The main objectives of the proposal are to:

1. Provide source control measures that help reduce excess water flows in the watershed: protect hilltops from erosion and rapid surface water runoff by planting arboreal and shrub vegetation; provide storage of excess flows in upstream areas through attenuation storage tanks and detention basins; propose the implementation of green roofs and rainwater harvesting in residential urban areas; propose the unsealing of parking lot surfaces and urban squares and the implementation of pervious pavements
2. Implement SUWM techniques as ‘treatment trains’ in different segments of the watershed in order to treat polluted stormwater and address wider water quality issues, such as the discharge of stormwater into watercourses and underground water systems
3. Provide infiltration measures in areas with a high potential permeability (see Drawing Annex 03) that are located downstream of proposed treatment train segments
4. Design implementation strategies that link SUWM techniques with the existing or proposed green infrastructure in order to enhance biodiversity, support local natural habitats, and provide wildlife corridors, while simultaneously promoting infiltration and evapotranspiration
5. Treat surface water as an asset and a resource, using it to design aesthetically pleasing and climatically comfortable public spaces that can help promote a more sustainable vision of water management in the city

Drawing Annex 16 identifies priority intervention areas and presents the proposed water management strategy at the watershed level, at a scale of 1:25.000. In order to provide a clearer explanation of the proposed strategy, the watershed was divided into eight segments (A-H), which represent sub-sections of the watershed, and which are shown individually here from Figure 4.1 to 4.8. Each of the segments contains a treatment train, where the most appropriate primary, secondary and tertiary treatment techniques were selected and implemented from upstream to downstream. The techniques are distributed by priority intervention areas and are numbered (e. g. A1, A2, A3…) in order that they can be more easily described here.

4.1 SEGMENT A

Figure 4.1 Intervention proposal for segment A (Image credits: Author)

Segment A is the highest part of the watershed, with its highest point at an altitude of 260 m. Intervention area A1-A3 (Fig. 4.1) is defined by a large area of undeveloped land in the northwest corner of the watershed, identified in white as an urban void. This is an important area for source control measures to be implemented, such as attenuation storage tanks and detention basins to provide storage for excess flows, and the planting of trees and shrubs to provide erosion control, reduce rapid surface water runoff, and promote infiltration. Intervention area A1-A3 is also identified in the geological map (Drawing Annex 01) as having an outcrop of the Mesozoic limestone and sandstone formations, which present very good permeability and can provide a means to recharge the Early Cretaceous Aquifer underlying Lisbon (see section 3.2.2.1). Thus, for the areas that receive unpolluted rainwater, the implementation of infiltration measures has also been proposed. Intervention area A1 would ideally be suited for the implementation of an urban park which could capture and store water, provide hilltop protection, shade and biodiversity through the planting of trees and shrubs, and provide a flow of unpolluted water within the park which could gradually be infiltrated to the underlying aquifer through the geologically permeable substrate.

Intervention area A4 and A5 comprise two pre-existing parks, the *Parque Central da Amadora* to the west and the *Parque Aventura* to the east. The *Parque Aventura* is an important park as it has been designed around a watercourse, the *Ribeira da Falagueira* (Fig. 4.1; A5). It is one of the only areas of the watershed where the natural watercourse is visible and protected, as at the southern (downstream) end of the Park the watercourse is piped and lost from view. For intervention area A4-A5 an attenuation storage tank and detention basin has been proposed as a source control technique, followed sequentially by a treatment train consisting of a gross pollutant captured device (GPCD), a sedimentation basin, and a bioretention system. These proposals could be integrated into both the pre-existing park structures.

Intervention area A6 and A7 consist of two flat areas further downstream where a sedimentation basin is proposed as a primary treatment technique, given the gentler gradient of the land at this point in the watershed. Both these areas flank an industrial site, and so are important locations to address the first stages of stormwater pollution control. Area A6, which is upstream of the industrial site, is a comics-themed park named *Parque Maurício*, where a sedimentation basin could be integrated within the existing structure of the park (Fig. 4.1; A6). Area A7, which is downstream of the industrial site, is an undeveloped site flanked by a residential area to the east and an informal urban agriculture site to the west (Fig. 4.1; A7; view to the south). Here, the sedimentation basin would form the first part of a treatment train that would continue on to the parking lot of the adjacent grocery stores and Rua Elias Garcia (intervention area A8) and towards the proposed wetland (intervention area A11) at the *Portas de Benfica* roundabout.

Intervention area A8 consists of the parking lot for the *Pingo Doce* and *Lidl* grocery stores, where a GPCD has been proposed, and Rua Elias Garcia, where a swale has been proposed. Rua Elias Garcia, located in the Amadora Municipality, is continuous with Estrada de Benfica in the Lisbon Municipality. These two roads are now separated by the Portas de Benfica roundabout, which used to be one of the gated entrances to the city of Lisbon. These two roads are historically very important as they used to constitute the Royal Road that linked Sintra to Lisbon in the 19th century. The swale is proposed along the 750 m extension of Rua Elias Garcia, before it meets the *Portas de Benfica* roundabout, where a constructed wetland has been proposed (Fig. 4.1; A11).

Intervention area A9 is a residential development along Rua Elias Garcia that is located on a floodplain. Here, rainwater harvesting and green roofs have been proposed as source control techniques, taking advantage of the fact that the buildings have flat roofs. Intervention area A10 is an undeveloped site (Fig. 4.1; A10) that forms a hilltop and one of the main ridges of the watershed. Here, an attenuation storage tank has been proposed to control flows reaching the downstream floodplain area.

4.2 SEGMENT B

Figure 4.2 Intervention proposal for segment B (Image credits: Author)

Segment B is a sub-section of the watershed where a green corridor system and SUWM strategies have been proposed perpendicularly to the hydrological network. A green corridor was proposed along the edge of the railway line as the railway constitutes an important barrier, acting effectively as a drainage line in the landscape. A green corridor was also proposed upstream of the railway line, in order to link the urban voids that were identified in this area, but also to reinvigorate the economic and social infrastructure of the area. This area of Amadora has three illegal housing neighbourhoods, *Bairro da Estrada Militar*, *Cova da Moura*, and *Bairro 6 de Maio*, which were developed from the 1970s onwards, and which today are known to be unsafe places with a variety of criminal activities, and are stigmatised as deprived neighbourhoods. The goal behind the implementation of this green corridor is to provide connections to the rest of the city through an integrated green infrastructure, as well as new public spaces that can help provide an improved quality of life to residents. This green corridor proposal can be an important source of support for the urban regeneration of the area and for the fight against social exclusion, and aims to act as a catalyst for an integrated approach to social, environmental and economic issues.

The first proposal in segment B is to protect the hilltop area that is currently undeveloped (B1) through the planting of arboreal vegetation. Intervention area B2 is currently undeveloped land where an attenuation storage tank has been proposed. Area B2 is included in the proposed green corridor upstream of the railway line, which links urban voids (such as the existing parks and gardens and undeveloped or urban agriculture sites), culturally relevant areas (the ruins of an 18th century palace, *Palácio dos Condes da Lousã* and the local Parish Council), and nearby socially deprived areas (the *Bairro da Estrada Militar*). The rainwater that falls in these areas (B1-B2) drains towards the railway line, and from there is drained eastward along the railway line. A treatment train has been proposed along this corridor (Fig. 4.2; B3), which includes GPCD's, sedimentation basins, and a swale, as well as the planting of hedges to promote biodiversity in the corridor. At the end of the treatment train a wetland has been proposed in an undeveloped site that faces the Benfica train station, an important public transportation node (Fig. 4.2; B4).

4.3 SEGMENT C

Figure 4.3 Intervention proposal for segment C (Image credits: Author)

Segment C is defined by the hydrological network downstream of *Portas de Benfica*, and is located within the Lisbon Municipality. Intervention area C1 is a flat undeveloped site where a sedimentation basin has been proposed. This sedimentation basin is located at the start of the green corridor that has been proposed along Estrada de Benfica (C2), in continuity with the proposed corridor for Rua

Elias Garcia (A4 - A5 - A7). The proposal for intervention area C2 is a treatment train consisting of a swale and bioretention systems (biopod configuration), as well as the planting of hedges to promote biodiversity in the corridor (Fig 4.3; C2). Green roofs have been proposed for the buildings with flat roofs in the residential area along Estrada de Benfica (C3), so as to provide vital stormwater retention benefits for these buildings that are located on a floodplain. Another important source control technique for this area is the attenuation storage tank proposed for *Parque Silva Porto* (C4), an urban park located on a very steep hillside (Fig 4.3; C4). The implementation of a swale further down Estrada de Benfica (C5) continues the treatment train described for C2. As Estrada de Benfica is a long road that receives stormwater from a large area, another treatment train is proposed further downstream, with a GPCD and sedimentation basin proposed in area C6, a linear urban void, and a wetland and infiltration measures proposed in area C7, an area of undeveloped land surrounding an old villa, *Quinta da Alfarrobeira*, which is located in an area of maximum infiltration where the geological substrate consists of alluvium and Paleogenic sedimentary rocks, which have a high permeability.

4.4 SEGMENT D

Figure 4.4 Intervention proposal for segment D (Image credits: Author)

Segment D consists of the Monsanto Forest Park, a hill with a maximum altitude of 220 m. This area is already densely forested, and so the proposal for intervention area D1, which encompasses the whole hill, is to implement attenuation storage tanks and detention basins, as well as infiltration measures, given that surface water runoff in this vegetated area will be largely unpolluted.

4.5 Segment E

Figure 4.5 Intervention proposal for segment E (Image credits: E2 right - Ambiente Magazine, 2016; Others - Author)

Segment E is a gently sloping sub-section of the watershed with several urban voids. In intervention area E1, currently a parking lot adjacent to the *Pontinha* metro station (Fig. 4.5; E1), pervious pavements and a sand filter have been proposed. The sand filter is used here as a secondary treatment technique due to the limited land area, with the water treatment being provided underground. Intervention area E2 is currently an urban void (Fig. 4.5; E2 left), where a municipal park has been proposed and is being developed, and which will house the new *Feira Popular* (Lisbon Amusement Park). The project for this new urban park includes the implementation of three large retention basins (Fig. 4.5; E2 right), which create a temporary “lake” when the precipitation is more intense. The project also includes plans for the sustainable management of water resources, and is incorporated in the Lisbon Municipality’s General Drainage Plan (Gromicho, 2016). Intervention area E3 is currently a large parking lot adjacent to the Benfica football stadium. The proposal for this area includes the implementation of pervious pavements, as well as a sedimentation basin and an attenuation storage tank or detention basin.

4.6 SEGMENT F

Figure 4.6 Intervention proposal for segment F (Image credits: Author)

Segment F includes two hilltop areas, one of which has an undeveloped site (F1) adjacent to an existing park, *Parque Bensaúde*. Here, an attenuation storage tank or detention basin has been proposed to control flows further downstream. The other, known as *Alto dos Moinhos*, is a narrow hilltop with steep slopes. Figure 4.6 (F2 - top) shows the type of grassland vegetation that can be found on this hilltop. The protection of the hilltop with arboreal vegetation has been proposed, which could also be linked to a proposal for an urban park, given the interesting views that the hilltop provides. Figure 4.6 (F2 - bottom) shows the view to the south, which encompasses the *Águas Livres* Aqueduct, Amoreiras, and Monsanto Forest Park. Intervention area F3 is the Lisbon Zoo, which is located along the southern hillside and base of the *Alto dos Moinhos* hilltop. The protection of the hillside and the implementation of bioretention systems have been proposed for this site, and so a combination of bioretention street trees and biopods could be used throughout the Lisbon Zoo, as well as bioretention swales to link these systems. Infiltration measures have also been proposed for this site, as the geological substrate is alluvium and Paleogenic sedimentary rocks, which have a high permeability.

4.7 SEGMENT G

Figure 4.7 Intervention proposal for segment G (Image credits: Author)

Segment G is a large sub-section of the watershed that includes important infrastructure such as the Lisbon airport, Lisbon's university city, and one of the main arteries of the city, Avenida da República. It also includes the Gulbenkian gardens, an important haven for biodiversity in the city, and *Praça de Espanha*, a main intersection of the city that has a history of flooding incidents. The upstream areas of this sub-catchment are important areas for the implementation of source control techniques. These can help manage the more frequent, everyday stormwater runoff, which is most affected by urbanisation and has the greatest impact on aquatic ecosystems' health (Hoban and South East Queensland Healthy Waterways Partnership, 2007). Source control techniques are proposed for area G1, G3, G6 and G7. Intervention area G1 is a large parking lot where pervious pavements, attenuation storage tanks, and an underground sand filter has been proposed, given the space constraints in this area. Intervention area G3 is an existing urban park, *Quinta das Conchas e dos Lilases*, where water management is a central theme to the park's design (Fig. 4.7; G3). Here an attenuation tank is proposed in order to complement the park's sustainable water design. Intervention area G6 is part of the Lisbon University's stadium, and is currently an undeveloped site (Fig. 4.7; G6). Area G7 is an undeveloped site adjacent to the Júlio de Matos healthcare complex. For both of these site, which are relatively large areas of undeveloped land, attenuation storage tanks or detention basins have been proposed.

Intervention area G2 encompasses two existing gardens adjacent to the metro station (Fig. 4.7; G2 top) and a community allotment (Fig. 4.7; G2 bottom). Here, the proposal is for a primary treatment GPCD and sedimentation basin to be integrated within these existing green spaces. Intervention area G4 is a main avenue in the *Alta de Lisboa* neighbourhood with a grassed channel as a central axis. As can be seen in Figure 4.7 (G4), the grassed central axis is already a swale, so the proposal here relates to maintenance of the swale and possible adjustments to the vegetation in order to potentiate the swale's filtering capacity. Intervention area G5 is an undeveloped site also in the *Alta de Lisboa* neighbourhood (Fig. 4.7; G5), where a sedimentation basin has been proposed as a primary treatment technique.

Intervention area G8 is an existing urban park, *Jardim do Campo Grande*, which dates back to the 19th century. The park is located along a watercourse and the geological substrate is alluvium, with a high permeability, so a treatment train was proposed for this area, which includes (upstream to downstream): a GPCD, a sedimentation basin, swale(s), bioretention system(s) and infiltration measures. Intervention area G9 and G10 are parking lots located near the university buildings, where pervious pavements have been proposed. Intervention area G11 is an important urban square, *Campo Pequeno*, with a deactivated bullring. The bullring was built in 1892 with a Romantic neo-Arabic architecture, and is now used as a multi-event venue. The proposal for this square is to unseal the paving as much as possible and develop a landscape design project that complements the impressive architectural building at the centre of the square and that implements bioretention systems such as biopods or bioretention street trees. If practical, an attenuation storage tank is also proposed for this site, given the large flows of water that usually occur in this part of the watershed.

Intervention area G12 is an undeveloped site adjacent to the railway line, where an attenuation storage tank and a sedimentation basin have been proposed. Area G13, known as the *Avenidas Novas* neighbourhood, has an ordered grid-like fabric, and was selected as a potential site for the implementation of green roofs and rainwater harvesting systems, given that it is such a high-density urban development. Green roofs have been proposed for the buildings with flat roofs, and governmental incentives for rainwater harvesting are also proposed as important measures to promote source control in this area. Intervention proposal G14 targets two streets in the *Avenidas Novas* neighbourhood for the implementation of a swale. The selected streets are Avenida Elias Garcia and Avenida Conde de Valbom, as both are lined with trees and are wide enough to support this kind of intervention without the need to alter traffic flows.

Intervention area G15 and G16 have been selected as proposed locations for tertiary-level treatment. Area G15 is the location of the Gulbenkian gardens, which was designed in the 1960s by António

Viana Barreto and Gonçalo Ribeiro Telles, and is an enduring testament to successful ecological planning and to the modernist design movement. The proposal here is to incorporate bioretention systems along the streams that run within the gardens to further enhance the water treatment process within this system (Fig. 4.7; G15). Area G16 is the Praça de Espanha intersection, a major traffic node in the city where flooding events occur frequently. The proposal here is to alter the traffic so as to unite the fragmented green spaces of the intersection, and implement a bioretention basin that could provide attenuation of flows as well as tertiary-level treatment.

