Impacts of Demographic Growth, Land Use/Land Cover Change, and Climate Change on Groundwater Resources in Setubal Peninsula

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Thesis to obtain the Master of Science Degree in
Environmental Engineering

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RESUMO

Com a expansão urbana e consequente alteração do uso do solo, decorrente do influxo de população, torna-se prioritário quantificar e qualificar os impactos dessas dinâmicas sobre os recursos hídricos. No distrito de Setúbal, observaram-se mudanças significativas no uso do solo e na população ao longo das últimas décadas, com repercussões nas necessidades de água para abastecimento público, industrial e agrícola. Uma vez que o fornecimento público de água nesta região depende exclusivamente de recursos hídricos subterrâneos, torna-se imperativo avaliar a tendência temporal da disponibilidade de para uma gestão integrada mais adequada.

Este estudo tem por base parâmetros físicos e hidro-climatológicos da região, alteração do uso do solo, crescimento demográfico e alterações climáticas como métricas para avaliar o estado dos recursos hídricos subterrâneos no distrito de Setúbal, em Portugal. A caracterização do uso do teve por base a informação disponibilizada pelo mapa CORINE Land cover entre os anos 1990 e 2018. Foram também avaliados os volumes de captação para este período, a evolução da população e o respetivo balanço hídrico temporal e espacial. Os cenários climáticos futuros tiveram por base os cenários RCP4.5 e RCP8.5.

Os resultados mostram que houve uma mudança muito significativa no uso do solo com uma extensão da área construída de 12,5% em 1990 para 19,2% em 2018. Simultaneamente ocorreu redução na área ocupada pela agricultura e pelos pinhais. A população desta região aumentou consideravelmente em todos os municípios, tendo aumentado cerca de 27% entre 1990 e 2018. Com base nisto, foi observado um aumento correspondente na captação de águas subterrâneas com a construção de cerca de 14.620 poços entre 1970 e 2018.

A aplicação do modelo WetSpass (Abdollahi et al., 2012) para o cálculo da recarga da área de estudo, mostrou uma variação muito significativa nos valores de recarga entre os anos analisados, espacial e temporalmente, relacionada sobretudo com a variação inter-anual da precipitação, agravada pela alteração do uso do solo.

A análise de cenários futuros (2041-2070) mostrou que em ambos os cenários de alterações climáticas, se a intensidade de precipitação em ambos os períodos for a mesma, observou-se uma recarga ligeiramente inferior em comparação com 2018.

A avaliação do risco de contaminação pelo Índice de suscetibilidade (Stigter et al., 2005) mostra que a principal zona de recarga identificada, caracteriza-se como suscetível à poluição com origem agrícola.

A análise das diferentes componentes da variação temporal das séries piezométricas teve por base a aplicação da análise de espectro singular (SSA). O resultado desta análise permitiu identificar na componente de longo prazo tendências de subida, de descida e não tendência.

A aplicação de várias metodologias neste trabalho permitiu obter uma visão holística do estado atual e futuro dos recursos hídricos subterrâneos na área de estudo. As ferramentas aplicadas demonstraram o seu potencial para o apoio à decisão, tanto na gestão de recursos hídricos como do território.

Palavras-Chave: Alterações no uso do solo, Alterações Climáticas, Crescimento Demográfico, Gestão de água subterrânea, Análise de Espectro Singular, Vulnerabilidade, Península de Setúbal, Nível Piezométrico, RCP.

ABSTRACT

The urban sprawl and consequent land use changes are a result from the continued and dynamic influx of population. The quantification and qualification of the impacts of these dynamics on groundwater resources are therefore required. All over the district of Setubal, significant changes have been observed in both land use and population in the past decades. This phenomenon is reflected on the water demands, which induced an increased search for groundwater, mainly for public supply, industrial use, or agriculture. As the water supply in the region depends exclusively on groundwater resources, it is imperative to assess the temporal trend of water availability for a more adequate integrated management.

This study is based on both physical and hydro-climatological parameters of the region, land use change, population growth and climate change as metrics to assess the state of groundwater resources in the district of Setúbal, Portugal. The characterization of the land use was based on the information provided by the CORINE Landcover map between the years 1990 and 2018. The abstracted groundwater volumes for this period, the demographic evolution and the respective temporal and spatial distribution of water balance were also evaluated. Future climate scenarios were applied based on RCP4.5 and RCP8.5 climate scenarios.