4.8 SEGMENT H

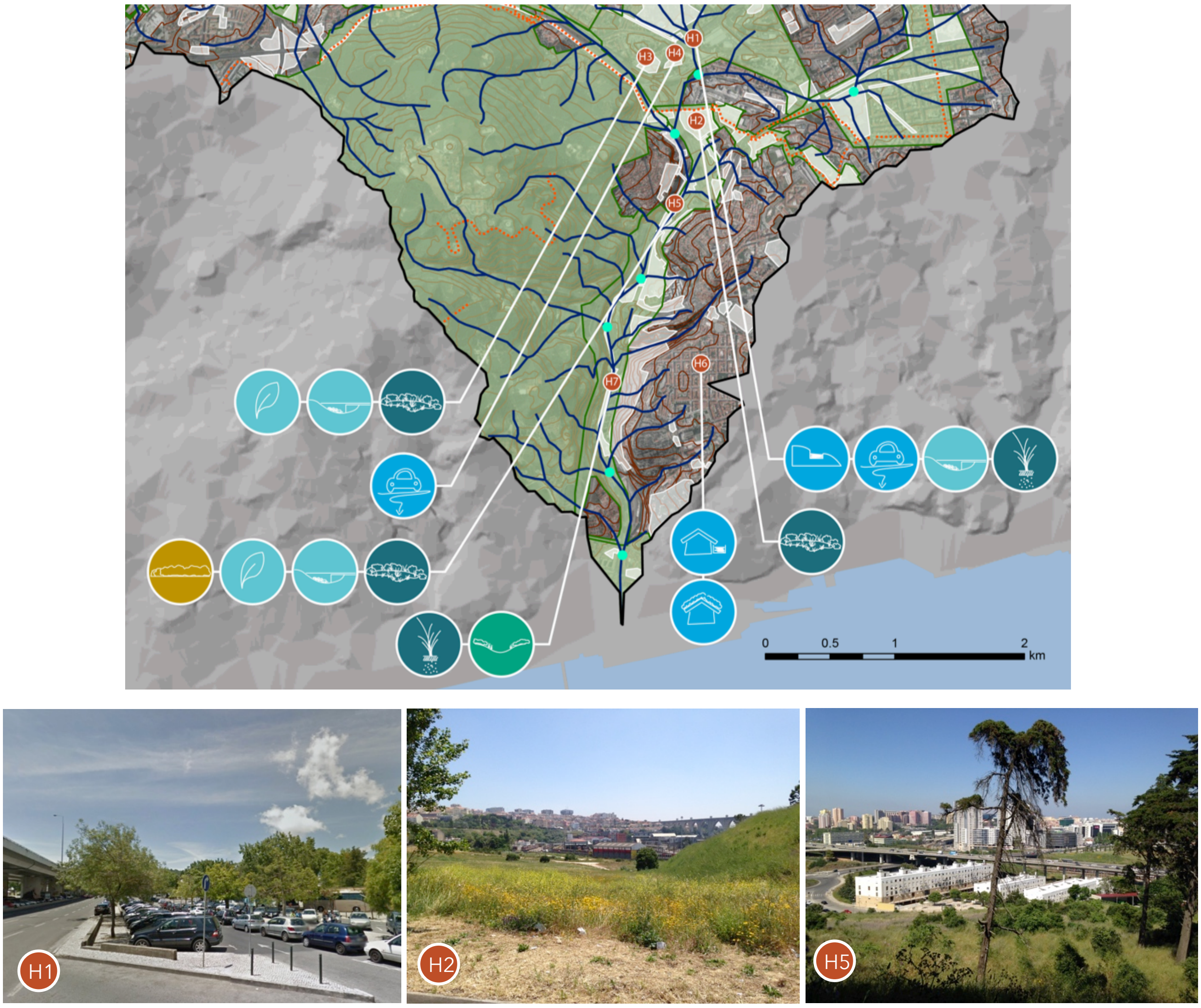

Figure 4.8 Intervention proposal for segment H (Image credits: H1 - Google Maps; Others - Author)

Segment H encompasses the original site of the Alcântara River, which has been piped since the mid-20th century. Intervention area H1 is Sete Rios, an important traffic and rail intersection in the city, which is directly adjacent to the Lisbon Zoo (Fig. 4.8; H1). Here an attenuation storage tank has been proposed, as well as pervious pavements for the existing parking lots. The proposal is to reduce the area occupied by traffic (reduce the number of traffic lanes and concentrate the parking spaces under the fly-over) and add more vegetation, a sedimentation basin and bioretention systems; either a bioretention basin or a system of bioretention street trees and biopods, depending on availability of space. The proposal is to develop a landscape design project that makes the area safer and more accessible for pedestrians, while also providing sustainable water management through detention of flows and water treatment processes, and a shaded, comfortable space for people to move through or to stay and enjoy. The Lisbon Municipality is currently undertaking a project for this area (Figure 4.9) with many of the same objectives of reducing the area occupied by traffic and adding more vegetation as well as more space for pedestrians (Boaventura, 2015).

Figure 4.9 The Lisbon Municipality's project for the Sete Rios urban square (Boaventura, 2015)

Intervention area H2 is a large undeveloped site where the Lisbon Municipality's General Drainage Plan has proposed an underground attenuation storage tank. Here the proposal is for a large constructed wetland, which will receive water from all sub-sections of the watershed (Fig. 4.8; H2). Intervention area A3 is an undeveloped site near the railway line, where a treatment train consisting of a GPCD, a sedimentation basin, and a constructed wetland have been proposed. Intervention area H4 is a parking area near the Sete Rios intersection and train station, where the implementation of pervious pavements has been proposed.

Intervention area H5 is set within the Alcântara River valley, and the proposal aims to complement the Lisbon Municipality's Alcântara green corridor project (see page 55). Hedges have been proposed along the area of the Municipality's project in order to increase the corridor's biodiversity value. A treatment train consisting of a GPCD and a sedimentation basin have been proposed to be located on the hillside of the Monsanto Forest Park (Fig. 4.8; H5), and a constructed wetland is proposed at the base of the hill, directly under the *Águas Livres* Aqueduct.

Intervention area H6, *Campo de Ourique*, is a historic and characteristic neighbourhood of the city of Lisbon that was built in the late 19th century. As another example of a high-density urban development where stormwater retention will have an important effect, green roofs have been proposed for the buildings with flat roofs, alongside a proposal for governmental incentives towards rainwater harvesting.

Intervention area H7 is Avenida de Ceuta, the avenue that runs above the piped Alcântara River, which is also included in the Lisbon Municipality's Alcântara green corridor project. The proposal for this avenue complements the Lisbon Municipality's vision (Fig. 4.10), with the implementation of a swale and bioretention systems, such as biopods or bioretention street trees, along the edges of the avenue that have been designated for pedestrians.

Figure 4.10 The Lisbon Municipality's vision for Avenida de Ceuta, as part of the green corridor project for the Alcântara valley (Image credits: Câmara Municipal de Lisboa, 2017c)

CHAPTER 5

CONCLUSION

This thesis has focused on how, through the implementation of measures that seek to restore the urban water cycle to a more natural state, spatial planning can contribute to a more sustainable management of urban water resources. These measures have been shown to have multiple benefits, such as mitigating the risk of flooding, reducing water pollution, promoting ecosystem integrity, protecting natural resources, and providing recreation and aesthetic benefits to the public, while simultaneously representing a cost-effective solution. This thesis has also highlighted the importance of a city-wide green infrastructure that integrates structural SUWM measures and potentiates their effect.

It has become clear that the implementation of SUWM can provide a wide range of benefits. Although conventional drainage solutions have an important role in urban water management and have had a critical historical role in addressing public hygiene and flood protection, the consensus now seems to be that relying solely on pipe networks is no longer appropriate or economic in the long term, and that alternative technologies and strategies for stormwater management are required. A realistic future vision calls for the implementation of decentralised stormwater treatment, used at the local level wherever possible, in conjunction with localised urban drainage networks (Chocat et al., 2007; Gleick, 2003; Faram et al., 2010; White, 2010).

In developing countries the scenario is different, as many of their urban areas do not have an inherited drainage infrastructure, and so the fusion between existing and new technologies is not such a relevant issue (Chocat et al., 2007). Given the high economic, human and resource cost of installing fully functional technocratic drainage solutions, it is not realistic to expect these systems to be easily implemented in developing countries in the near future. The development of solutions that are environmentally sustainable, economically feasible, and that provide education and employment opportunities within new and appropriate technological paradigms will be critical for the developing world, where most of the future global population growth and urbanisation will take place.

Urban water management is a complex field that cannot be dissociated from its socio-economic context; it is directly affected by political governance processes, development goals, private investments, community and local projects, as well as by individual attitudes and behaviours. In short, it is directly affected by ‘how we live, where we live, and how we govern’ (White, 2010). This thesis has focused on the implementation of structural measures that can be designed as part of a city-wide spatial planning strategy. However, along with the proposed need for alternative technologies and strategies within stormwater management, there is also a need for more flexible institutional arrangements and increased water awareness among all stakeholder groups. Non-structural measures, such as education and sensitisation regarding demand management, wastewater reduction and greywater recycling are equally important themes that are relevant to an integrated water cycle management and are mainly concerned with adaptation to a changing reality. A good example of a non-structural solution is the re-engineering of substances and materials used in the household in an effort to make household liquid waste less polluted and to save costs in downstream water treatment. Another example is to raise awareness of water issues in the urban environment by employing water re-use and recycling measures, and making these visible as well as educational (Chocat et al., 2007). An example of a non-structural measure that focuses on providing improved data on global hydrology is the development of better forecasting technologies. This has been discussed in section 2.1.1 with the presentation of the Surface Water and Ocean Topography (SWOT) satellite mission and in section 3.2.1 with the discussion of the Lisbon Municipality's proposal to invest in real-time modelling systems. Such technologies provide improved weather and marine forecasts, information on flooding and drought, as well as improved data on urban hydrology, and address current societal concerns over water on a global scale.

The application of the theoretical components of SUWM to a practical case study has shown that it is possible to use spatial planning to support the sustainable management of the urban water cycle. The study has also shown that the analysis of the fundamental ecological components as well as of the anthropic components of a landscape are vital in providing relevant information for decision-making regarding the implementation of SUWM measures. The case study has highlighted the importance of collaborating across boundaries when working in water management. In this case, the successful design of an integrative strategy for the watershed implied working across three municipal boundaries.

By proposing spatial planning measures that seek to restore the urban water cycle to a more resilient state, this thesis has provided an important starting point for establishing Lisbon as a water sensitive city. In order to fully transition to a water sensitive city, a variety of structural and non-structural measures need to be ensured, such as: environmental repair and protection; water supply security; public health and economic sustainability through water sensitive urban design; enlightened social and institutional investment in water management; and diverse and sustainable technological choices (Hoban and South East Queensland Healthy Waterways Partnership, 2007). In short, the water sensitive city ensures that water management is an integrated process, characterised by a holistic approach that addresses political decisions, social and institutional investment, advances in technology, and individual attitudes and responsibilities.

GLOSSARY OF TERMS

Average Recurrence Interval: The average or expected value of the periods between exceedances of a given rainfall total accumulated over a given duration. It is implicit in this definition that the periods between exceedances are generally random.

Critical duration: Duration of an event for a specified return period that results in the highest peak flow rate, flood volume or flood level at a particular location.

Depth of extended detention: Temporary storage on the surface of a SUWM component that captures the volume of water that requires treatment and, if required, provides attenuation of flows.

Probability of occurrence: Expressed as a percentage, this value is calculated as 1/return period. For example, an event with a 100-year return period has a probability of occurrence of 1%.

Return period: The average time between events of a given or greater magnitude, usually expressed in years. For example, an event with a 100-year return period indicates an event that occurs or is exceeded on average once every one hundred years or more. It can also be expressed as the 1 in 100 year event or 100-year event.

Time of concentration: The time needed for water to flow from the most remote point in a watershed to the watershed outlet. It measures the response of a watershed to a rain event and is defined by Kirpich's equation, which is a function of travel length (L) and slope (S) between the watershed's most remove point and its outlet.

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ANNEXES

ANNEX 1. KEY IMPACTS OF CLIMATE CHANGE ON URBAN AREAS

Table 4 Key impacts of climate change on urban areas (Adapted from Dawson, 2007)

Climate factor	Effect on cities
Sea-level rise	• Increased risk of storm-surge flooding and coastal erosion • Saline intrusion into freshwater aquifers and impeded drainage of extreme flows • Reduced area for intertidal habitats and salt marshes
Changes to temperature and precipitation patterns	• The number of intense precipitation events is expected to increase, placing additional strain on fluvial and urban flood systems, increasing flood risk • Changes to temperature and precipitation patterns as well as groundwater movement can lead to increased damage from subsidence, heave and landslides • Increased temperatures can lead to infrastructure damage, including the risk of energy distribution networks overheating • Increased demand for air conditioning can strain energy generation during heat waves • Deleterious effects on health, including increased incidence of cataracts and skin cancer from UV exposure, reduced air quality from photochemical smog and ozone, vector and water-borne diseases, and heat stress-related deaths. • Changes to the phenology of plants and animals
Extreme weather	• More frequent and intense windstorms and other extreme weather are likely to cause increased damage to buildings and infrastructure • Transport networks will likely be affected by extreme weather events • Increased temperature will exacerbate the heat-island effect of cities, leading to a need for an increased demand for air conditioning, which could be coupled with water shortages
Droughts	• Implications for water resources in terms of quality and availability

ANNEX 2. FOUR SCENARIOS FOR THE PROVISION OF URBAN DRAINAGE SERVICES

The following section summarises four different scenarios presented by Chocat and colleagues (2007) for the provision of urban drainage services.

A. The Green Scenario

In this scenario a balanced and integrated approach seeks to combine structural and non-structural measures to achieve sustainable urban drainage. Solutions and responsibilities are decentralised, and there is widespread use of source control techniques, infiltration systems and water recycling, while large end-of-pipe treatment plants are no longer used. Potential risks with this scenario are focussed around the increased responsibility placed on individual property owners, and on the difficulties that would arise in attempting to monitor and regulate common water quality standards. There is also a risk in allowing individual property owners to capture, recycle, and reuse water as a mainstream solution, as this may create insanitary conditions if not properly regulated.

B. The Technocratic Scenario

This approach focuses strictly on technology and operates largely independently of the political context. The system is centralised and mostly public, run by publicly employed engineers, who make sure they employ the most sophisticated solutions so the system does not fail. Although solutions are expensive, they are also robust and impressive from a technological point of view. There is widespread implementation of end-of-pipe solutions as well as technocratic source-control measures. It is important to note that this scenario would not likely be implemented in developing countries, due to lack of funds, lack of engineering expertise, and lack of operation and maintenance capacities. With this solution, there is always the possibility that a rainfall event that is larger than the design storm can occur. In this sense, the technocratic solution does not offer a flexible solution to deal with unexpected and rare events, which could have catastrophic effects.

C. The Privatisation Scenario

When an ageing infrastructure requires large investments in order to remain operational, selling this infrastructure to a private company might present an attractive solution. In this scenario private companies are in charge of the urban water and drainage services and decisions are made with cost-efficiency and profit in mind. The risks with this scenario are that the price of water might become unreasonable, especially for developing countries. Also, it could lead to a situation where only a few companies manage the planet's water resources. Another risk is that if a company becomes bankrupt, it could stop operating overnight, which is an unacceptable scenario when it comes to the provision of water services. Finally, there is the risk that companies might disregard long-term sustainability issues in favour of short-term return on investment.

D. The Business-as-usual Scenario

In this scenario, water services continue to be managed as for the past thirty years, without a clear strategy or political vision. This scenario essentially comprises a mix of the three above-described scenarios, and issues emerge because of a lack of clear-cut priorities. This scenario is also incompatible with developing countries, due to lack of inherited infrastructure, funds, and experienced engineers, and would lead to a widening of the gap between rich and poor countries.

ANNEX 3. GLOBAL PATTERNS IN ACCESS TO SAFE WATER AND SANITATION

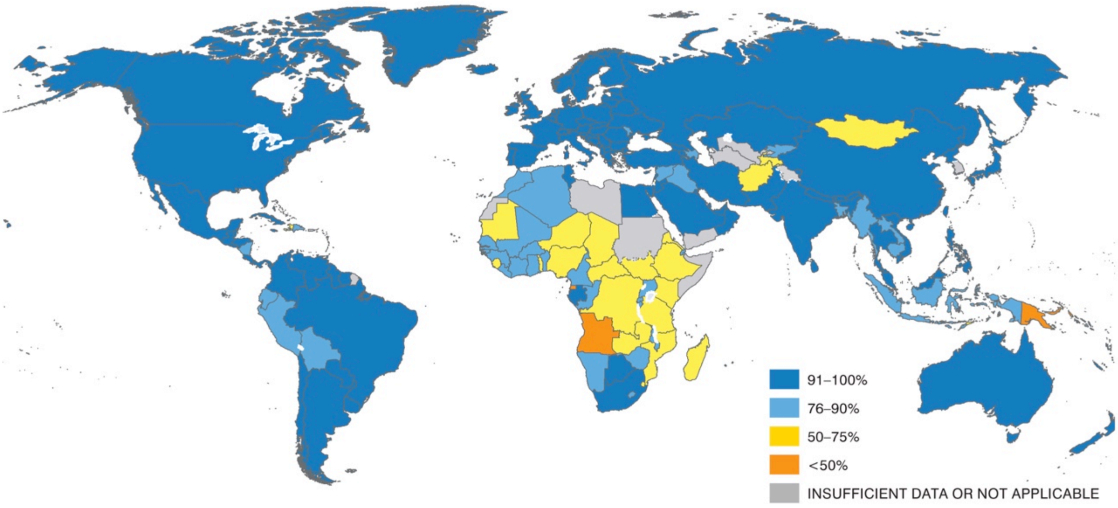


Figure A.1 Proportion of the population using improved drinking water sources in 2015 (UNICEF and World Health Organization, 2015)

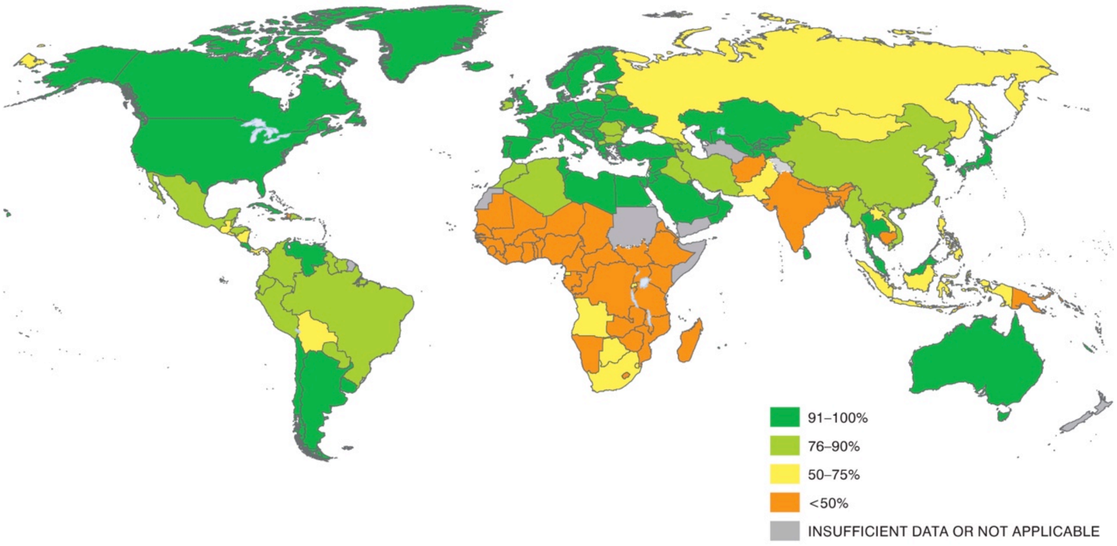
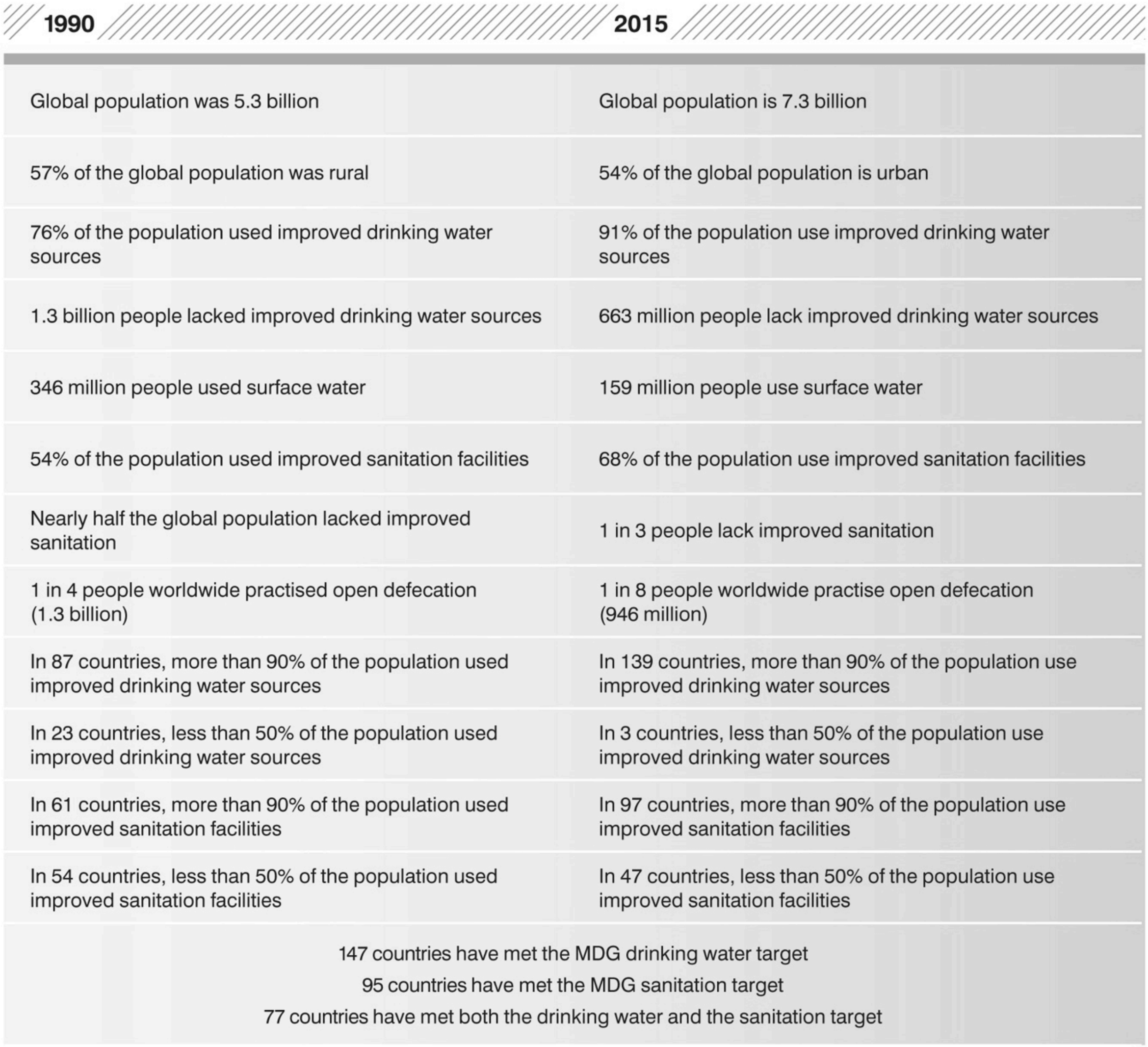


Figure A.2 Proportion of the population using improved sanitation facilities (UNICEF and World Health Organization, 2015)

ANNEX 4. GLOBAL PROGRESS REGARDING WATER SOURCES AND SANITATION BETWEEN 1990 AND 2015

Table 5 Global progress regarding water sources and sanitation between 1990 and 2015 (UNICEF and World Health Organization, 2015)



1990	2015
Global population was 5.3 billion	Global population is 7.3 billion
57% of the global population was rural	54% of the global population is urban
76% of the population used improved drinking water sources	91% of the population use improved drinking water sources
1.3 billion people lacked improved drinking water sources	663 million people lack improved drinking water sources
346 million people used surface water	159 million people use surface water
54% of the population used improved sanitation facilities	68% of the population use improved sanitation facilities
Nearly half the global population lacked improved sanitation	1 in 3 people lack improved sanitation
1 in 4 people worldwide practised open defecation (1.3 billion)	1 in 8 people worldwide practise open defecation (946 million)
In 87 countries, more than 90% of the population used improved drinking water sources	In 139 countries, more than 90% of the population use improved drinking water sources
In 23 countries, less than 50% of the population used improved drinking water sources	In 3 countries, less than 50% of the population use improved drinking water sources
In 61 countries, more than 90% of the population used improved sanitation facilities	In 97 countries, more than 90% of the population use improved sanitation facilities
In 54 countries, less than 50% of the population used improved sanitation facilities	In 47 countries, less than 50% of the population use improved sanitation facilities

147 countries have met the MDG drinking water target
95 countries have met the MDG sanitation target
77 countries have met both the drinking water and the sanitation target

ANNEX 5. VEGETATION SPECIFICATIONS FOR BIORETENTION SYSTEMS

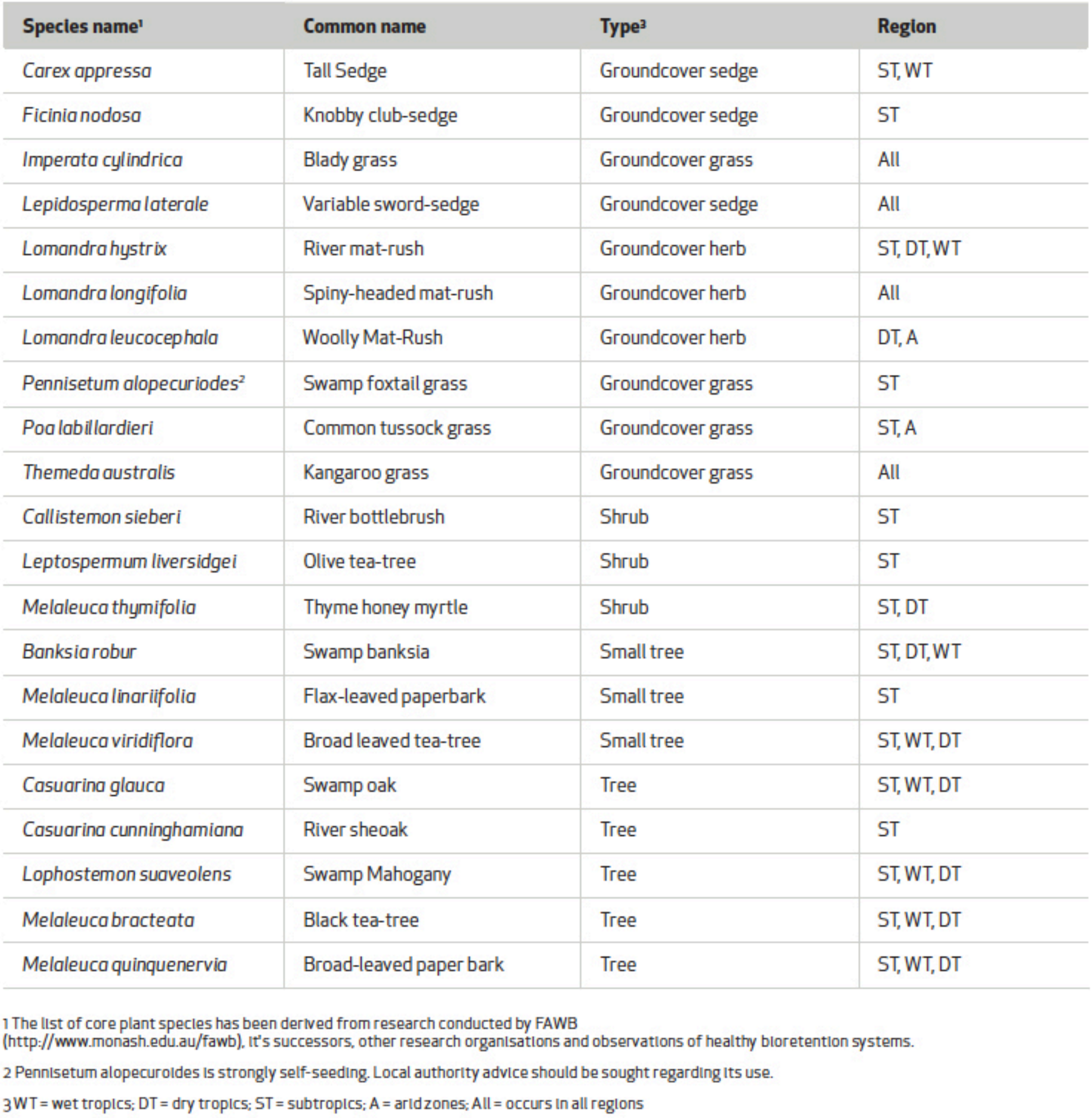
Species diversity

For small-scale urban areas, a minimum of two plant species should be used for filter areas of <100m^2 and four plant species for filter areas ≥100m^2. At medium to large-scale urban areas, the minimum number of plant species is six, and for natural areas the minimum number is ten.

Plant species

A list of core (Table 6) and supplementary (Table 7) bioretention plant species is provided below.

Table 6 Core functional bioretention plant species (Water by Design, 2014)



Species name[1]	Common name	Type[3]	Region
Carex appressa	Tall Sedge	Groundcover sedge	ST, WT
Ficinia nodosa	Knobby club-sedge	Groundcover sedge	ST
Imperata cylindrica	Blady grass	Groundcover grass	All
Lepidosperma laterale	Variable sword-sedge	Groundcover sedge	All
Lomandra hystrix	River mat-rush	Groundcover herb	ST, DT, WT
Lomandra longifolia	Spiny-headed mat-rush	Groundcover herb	All
Lomandra leucocephala	Woolly Mat-Rush	Groundcover herb	DT, A
Pennisetum alopecuriodes[2]	Swamp foxtail grass	Groundcover grass	ST
Poa labillardieri	Common tussock grass	Groundcover grass	ST, A
Themeda australis	Kangaroo grass	Groundcover grass	All
Callistemon sieberi	River bottlebrush	Shrub	ST
Leptospermum liversidgei	Olive tea-tree	Shrub	ST
Melaleuca thymifolia	Thyme honey myrtle	Shrub	ST, DT
Banksia robur	Swamp banksia	Small tree	ST, DT, WT
Melaleuca linariifolia	Flax-leaved paperbark	Small tree	ST
Melaleuca viridiflora	Broad leaved tea-tree	Small tree	ST, WT, DT
Casuarina glauca	Swamp oak	Tree	ST, WT, DT
Casuarina cunninghamiana	River sheoak	Tree	ST
Lophostemon suaveolens	Swamp Mahogany	Tree	ST, WT, DT
Melaleuca bracteata	Black tea-tree	Tree	ST, WT, DT
Melaleuca quinquenervia	Broad-leaved paper bark	Tree	ST, WT, DT

[1] The list of core plant species has been derived from research conducted by FAWB (http://www.monash.edu.au/fawb), it's successors, other research organisations and observations of healthy bioretention systems.