The results show that there was a very significant land use change. An extension of the built-up area from 12.5% in 1990 to 19.2% in 2018 is observed. At the same time, there was a reduction in the area occupied by agriculture and pine forests. The population of this region has increased considerably in all municipalities. The increase is about 27% between 1990 and 2018. Based on this, a corresponding increase in groundwater abstraction was observed with the construction of about 14,620 wells between 1970 and 2018.

The application of the WetSpass (Abdollahi et al., 2012) model to calculate the recharge in the study area showed a very significant variation in recharge values between the analyzed years. This spatial and temporal variation is mainly related to the inter-annual variation in precipitation, exacerbated by the land use change.

The analysis of future scenarios (2041-2070) showed that in both climate change scenarios, there observed a slightly lower recharge as compared to 2018, if the precipitation intensity in both periods is the same.

The risk assessment to contamination by the application of the susceptibility index (Stigter et al., 2005) shows that the main recharge zones are classified as susceptible to pollution from agricultural sources.

The analysis of the different components of the temporal variation of the piezometric series was based on the application of singular spectrum analysis (SSA). The result of this analysis allowed the identification of upward, downward, and non-trend trends in the long-term components.

The application of several methodologies in this work was to obtain a holistic view of the current and future status of groundwater resources in the study area. The tools applied demonstrated their potential for decision support, both in the management of water resources and the territory.

Keywords: Land use change, Climate Change, Demographic Growth, Groundwater Management, Singular Spectrum Analysis, Vulnerability, Setubal Peninsula, Piezometric Level, RCP.

Contents

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

AET	ACTUAL EVAPOTRANSPIRATION
CORINE	COORDINATION OF INFORMATION ON THE ENVIRONMENT
DEM	DIGITAL ELEVATION MODEL
IPMA	PORTUGUESE INSTITUTE OF THE SEA AND ATMOSPHERE
LULC	LAND USE LAND COVER
MCM	MILLION CUBIC METERS
PET	POTENTIAL EVAPOTRANSPIRATION
PORDATA	DATABASE OF CONTEMPORARY PORTUGAL
RCP	REPRESENTATIVE CONCENTRATION PATHWAYS
SNIRH	NATIONAL WATER RESOURCES SYSTEM
SSA	SINGULAR SPECTRUM ANALYSIS

1 INTRODUCTION

1.1 BACKGROUND

The field of urban hydrology has been one of the fast-growing areas of research as there is continuous migration of people from rural to urban areas leading to the urban areas expanding to accommodate this growing population. The exploitation and use of natural resources due to this urban sprawling can lead to a change in many natural processes (especially the hydrological cycle). The effects of this can be seen in the increase of impervious surfaces, increased water demand and abstraction, reduced agricultural, forest, and green areas and among others. All these have implications on both the quantity and quality of groundwater resources. Figure 1.1 shows the change in hydrological cycle components with a change in urbanization.

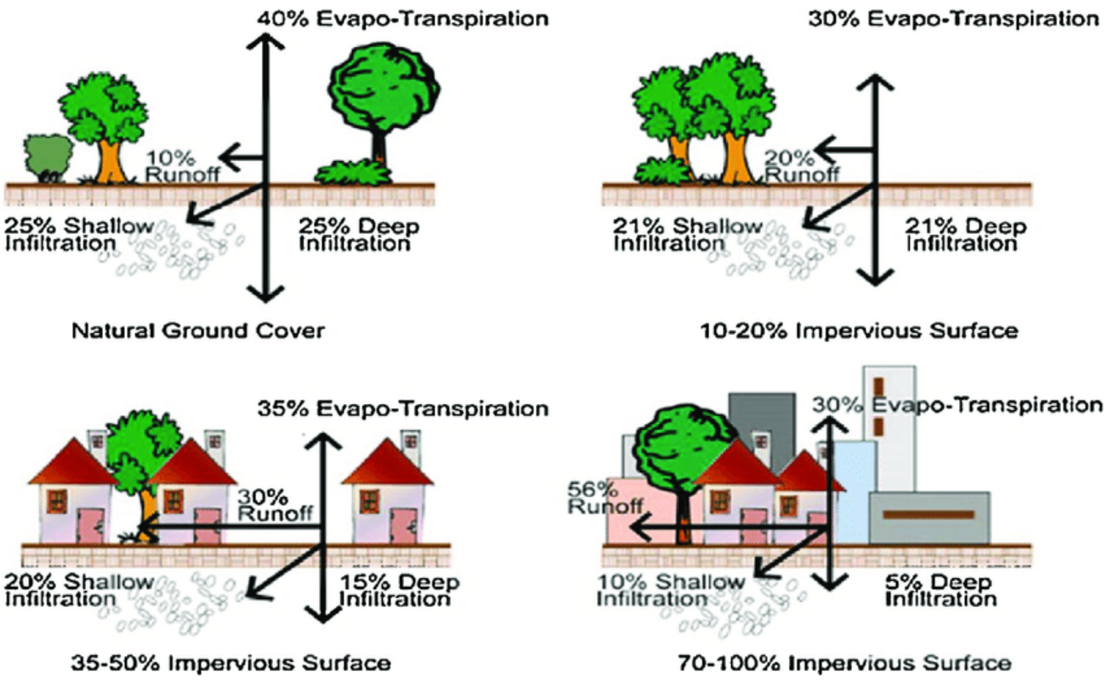


Figure 1.1: Conceptual diagram of hydrological components with urbanization (Saraswat et al., 2016)

An increase in a country's urban population can be due to three causes: the natural growth rate of the urban population, the re-classification of rural settlements as they grow to cities and towns, and rural-urban migration (Cain, 1972). The latter has played the most significant role in urban population growth in many countries of the world. This growing population and expansion of the urban areas have significant effects on natural processes like the hydrological cycle. Urbanization produces numerous changes in the natural environments it replaces. The impacts include habitat disintegration and changes to both the quality and quantity of the rainwater runoff and result in changes to hydrological systems. Population growth is, of course, not the only metric for urbanization.

Multiple studies have addressed urban expansion using metrics ranging from total population and population density to total or effective impervious area as a driver for hydrological dynamics, though a comprehensive metric of urban space remains elusive (McGrane, 2016). Walsh et al. (2012) argued that urbanization leads to an increase in the impervious surface can cause a dramatic change in the magnitude, timing, and runoff pathways. This increased magnitude of runoff will lead to a reduction in infiltration and ultimately affect potential recharge. Urban expansion has brought serious losses of agricultural land, vegetation land, and water bodies. Urban sprawl due to demographic growth causes variations in water demands that are reflected for example, in groundwater abstractions for public supply, industries, or agriculture. The impacts of this exponential groundwater use can therefore be directly related to overexploitation, pollution, or indirectly in groundwater-dependent ecosystems deterioration. Adding to this, land-use change may alter the maximum infiltration areas and the local water balance due to irrigation in agricultural areas.

This change in population and migration has also been significant in many regions in Portugal. Portuguese population dynamics thus exhibit some rural depopulation (mainly of the young people), some urbanization (migration to more densely settled regions around the biggest cities), some suburbanization (de-concentration within the largest urban regions), and some regional flows to resource exploiting regions (sun and sea in the resort coast of the Algarve). Population gains in the 1981-1991 decade also occurred in several coastal and small interior towns and medium-sized urban centres outside Lisbon and Porto (Rees et al., 1998). This reveals that urbanisation was not just a metropolitan phenomenon but was an overall process. Locally, some places have decreased in population over the last decades while some have increased. This can be attributed to the centralisation of the population as people migrate from rural to urban areas to live a more prosperous life.

The increase of population and development process tends to change the usage of land. For example, more built-up areas are expected, and a decrease in agricultural land is also expected as industrialisation continues. The change in land use can increase the percentage of impervious surface thereby increasing surface runoff and reducing potential recharge. If this is correlated to population growth and increased water consumption, a depletion in the aquifer is not far expected.