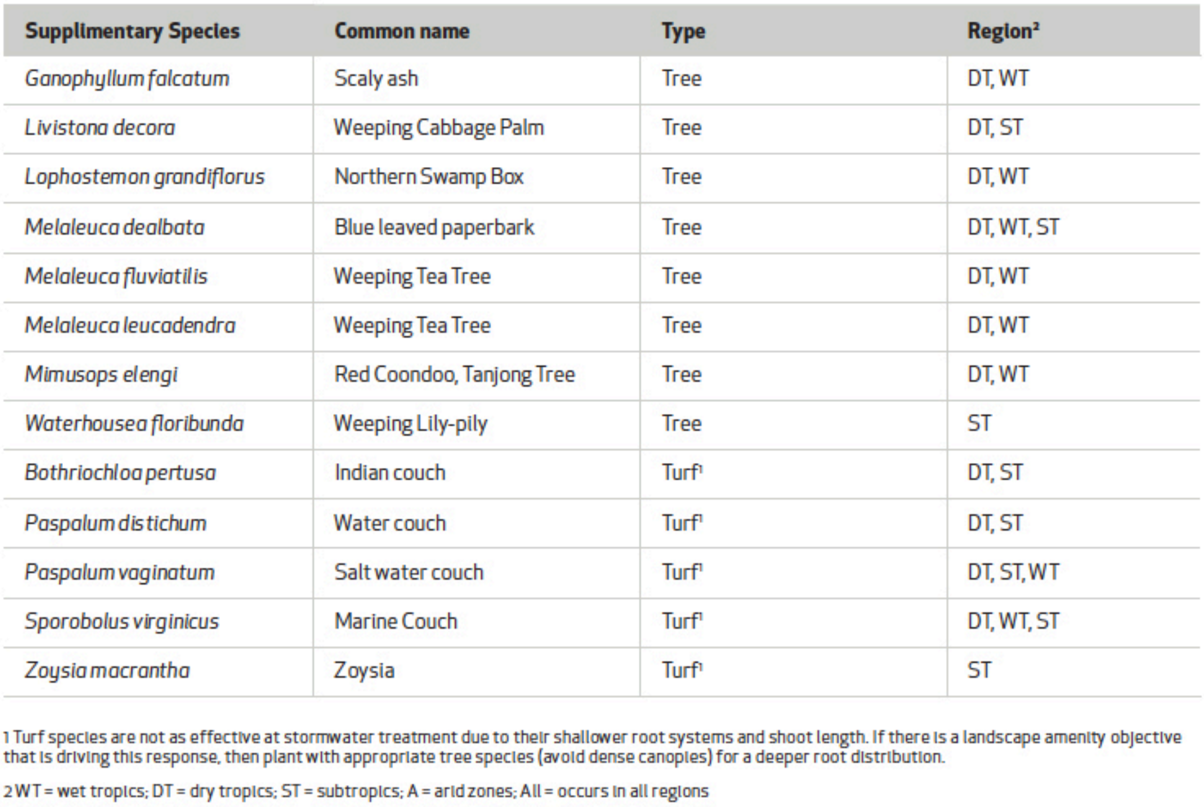
[2] Pennisetum alopecuroides is strongly self-seeding. Local authority advice should be sought regarding its use.

[3] WT = wet tropics; DT = dry tropics; ST = subtropics; A = arid zones; All = occurs in all regions

Table 7 Supplementary bioretention plant species (Water by Design, 2014)

Supplimentary Species	Common name	Type	Region[2]
Cymbopogon refractus	Barbed wire grass	Groundcover grass	DT, WT, ST
Fimbristylis dichotoma	Common fringe sedge	Groundcover sedge	All
Fimbristylis ferruginea	Rusty fringe sedge	Groundcover sedge	All
Fimbristylis tristachya		Groundcover sedge	DT, WT, ST
Fuirena umbellata		Groundcover sedge	DT, WT, ST
Gahnia aspera	Saw sedge	Groundcover sedge	ST, DT, WT
Gahnia seiberiana	Red-fruit saw-sedge	Groundcover sedge	ST, WT, DT
Juncus polyanthemus	Striated rush	Groundcover sedge	DT, WT, ST
Juncus usitatus	Common rush	Groundcover sedge	DT, WT, ST
Lomandra confertifolia	Dwarf mat rush	Groundcover sedge	ST
Rhynchospora corymbosa	Matamat	Groundcover sedge	All
Scleria polycarpa	Many-fruited sedge grass	Groundcover sedge	DT, WT
Aidia racemosa	Archer Cherry	Shrub	DT, WT
Alphitonia excelsa	Red ash	Shrub	All
Atractocarpus fitzalanii	Native Gardenia	Shrub	DT, WT
Austromyrtus dulcis	Midgen berry	Shrub	ST
Breynia oblongifolia	False coffee bush	Shrub	All
Cordyline manners-suttoniae	Giant palm lily	Shrub	ST, WT
Hibiscus heterophyllus	Native rosella	Shrub	DT, WT, ST
Leptospermum polygalifolium	Wild May	Shrub	DT, WT, ST
Melastoma malabathricum	Blue tongue	Shrub	ST, WT
Myoporum acuminatum	Coastal boobialla	Shrub	All
Xanthorrhoea fulva	Swamp grass tree	Shrub	ST
Albizia canescens	Townsville siris	Tree	DT, WT
Casuarina equisetifolia	Coast She Oak	Tree	DT, WT, ST
Buckinghamia celsissima	Ivory curl flower	Tree	DT, WT
Callistemon viminalis	Weeping bottle brush	Tree	All
Chionanthus ramiflora	Native olive	Tree	DT, WT, ST
Colubrina asiatica	Latherleaf	Tree	DT, WT
Corymbia tesselaris	Moreton Bay Ash	Tree	DT, WT, ST
Cupaniopsis anacardioides	Beach tuckeroo	Tree	DT, WT, ST
Eucalyptus raveretiana	Black ironbox	Tree	DT
Eucalyptus tereticornis	River blue gum	Tree	DT, WT, ST
Eugenia reinwardtiana	Cedar Bay cherry	Tree	DT, WT, ST

Table 7 continued



Supplimentary Species	Common name	Type	Region[2]
Ganophyllum falcatum	Scaly ash	Tree	DT, WT
Livistona decora	Weeping Cabbage Palm	Tree	DT, ST
Lophostemon grandiflorus	Northern Swamp Box	Tree	DT, WT
Melaleuca dealbata	Blue leaved paperbark	Tree	DT, WT, ST
Melaleuca fluviatilis	Weeping Tea Tree	Tree	DT, WT
Melaleuca leucadendra	Weeping Tea Tree	Tree	DT, WT
Mimusops elengi	Red Coondoo, Tanjong Tree	Tree	DT, WT
Waterhousea floribunda	Weeping Lily-pily	Tree	ST
Bothriochloa pertusa	Indian couch	Turf[1]	DT, ST
Paspalum distichum	Water couch	Turf[1]	DT, ST
Paspalum vaginatum	Salt water couch	Turf[1]	DT, ST, WT
Sporobolus virginicus	Marine Couch	Turf[1]	DT, WT, ST
Zoysia macrantha	Zoysia	Turf[1]	ST

1 Turf species are not as effective at stormwater treatment due to their shallower root systems and shoot length. If there is a landscape amenity objective that is driving this response, then plant with appropriate tree species (avoid dense canopies) for a deeper root distribution.

2 WT = wet tropics; DT = dry tropics; ST = subtropics; A = arid zones; All = occurs in all regions

Planting density

Planting densities must provide rapid coverage to prevent the establishment of weeds and must ensure 90% coverage in two growing seasons. The root zone in the filter media should be uniformly developed, enabling bioretention performance objectives to be met.

ANNEX 6. CRITERIA FOR THE IMPLEMENTATION OF SOURCE CONTROL TECHNIQUES OUTLINED BY THE LISBON MUNICIPALITY'S GENERAL DRAINAGE PLAN

According to the Lisbon Municipality's General Drainage Plan (Leboeuf et al., 2015, p. 21-22), the implementation of source control techniques should consider the following:

- Land use and availability of physical space
- Topography and soil type: resistance capacity, permeability, and behaviour when in contact with water
- Water table level during the rainy and dry season
- Rainwater pollution levels
- The impact of rainwater on groundwater
- The impact of polluted rainwater on surrounding basins (and the possible requirement for pre-treatment of rainwater before infiltration)
- Impact on the environment and on pollution levels
- Hydraulic behaviour and performance in situations of increased risk
- Slope of roofs
- Landscape integration and the possibility of using the space for recreational purposes
- Construction difficulty level and issues relevant to post-construction management
- Investment, maintenance and operation costs (including energy consumption)
- Frequency and difficulty level of maintenance operations
- Lifetime of the infrastructure

ANNEX 7. GEOLOGICAL FORMATIONS

Annex 7.1 Time scale of the geological formations in the Alcântara watershed

Table 8 Time scale of the geological formations in the Alcântara watershed

Era	Period	Epoch	Age	Formation (Alcântara watershed)
Cenozoic	Quaternary	Holocene	-	Alluvium
		Pleistocene	-	Marine terrace deposits
	Neogene	Pliocene	Piacenzian	-
			Zanclean	-
		Miocene	Messinian	-
			Tortonian	-
			Serravallian	Stoneware clay (Grilos) Limestone (Quinta das Conchas) Clay (Xabregas)
			Langhian	Limestone (Musgueira) Sand (Vale de Chelas)
			Burdigalian	Sand with Miocene Plaque Limestone (Casal Vitroso) Sand (Quinta do Bacalhau) Clay (Forno do Tijolo) Limestone (Entrecampos) Sand (Estefânia) Clay (Prazeres)
			Aquitanian	-
	Paleogene	Oligocene	-	Sedimentary rocks (Benfica)
		Eocene	-	
		Paleocene	-	-
Mesozoic	Cretaceous	Late Cretaceous	Maastrichtian	Lisbon Volcanic Complex Basalt
			Campian	
			Santonian	
			Conician	
			Turonian	
			Cenomanian	Limestone (Bica)
		Early Cretaceous	Albian	Limestone and sandstone (Caneças)

Annex 7.2 Description of the geological formations in the Alcântara watershed

I. MESOZOIC

Early Cretaceous; Albian (100.5 – 113 million years)

- Limestone and sandstone (Caneças): Dolomitic marly limestone. Thickness: 60-420m.

Late Cretaceous; Cenomanian (93.9 – 100.5 million years)

- Limestone (Bica): Compact limestone, white, pink or reddish, sometimes crystalline, with flint nodules. Towards the top of the unit the limestone becomes marly. Thickness: 50m.

Late Cretaceous (66.0 – 100.5 million years)

- Lisbon Volcanic Complex: Volcanic units are intercalated with sedimentary units, indicating different magmatic episodes with periods of rest. Magmatic activity was essentially effusive and lavic, with subsidiary pyroclastic material. Minimum age of the LVC is 130 million years (Late Cretaceous). Variable thickness: 15-200m.

II. CENOZOIC

Palaeogene; Eocene – Oligocene (23.03 – 56.0 million years)

- Sedimentary rocks (Benfica): Marls and red-orange clay, sometimes with large pebbles and some limestone. Presence of conglomerates with limestone blocks. Thickness: 400m.

Neogene; Miocene; Burdigalian (15.97 – 20.44 million years)

- Clay (Prazeres): Lacustrine marlstone and clays predominate. Presence of corals, bryozoans and argillites. Thickness: 45m.
- Sand (Estefânia): Fine sands, clay sands, argillites and some bio-calcarenite beds. Thickness: 500m in Belverde.
- Limestone (Entrecampos): Bio-calcarenites with abundant detritic fractions, sometimes with clay. Very fine sands and grey clay siltstone at the top of the unit.
- Clay (Forno de Tijolo): Fine pyritic clay sands, blue-grey colour, with molluscs.
- Sand (Quinta do Bacalhau): Deposits of riverine sands, with argillite bed that corresponds to a flood plain deposits.
- Limestone (Casal Vistoso): Carbonated bed with stoneware clay, very rich in molluscs and red algae. Thickness: 3-12m.
- Sands with Miocene Plaque: Yellow fluvial sands with large pebbles and sandy clay with vegetation and oysters.

Neogene; Miocene; Langhian (13.82 – 15.97 million years)

- Limestone (Musgueira): White or yellow sandy bio-calcarenite, often coarse, rich in molluscs.

- Sand (Vale de Chelas): Feldspar fluvial sand, loose or cemented, sometimes coarse and compacted.

Neogene; Miocene; Serravalian (11.62 – 13.82 million years)

- Limestone (Quinta das Conchas): In Lisbon, these represent the beginning of the relative change in sea level. Coarse bio-calcarenites and silty clay bio-calcarenites.
- Stoneware clay (Grilos): Yellow bio-calcarenites with rounded mollusc fragements and coarse sand deposits.
- Clay (Xabregas): Silty blue-grey clay, sometimes with fine sands. Generally very rich in molluscs, Foraminifera and Ostracods.

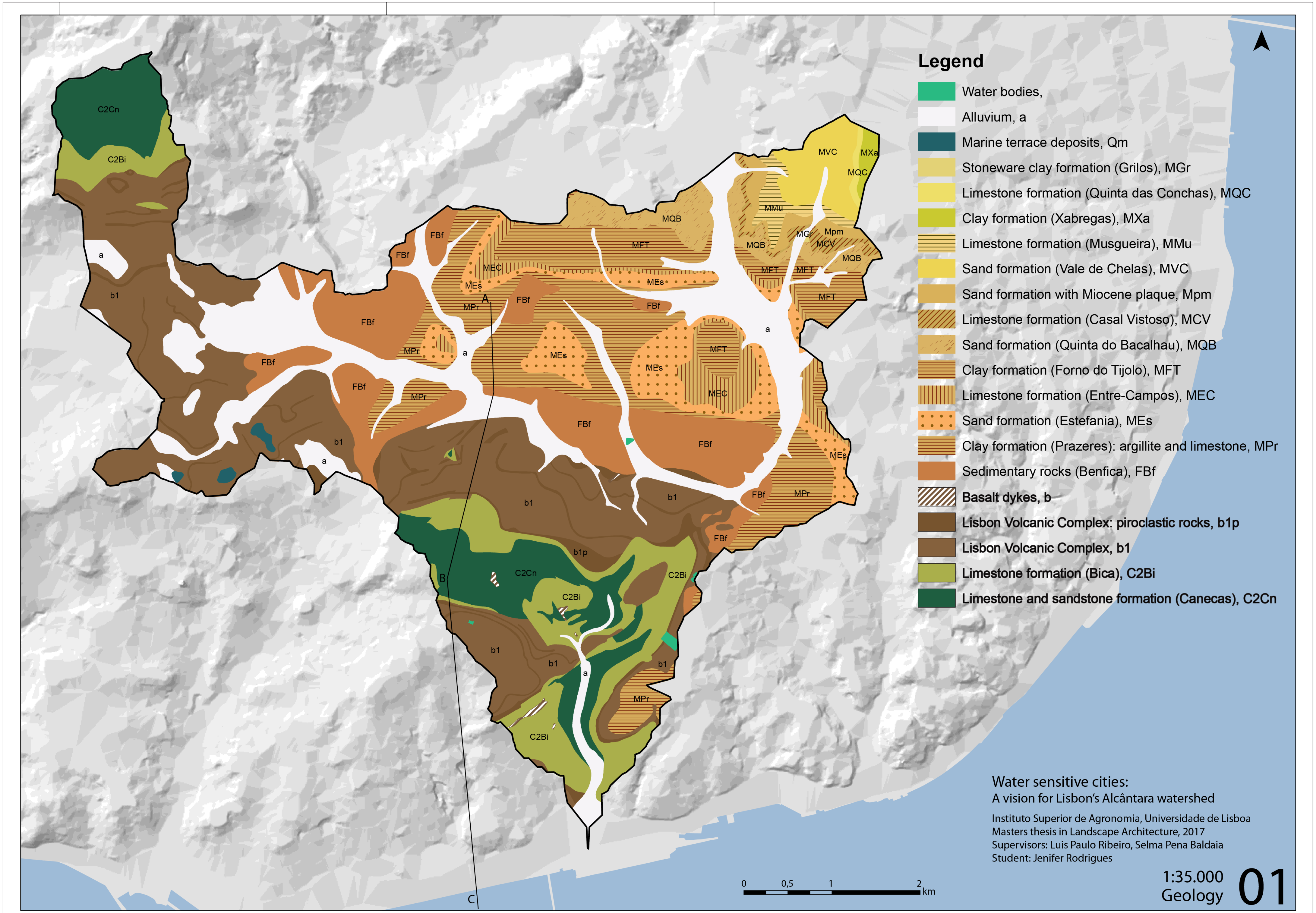
Quaternary; Pleistocene (0.126 – 2.58 million years)

- Marine terrace deposits: Three areas were mapped as “Pleistocenic beach pebbles”, but these areas can no longer be studied as they have been hidden by the urban expansion in the municipality of Amadora.