Global climate change also has a mutual relationship with land use and population growth. Climate change means a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable periods (United Nations Framework Convention, 1992). With the global issue of climate change, including the change in precipitation and temperature regimes, the hydrological cycle and water balance are expected to change. This has both environmental and socioeconomic consequences. Since there is a strong interplay between the components of the earth, it is expected that the land use greatly influences the climate of a region. Generally, the effects of climate change on water resources will not be felt directly by aquifer recharge because groundwater, especially deep aquifers, respond slowly to climate change. The issue here is that as climate begins to change and there is less precipitation or increased precipitation intensity leads to increased runoff or flash floods and more evaporation due to change in temperature regimes, more dependence will be on groundwater systems as the mainstream water supply and consumption. This will lead to the depletion of the aquifer.

These effects on groundwater resources can be monitored by piezometric trend analysis. The upward and downward variation of the piezometric time series gives insight into groundwater depletion and recharge, especially in shallow aquifers. Thus, the piezometric time series is the principal source of information concerning the effect of hydrological and anthropogenic stresses on the groundwater system (Ribeiro et al., 2015).

1.2 PROBLEM STATEMENT, OBJECTIVES, HYPOTHESIS AND QUESTIONS

1.2.1 PROBLEM STATEMENT

As urban space continues to grow to accommodate the influx of people from rural areas, there remains a real need to quantify and qualify its impacts on groundwater systems. The extension of global urban areas has led to significant variations in water demands that are reflected in groundwater abstractions for public supply, industries, or agriculture. Therefore, the impacts of this exponential groundwater use can be directly related to overexploitation, pollution, or indirectly in groundwater-dependent ecosystems deterioration. The increase of the urban population can also be correlated to a substantial change in land use and land cover. The urban landscape influences infiltration and evapotranspiration, affecting the water available for groundwater as recharge.

The imperviousness of the surface and the terrain slope play a key role in influencing the hydrological cycle. If the percentage of impervious surfaces and the slope of surface terrain is greatly influenced, the water balance will be altered, leading to increased runoff and reduction in infiltration (potential recharge). Climate change will also have a strong impact on the recharge variation in the future, especially in stressed areas. Therefore, it is important to assess the broader impacts of substantial development on groundwater's quantity and quality dynamics. Furthermore, with the increased water consumption in groundwater-dependent counties, the sustainability of water abstractions and the future state should be evaluated for proper planning and management. This work focuses on assessing the impacts of climate change, land use/land cover change and demographic growth on the groundwater system in five counties in Setubal Peninsula, Portugal.

1.2.2 AIM AND OBJECTIVES.

This work aims to evaluate the impacts of land use/land cover change, demographic growth, and climate change on the groundwater in the Setubal Peninsula.
This primary aim was achieved by completing the following specific objectives;

- To review the change in population over the past three decades;
- To assess the stress on groundwater system by analysing the number of wells constructed and water consumptions;
- To assess the land use/land cover change in the study area from 1990;
- To evaluate the spatial recharge and water balance change concerning land use change using WetSpass-M;
- To assess the impacts of climate change on water balance and recharge using two RCP scenarios (4.5 and 8.5);
- To assess the vulnerability of groundwater to pollution using the susceptibility index;
- To evaluate the stress on groundwater using piezometric trend analysis.

1.2.3 RESEARCH HYPOTHESIS

- Land use and land cover change has had significant effects on water balance (potential recharge) over the past decades;
- The population growth has increased water consumption leading to higher groundwater abstraction;
- Climate change will have a very strong effect on the hydrological cycle, especially precipitation till the end of the century;
- Increased groundwater abstraction will lead to depletion of groundwater and increased vulnerability to pollution.

1.2.4 QUESTIONS

- Has the population growth had substantial effects on groundwater consumption?
- Has there been overexploitation and abstraction of groundwater?
- What has been the impacts of land use groundwater recharge?
- Will climate change have a significant effect on groundwater recharge?
- Is the groundwater vulnerable to pollution?

1.3 OVERVIEW OF GROUNDWATER STATE IN THE STUDY AREA

Population growth: the drastic change in population has been one of the major concerns in this district. This is attributed to the migration of people from rural areas and the return of people from the colony countries (Araya & Cabral, 2010). According to Goncalves (2019) (Director of the Production and Control Department of Almada SMAS Water Quality), the district has increased dramatically since the 50s (about 167%) to the last century, and this would increase water demand and supply. From all the municipalities, the population growth is more significant in Seixal, Almada, Sesimbra and Palmela.

Groundwater Abstraction: the origin of public water supply in the region is made exclusively from groundwater, counting more than 180 wells constantly working (Goncalves, 2019; RASARP, 2021). The groundwater condition has been of great concern as abstraction and agricultural activities have intensified over the past few decades. In addition, the drastic increase in population has increased the water demand. No significant research has been done in this area to assess the effects of abstraction on the groundwater system, but there have been many agitations and concerns over water abstraction and inefficient management. More importantly, there has been a risk of over abstraction from illegal wells, as reported in Goncalves (2019).

To comply with the drinking water demands, wells were built since the middle of the last century. Thus, hundreds of public and private wells caused a significant “drawdown” of the water level of the Aquifer. There are even catchment hubs that in the 50s (beginning of the “intensive” exploration in the peninsula) had positive artesianism and where, currently, the hydrostatic level is more than 30 meters deep (Almeida et al., 2000; Goncalves, 2019). Goncalves (2019) specifically pointed a well in 1951, constructed in Almada region, whose pressure was so high that when the well crossed the confining layers completely, water in the well-pipe would rise to a height corresponding to the ground surface (flowing artesian well). Currently, with the constant increase in the volume of the water abstracted, the hydrostatic levels in the same area are approximately

20 meters in depth from the ground surface. This exploitation, if not controlled, can lead to groundwater contamination and sea water intrusion since the area is along the coast.

Land use/ land cover change: there is always a positive correlation between demographic growth and land use change. Land use patterns studied over a period can be used to understand the effects of population change on the environment. In their work on two municipalities (Setúbal and Sesimbra) within the study area, Araya & Cabral (2010) discovered that the land use has substantially changed between 1990 and 2006, which is evident in the percentage increment of urban areas by 91.10% and 6.34% between 1990 and 2000, and 2000 and 2006 respectively. This change has great effects on the natural processes by altering the natural terrains. For example, more impervious surfaces will be formed.

Climate Change: apart from population growth and water consumption, Goncalves (2019) also pointed the effects of climate change on water availability. The reduction of the amount of precipitation or the increased intensity of precipitation over a short period will reduce the recharge over the years. Lower precipitation is going to lead to drought and more dependence on groundwater for other consumption. This effect of climate change is already being felt as the precipitation dropped significantly in the last decade. If the population continues to grow and the consumptions increase with less recharge, there will be a severe problem of water scarcity in the future.

Vulnerability: overexploitation, intensification of agriculture and increased industrialization will cause the groundwater to be vulnerable to pollution, either from sea water intrusion or direct chemical contamination.

This work thereby gives a holistic assessment of the state of groundwater resources in the study area by measuring the impacts of climate change, demographic growth, and land use change. In addition, the future situation is also assessed, especially under the changing climate.

1.4 SIGNIFICANCE OF THE STUDY

This study is relevant for (ground)water management and urban planning. With this work, the municipalities can have full knowledge of the effects of abstraction and land use on the groundwater system, and the future projections can be adopted for decision support in licence issuance for groundwater abstraction, permissible rate of abstraction and land use. It also helps the government do a demographic review and manage the rising population, especially the influx of immigrants.

1.5 THESIS STRUCTURE AND RESEARCH FRAMEWORK

This work is divided into six chapters. The first chapter gives a clear introduction to the work. The problem and motivation for this work, the aim and objectives and the justifications for undertaking this research. The second chapter presents the physical aspects of the study area. The third chapter explains the various methodologies adopted for achieving these aims: strategies for data acquisition and the various software used at every stage to achieve specific objectives: how the piezometric trend was analysed using the singular spectrum analysis; the land use classification with Corine maps integrated in GIS environment; and the use of WetSpass-M for spatial recharge estimation and water balance.