Quaternary; Holocene (0 – 0.0117 million years)

- Alluvium: They occur along the main water lines of the Lisbon area, with variable thickness.

(Pais et al., 2006)



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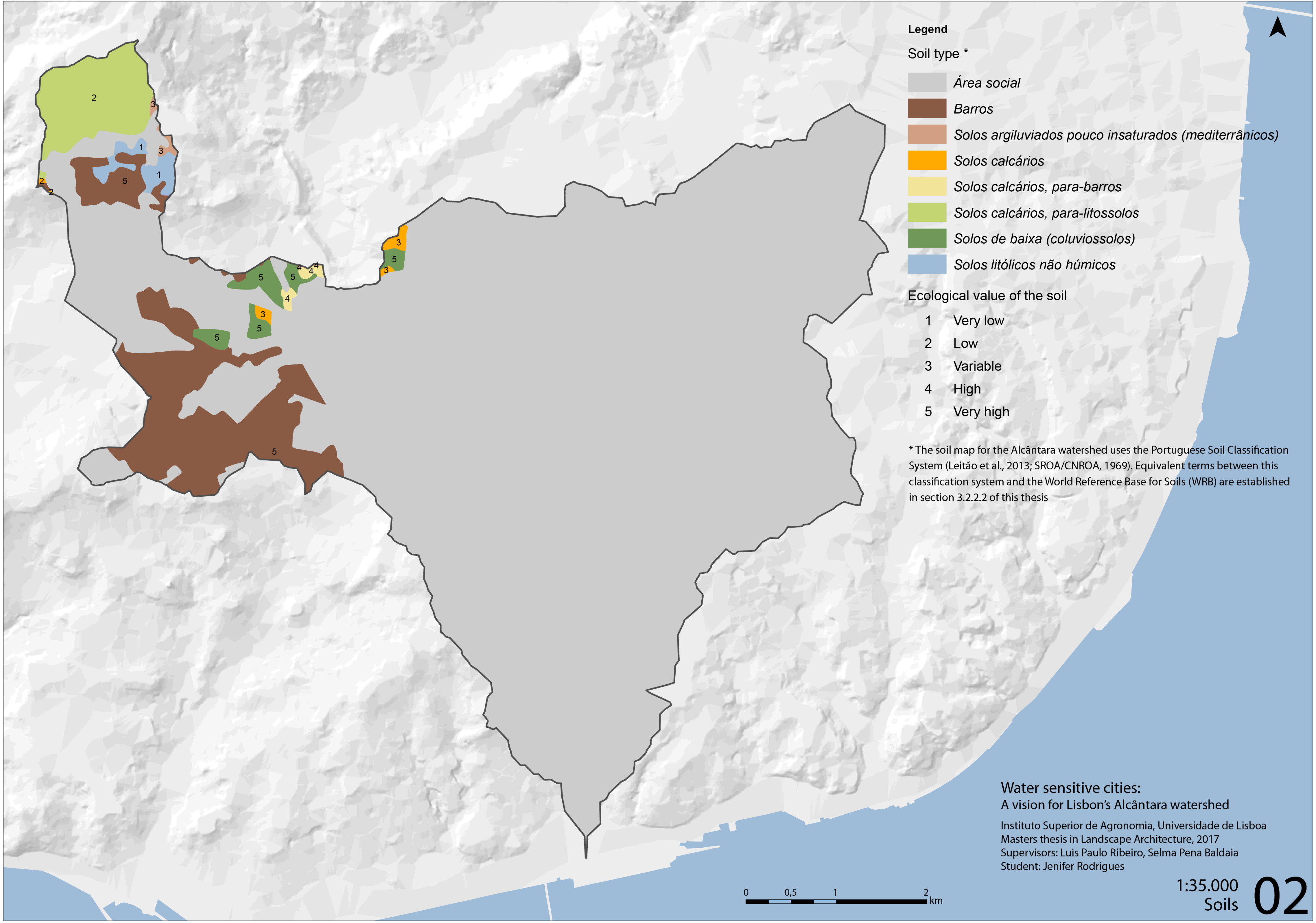
Geology

01



Legend

Soil type *

- ⬜ *Área social*
- 🟫 *Barros*
- 🟫 *Solos argiluviados pouco insaturados (mediterrânicos)*
- 🟧 *Solos calcários*
- 🟨 *Solos calcários, para-barros*
- 🟩 *Solos calcários, para-litossolos*
- 🟩 *Solos de baixa (coluviossolos)*
- 🟦 *Solos litólicos não húmicos*

Ecological value of the soil

1	Very low
2	Low
3	Variable
4	High
5	Very high

* The soil map for the Alcântara watershed uses the Portuguese Soil Classification System (Leitão et al., 2013; SROA/CNROA, 1969). Equivalent terms between this classification system and the World Reference Base for Soils (WRB) are established in section 3.2.2.2 of this thesis

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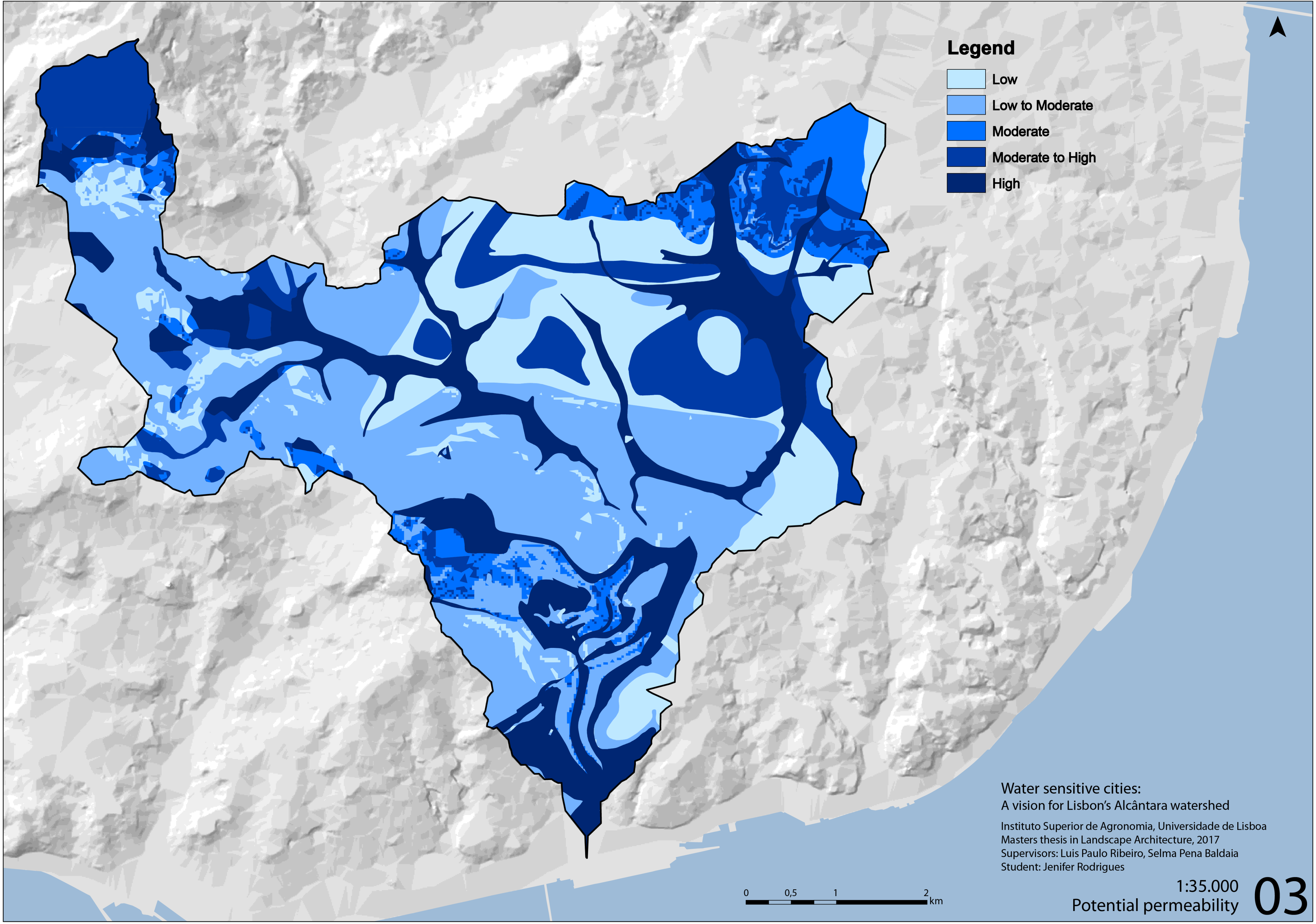
Soils

02



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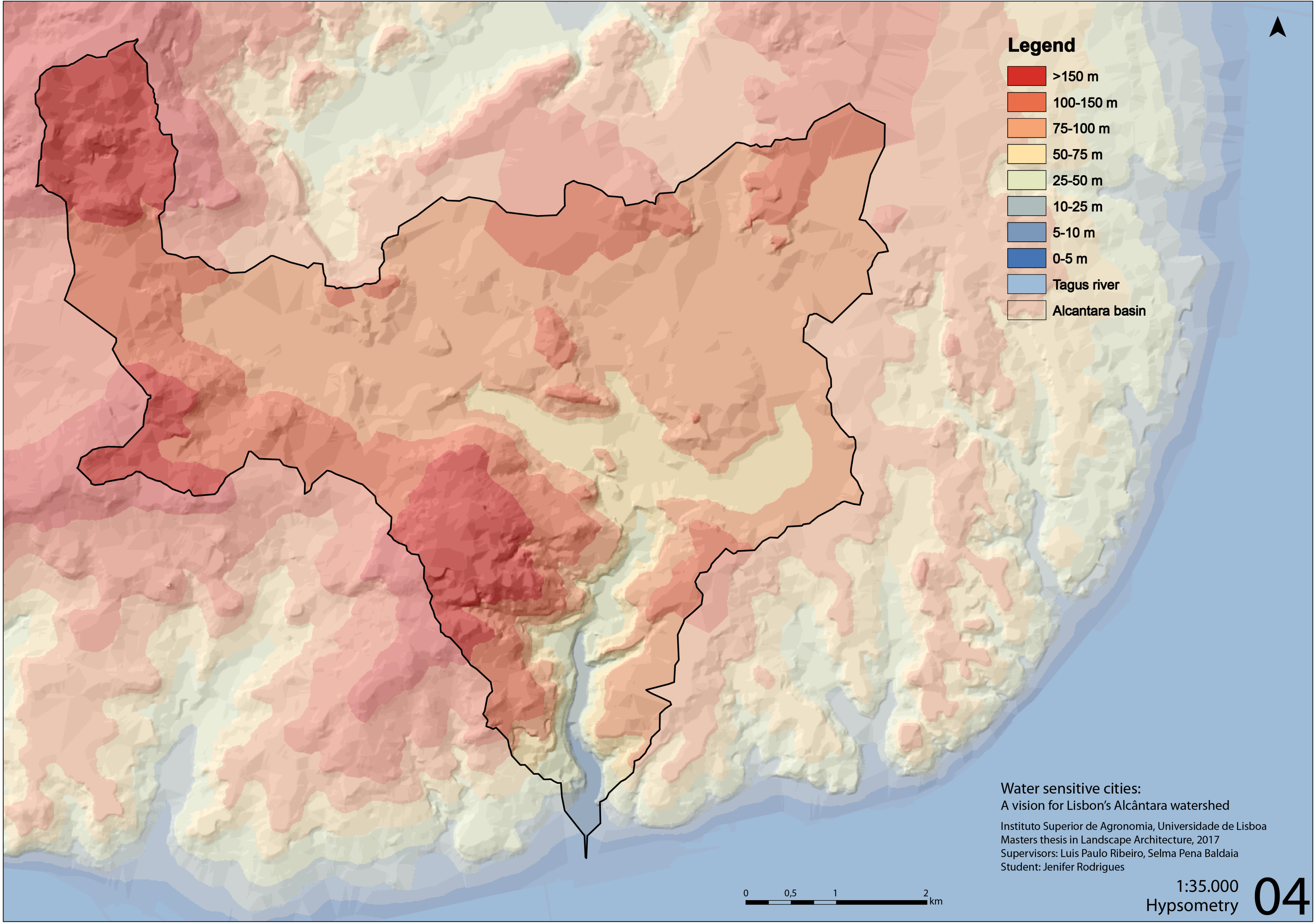
Potential permeability

03



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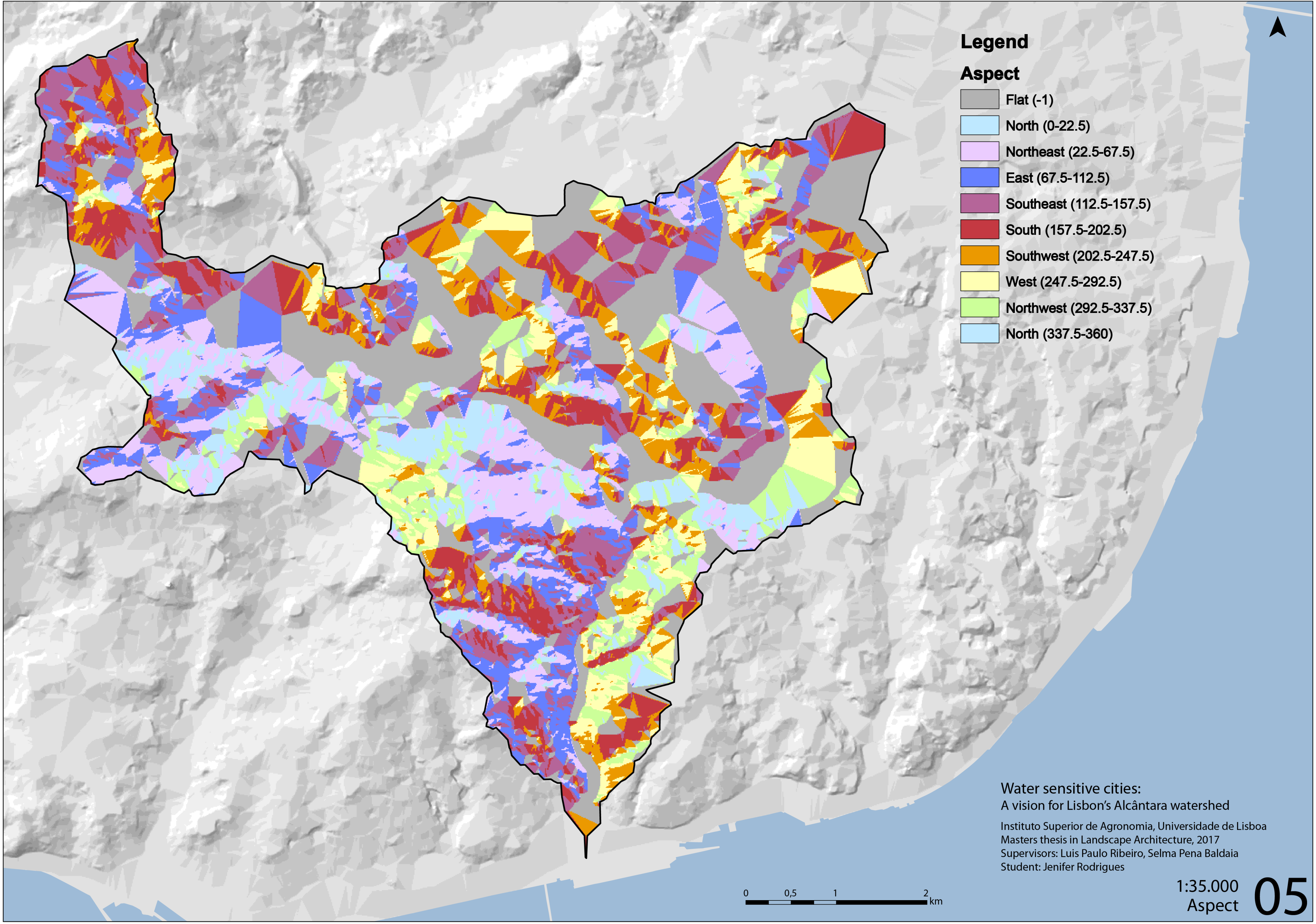
Hypsometry