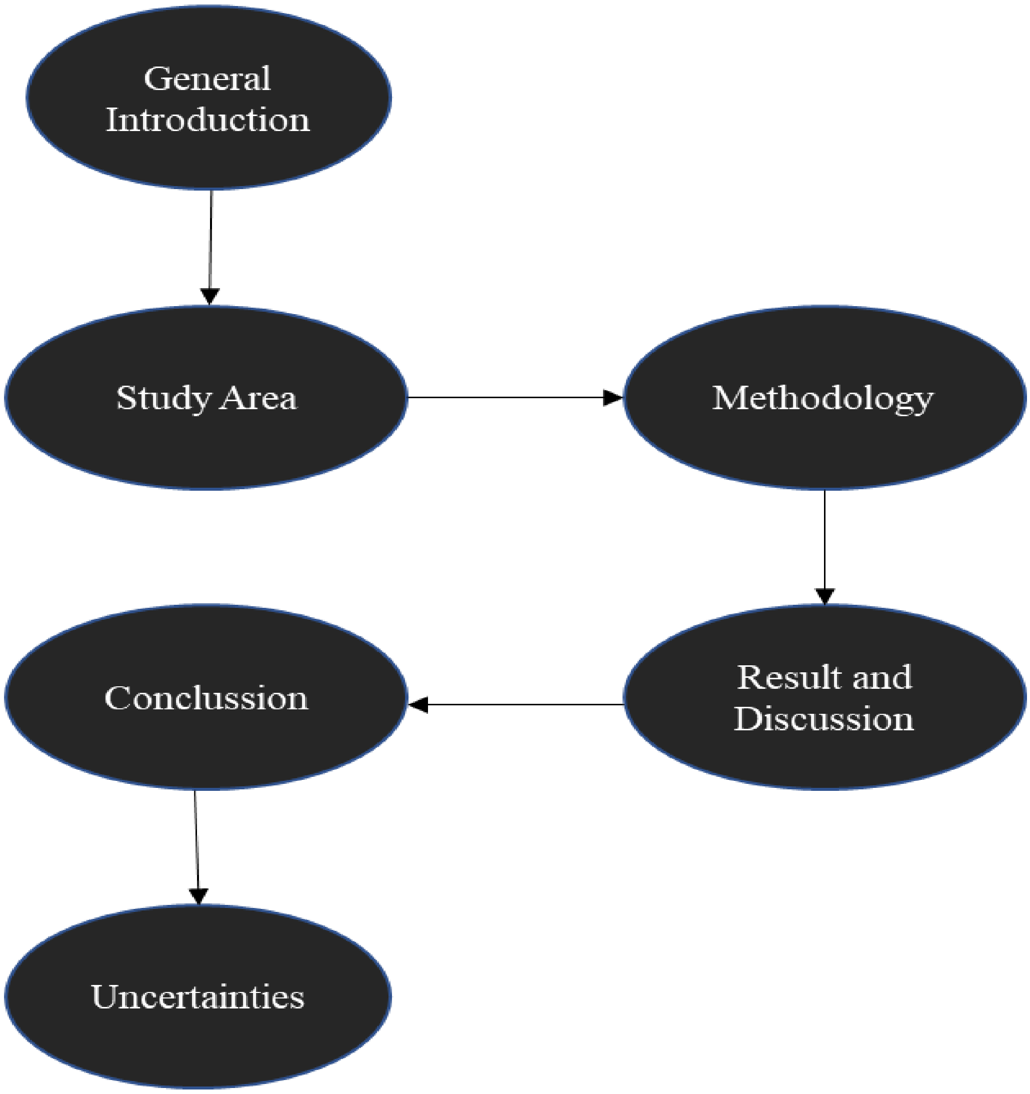


Figure 1.2: The structure of the thesis

The fourth chapter presents the results and discusses them explicitly. The result from land use classification, population change, the volume of water that has been abstracted in the past years, the piezometric trend, and the recharge variation, aquifer vulnerability and sustainability analysis. The outcomes of this investigation were presented and explained comprehensively for anyone to understand. The fifth chapter gives the summary of the work, conclusions, and recommendations. The sixth chapter explains the limitations and the uncertainties of the work.

2 STUDY AREA

The study area is the district of Setubal consisting of nine municipalities which include Alcochete, Almada, Barreiro, Moita, Montijo, Palmela, Seixal, Sesimbra and Setúbal. It is delimited by Lisbon District and Santarém District on the north, Évora District on the east, Beja District on the south and the Atlantic Ocean on the west. The specific counties evaluated in this study are Almada, Palmela, Sesimbra, Seixal and Setubal. The selection of these counties was motivated by the situational report of Goncalves (2019) on the state of groundwater in the peninsula. As explained in section 1.3, the five municipalities are of great concern due to increased population and groundwater abstraction. The total area of the five municipalities is about 995km^2. Figure 2.1 shows the location of the entire study area and each municipality.