04



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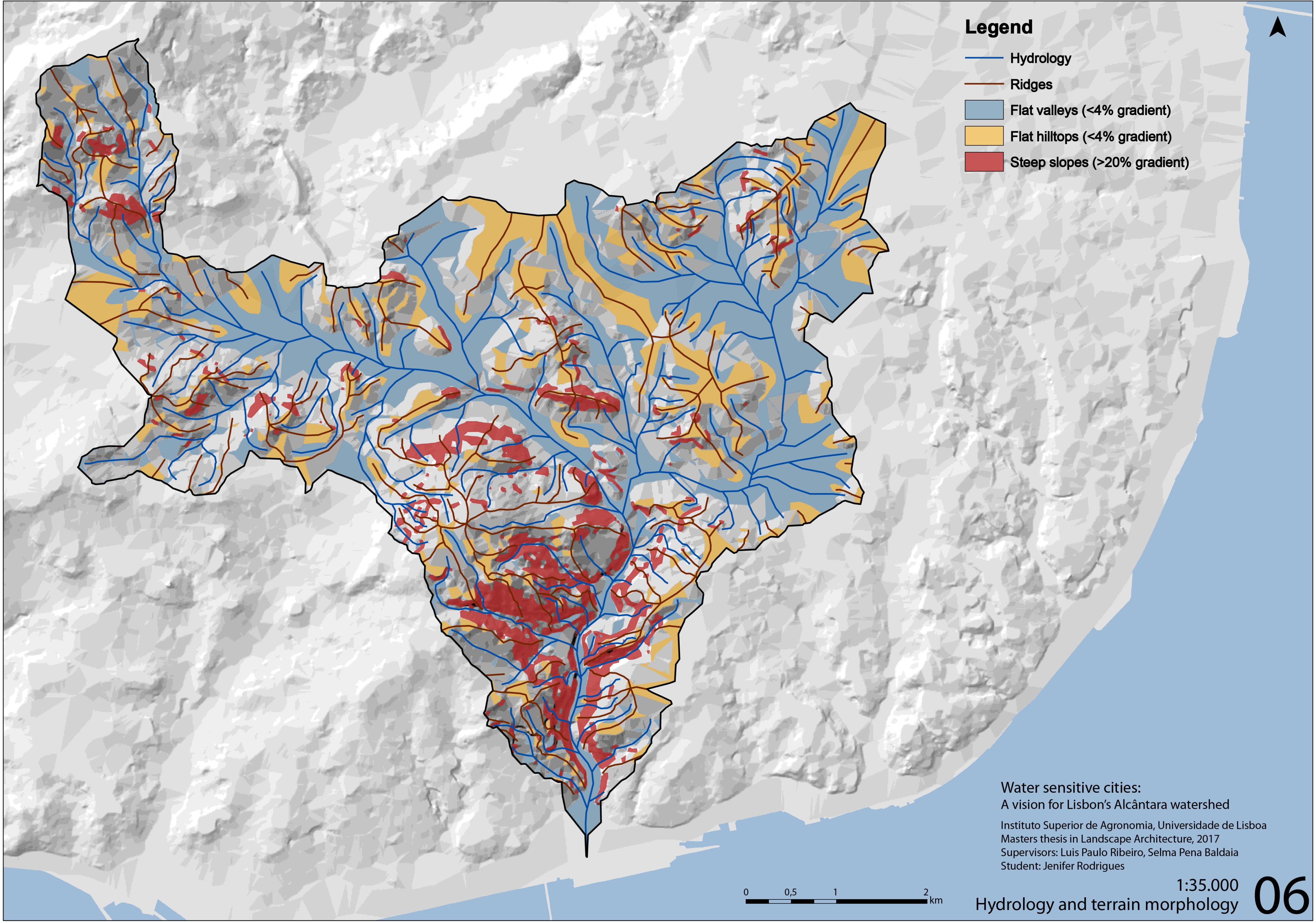
Aspect
05



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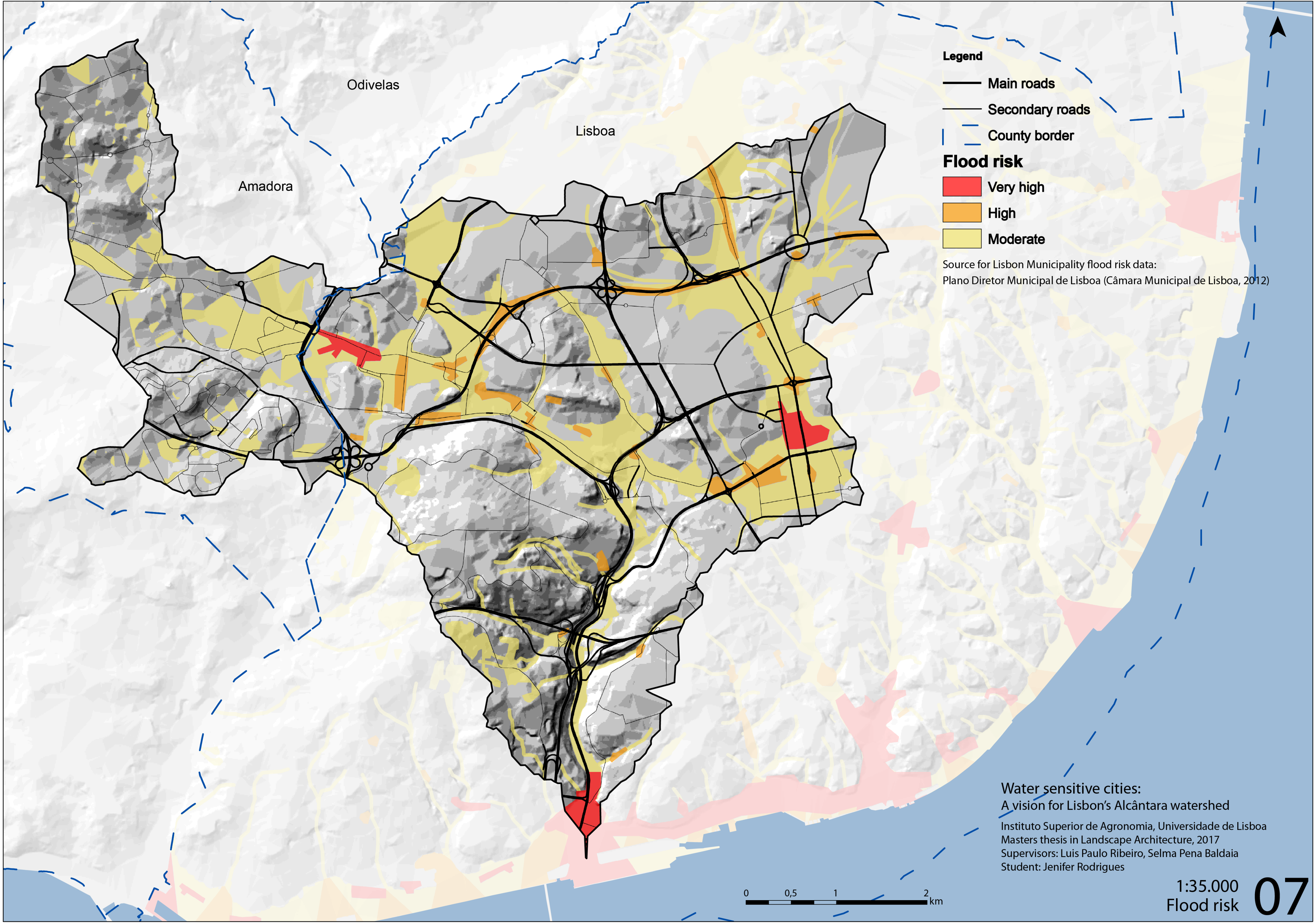
Hydrology and terrain morphology

06



Source for Lisbon Municipality flood risk data:
Plano Diretor Municipal de Lisboa (Câmara Municipal de Lisboa, 2012)

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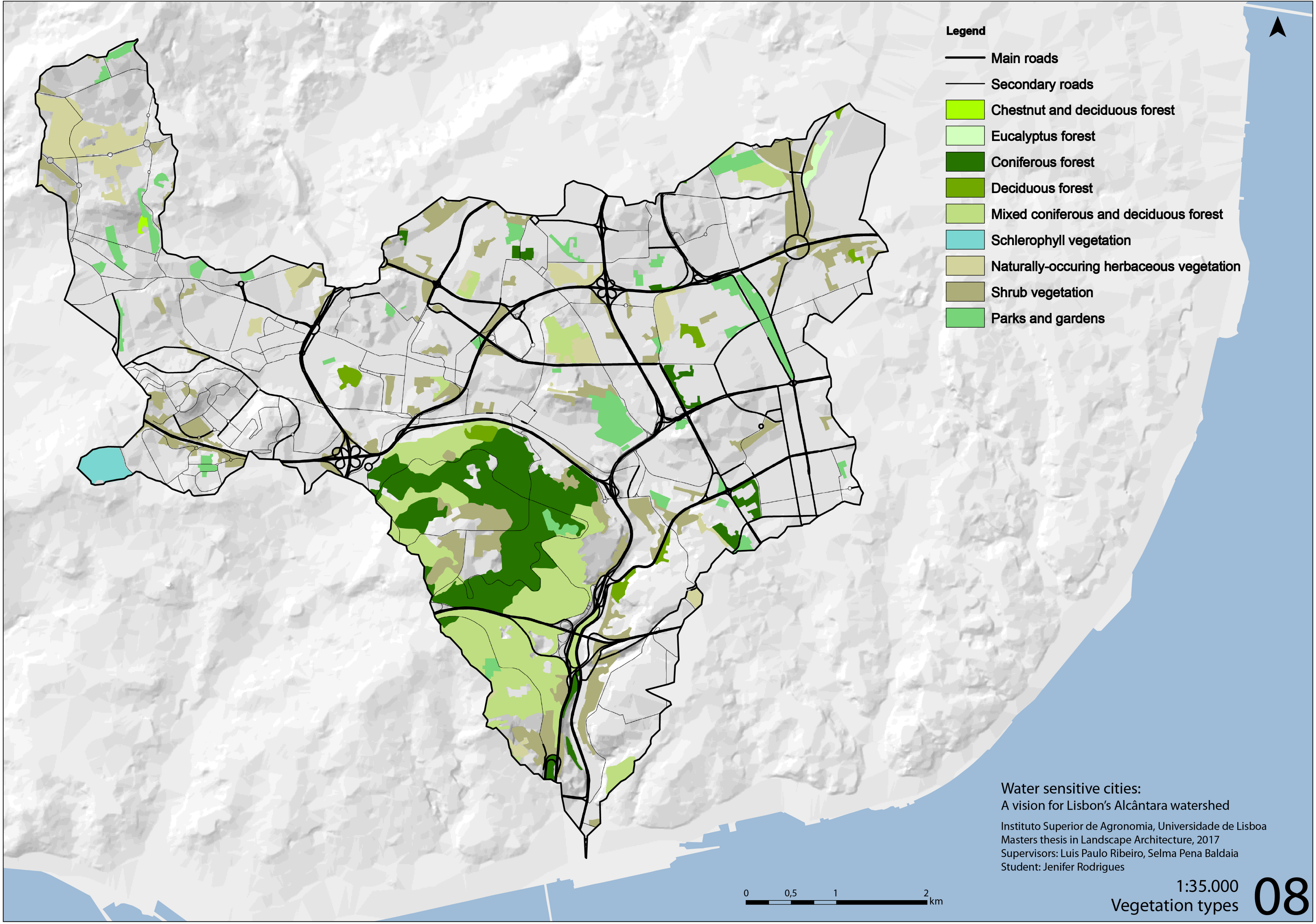
Flood risk

07



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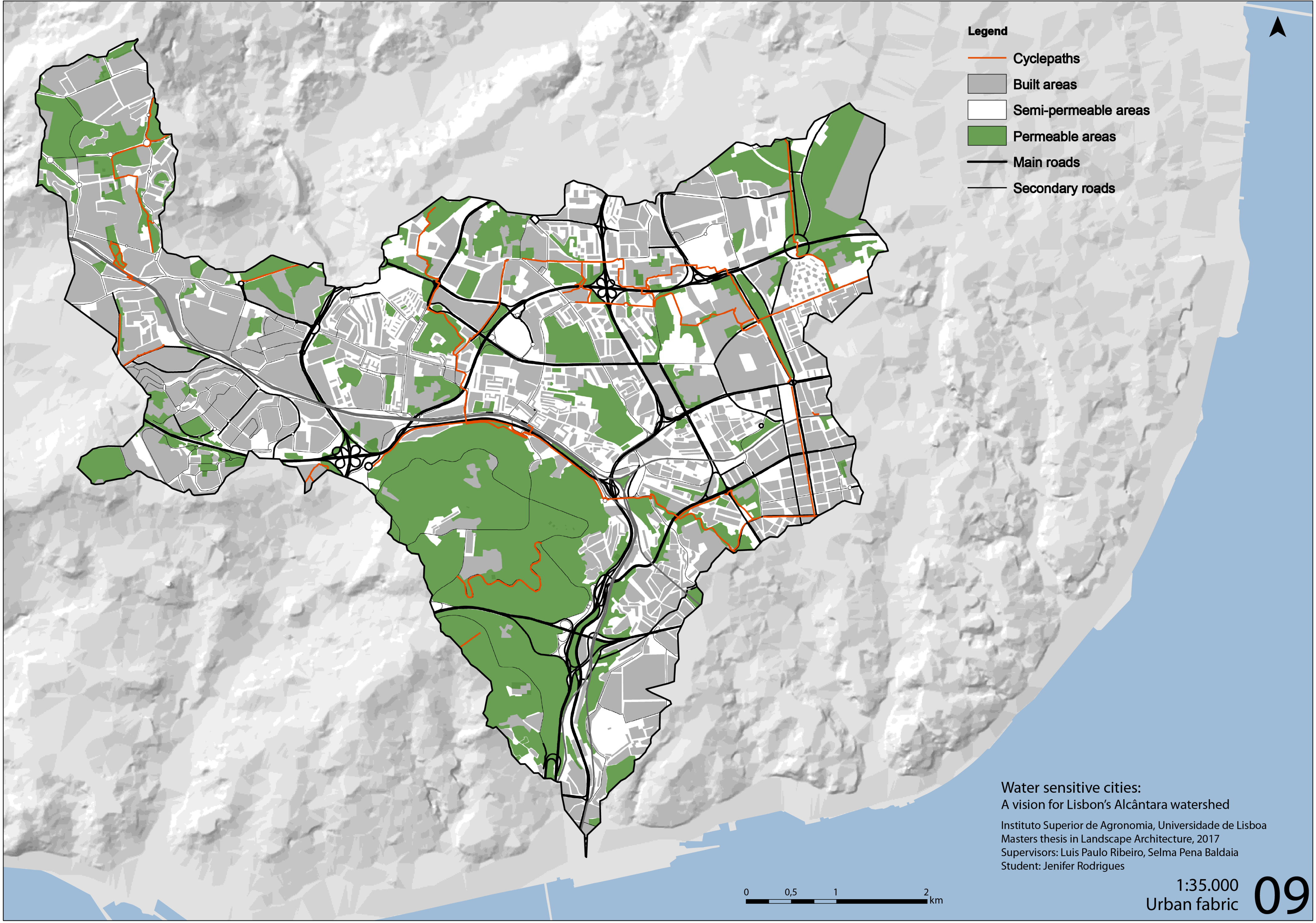
Vegetation types

08



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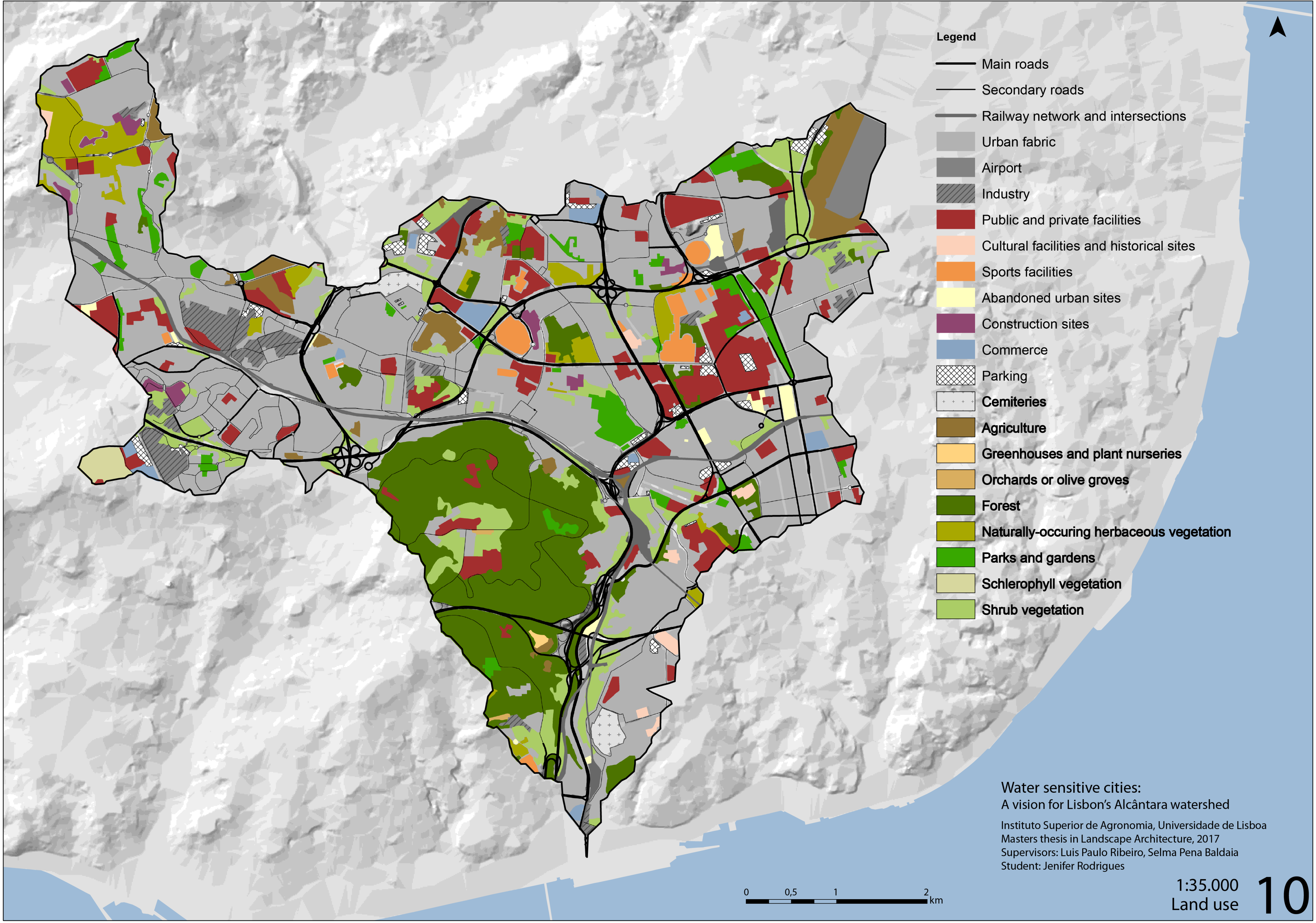
Urban fabric

09



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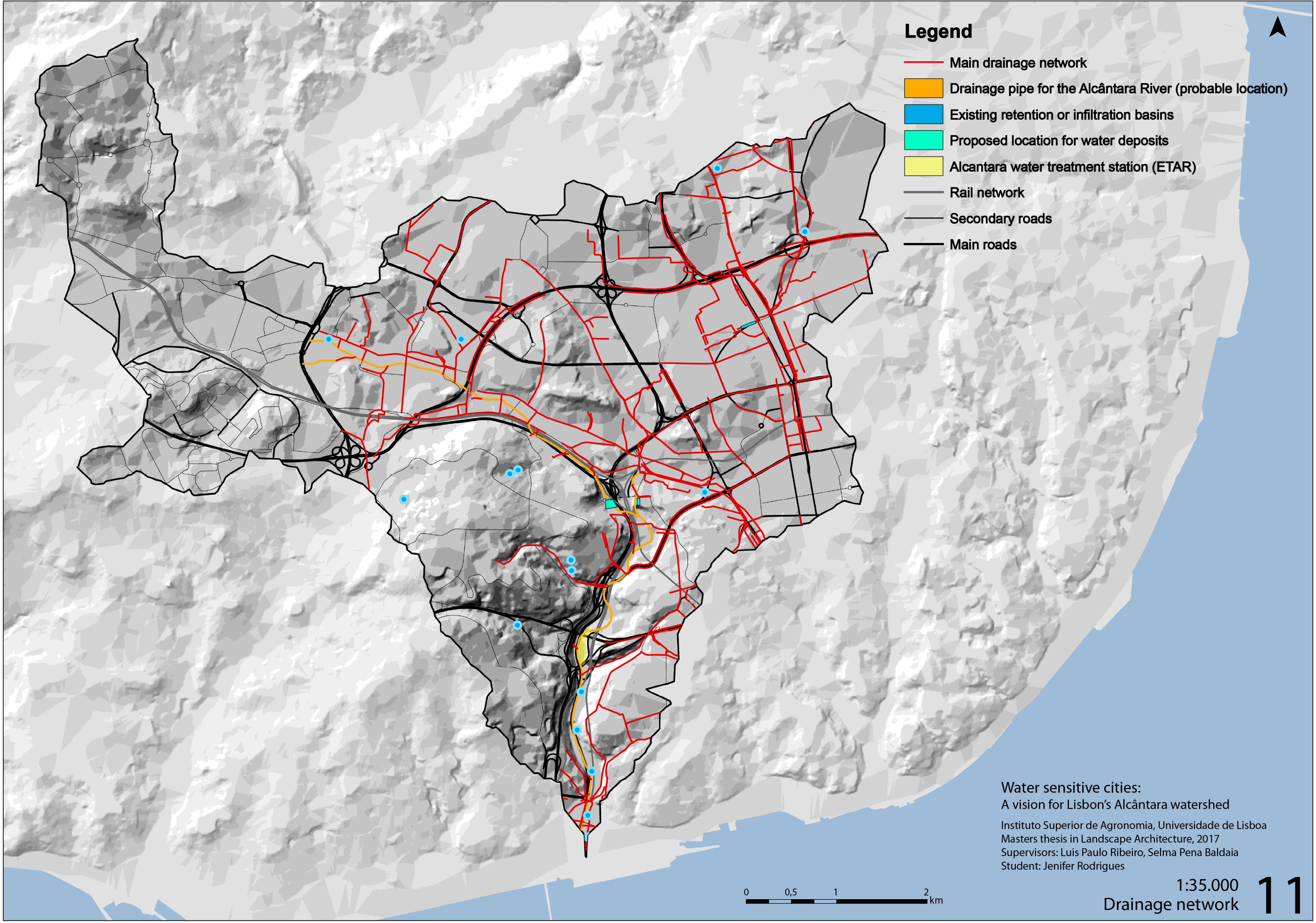
Land use

10



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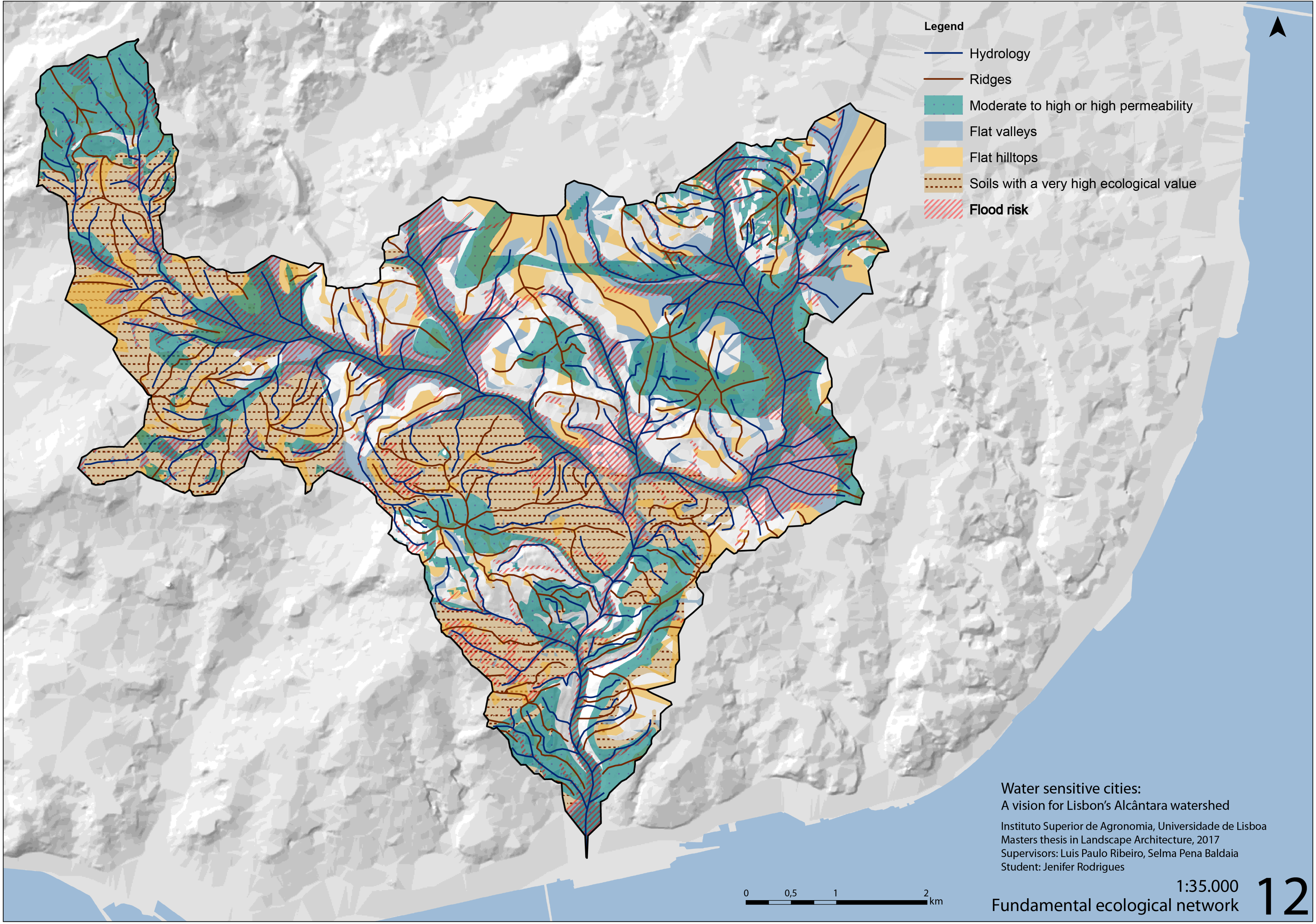
Drainage network



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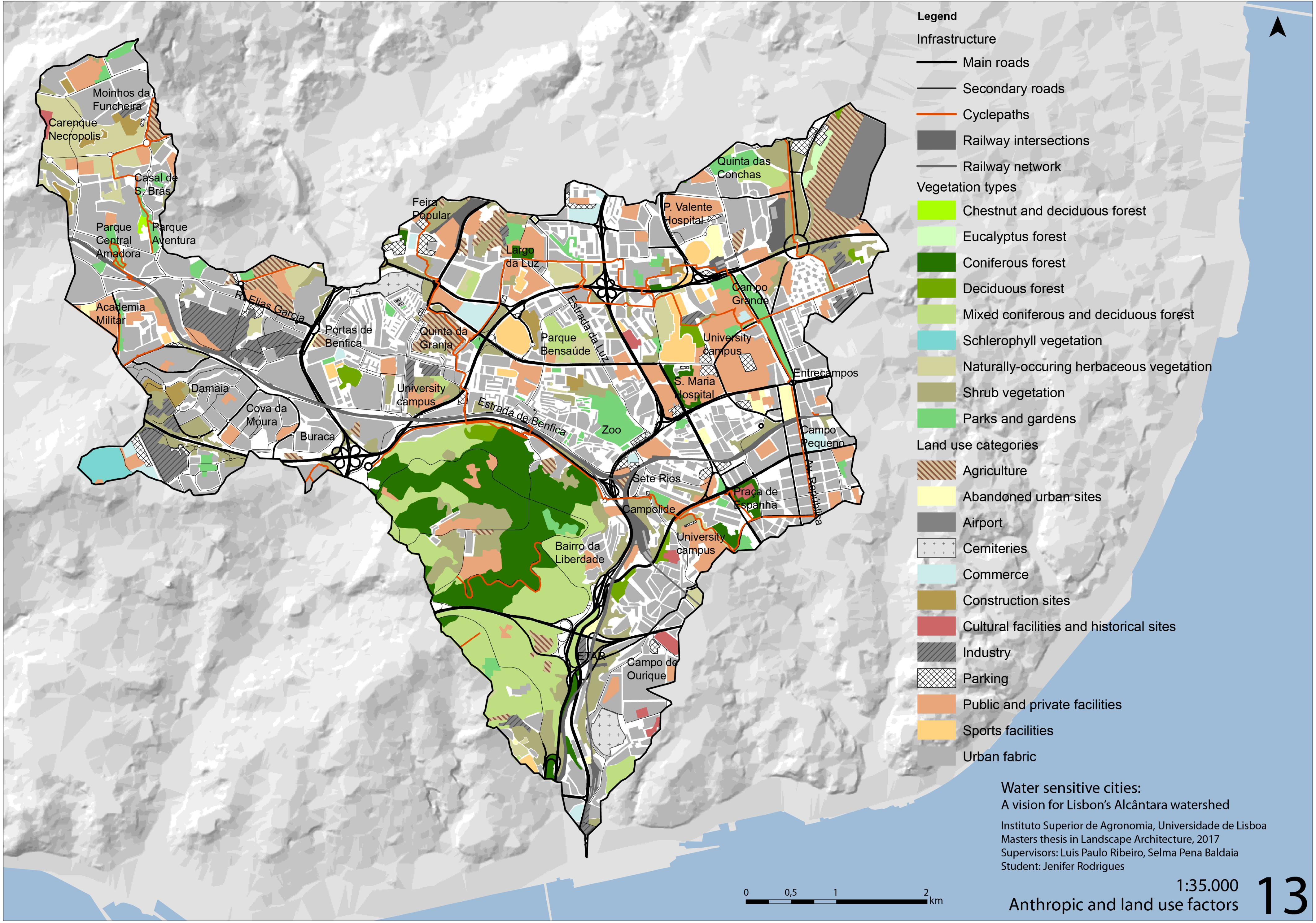
Fundamental ecological network

12



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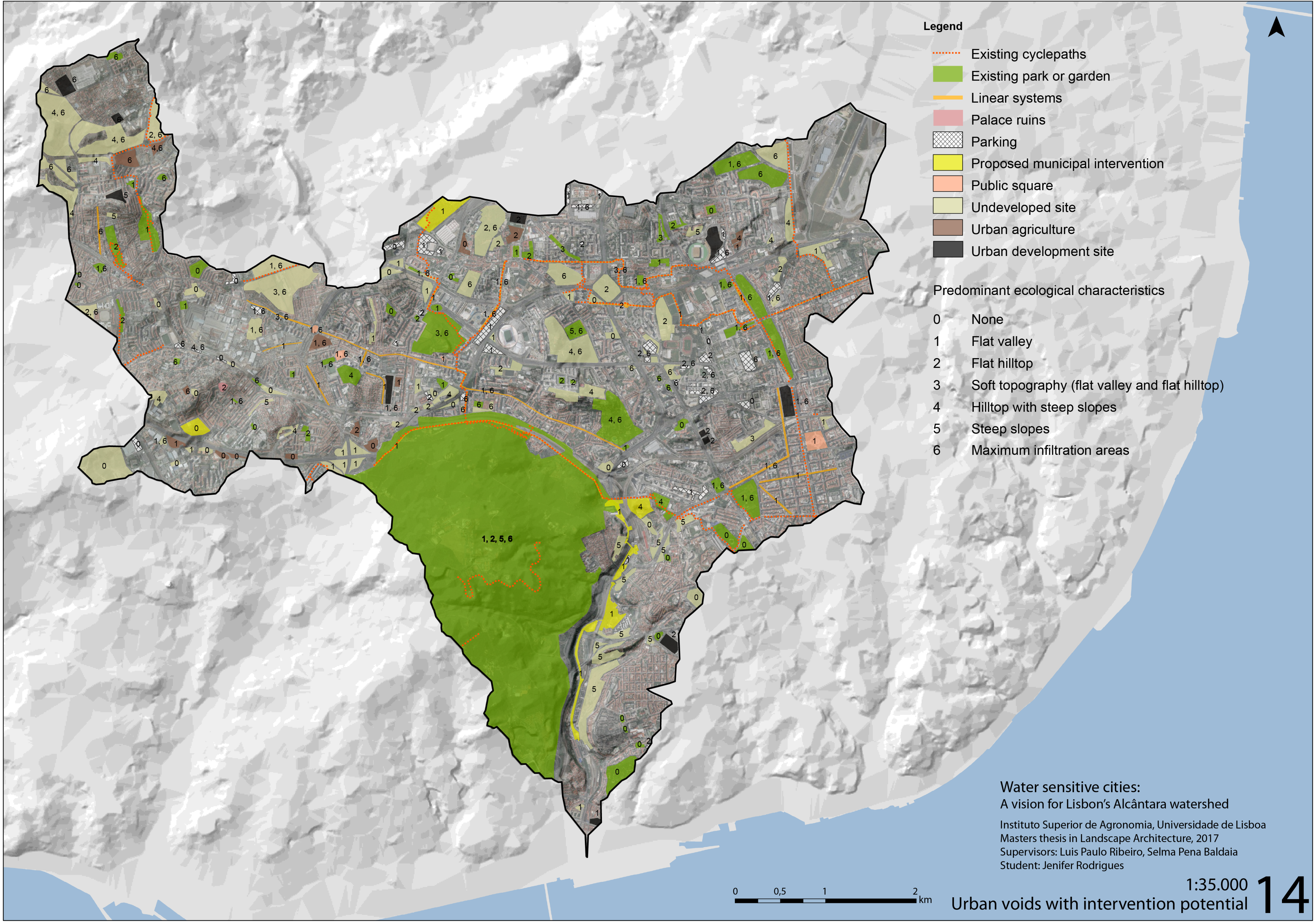
Anthropic and land use factors

13



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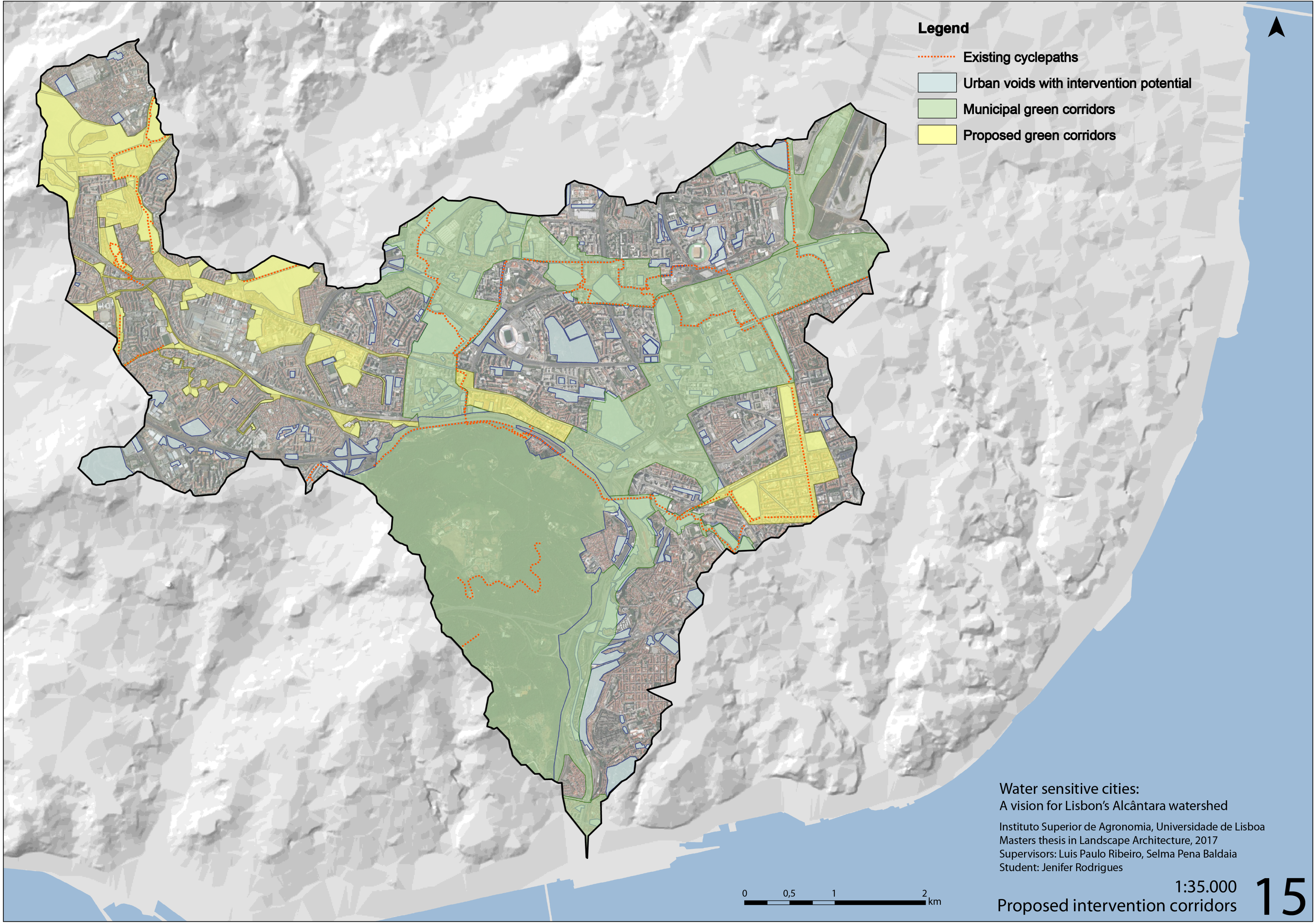
Urban voids with intervention potential

14



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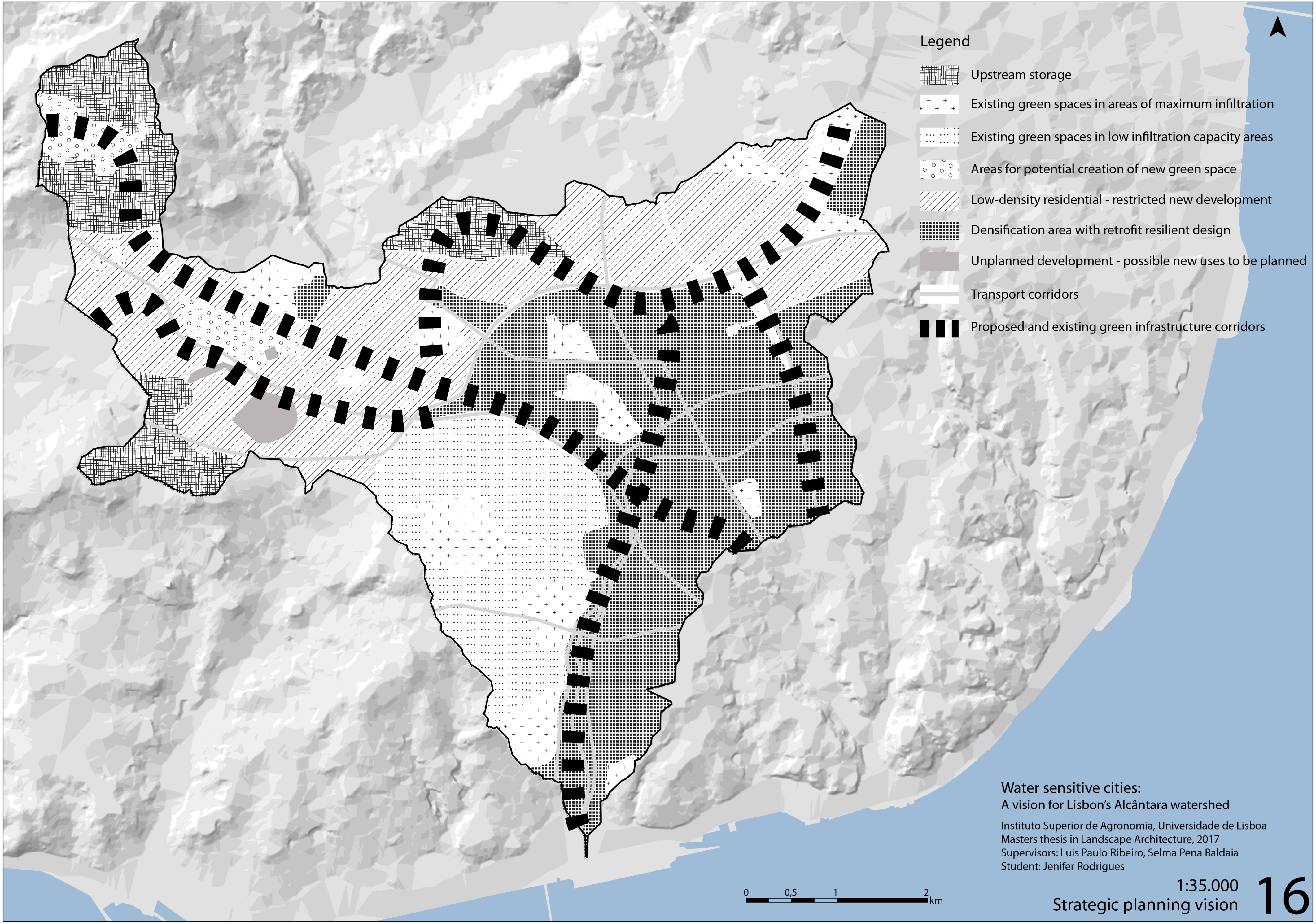
Proposed intervention corridors



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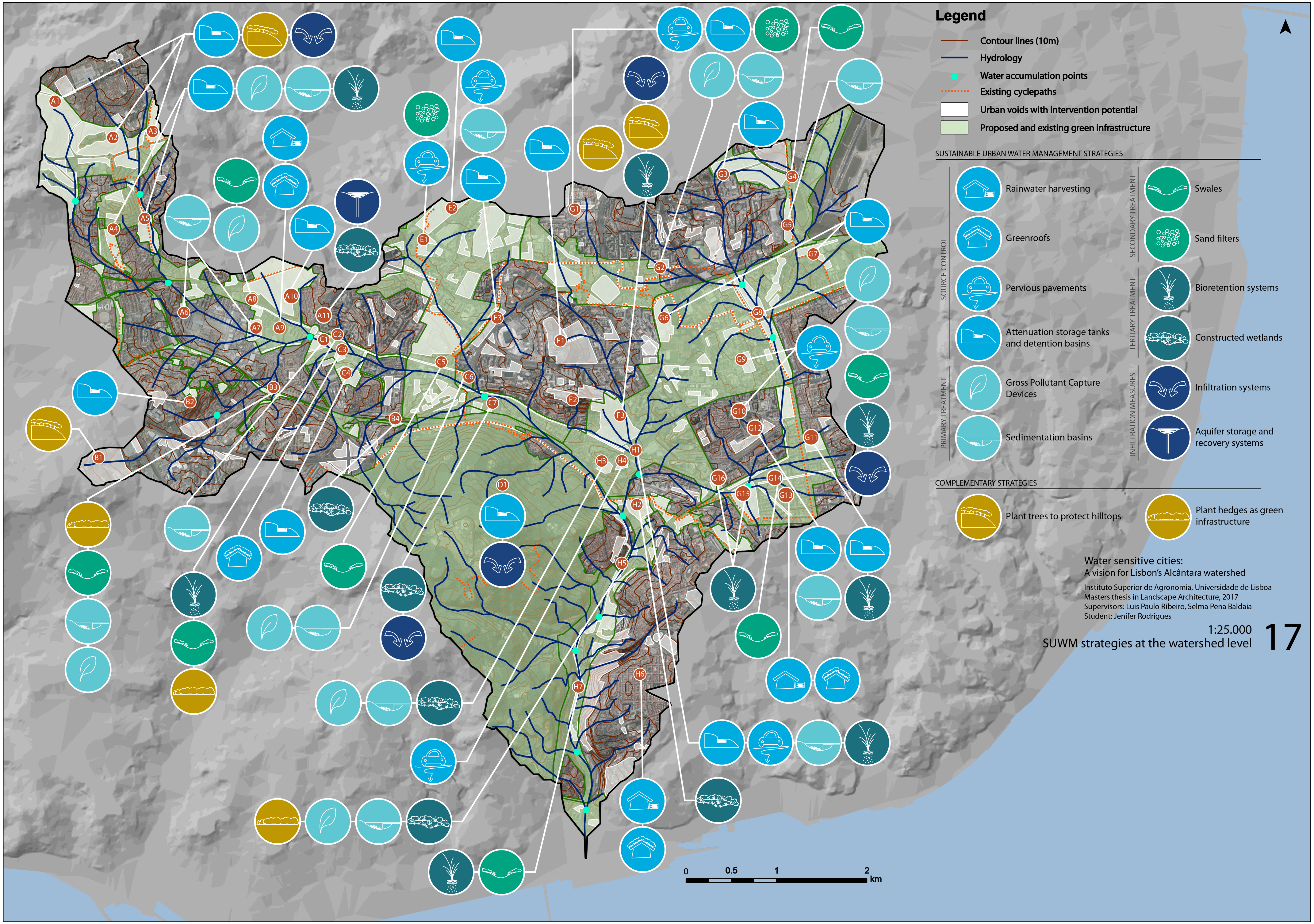
Strategic planning vision

16



Legend

- Contour lines (10m)
- Hydrology
- ● Water accumulation points
- Existing cyclepaths
- ☐ Urban voids with intervention potential
- 🟩 Proposed and existing green infrastructure

SUSTAINABLE URBAN WATER MANAGEMENT STRATEGIES

SOURCE CONTROL
- Rainwater harvesting
- Greenroofs
- Pervious pavements
- Attenuation storage tanks and detention basins

PRIMARY TREATMENT
- Gross Pollutant Capture Devices
- Sedimentation basins

SECONDARY TREATMENT
- Swales
- Sand filters

TERTIARY TREATMENT
- Bioretention systems
- Constructed wetlands

INFILTRATION MEASURES
- Infiltration systems
- Aquifer storage and recovery systems

COMPLEMENTARY STRATEGIES
- Plant trees to protect hilltops
- Plant hedges as green infrastructure

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SUWM strategies at the watershed level

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