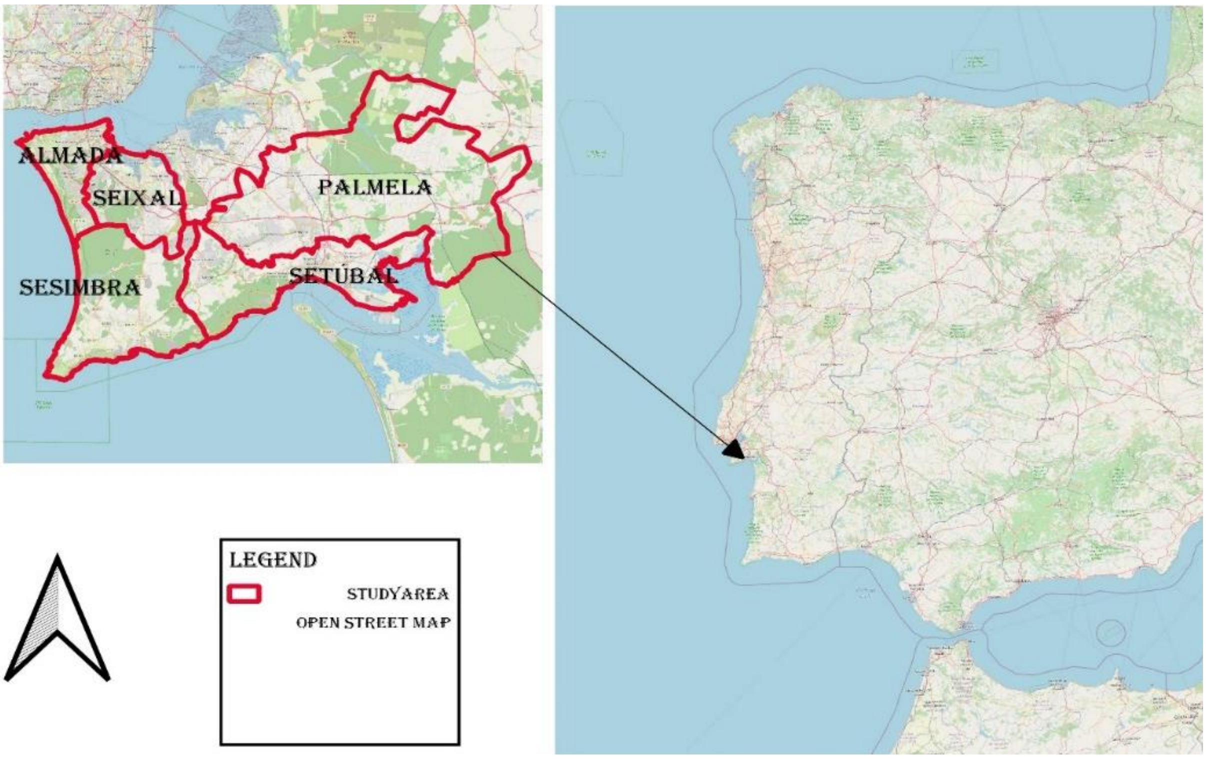


Figure 2.1: Location of study area

Over the past decades, the area has experienced considerable change in population in two distinct phases: the rural to urban migration and the return of people from the colony countries (Araya & Cabral, 2010). The primary source of water for all consumptions in this area is groundwater.

2.1 TOPOGRAPHY

The elevation of the study area can be classified into three groups. Looking at Figure 2.2, the elevation is very high in some parts of the study area, which can be grouped in the high-altitude zone. The southern part presents altitudes of about 500 m. The other zone is the intermediate altitude zone, where the altitude is about 200 – 400m. This zone is immediately after the high-altitude zone towards the northern part of the study area. Finally, the low altitude zones have an elevation of less than 100m. This is particularly found in the western part of the study area, where the land use is majorly agriculture. This characteristic is expected to have a substantial effect on recharge and surface runoff and the vulnerability of the groundwater resource to pollution by nutrients.

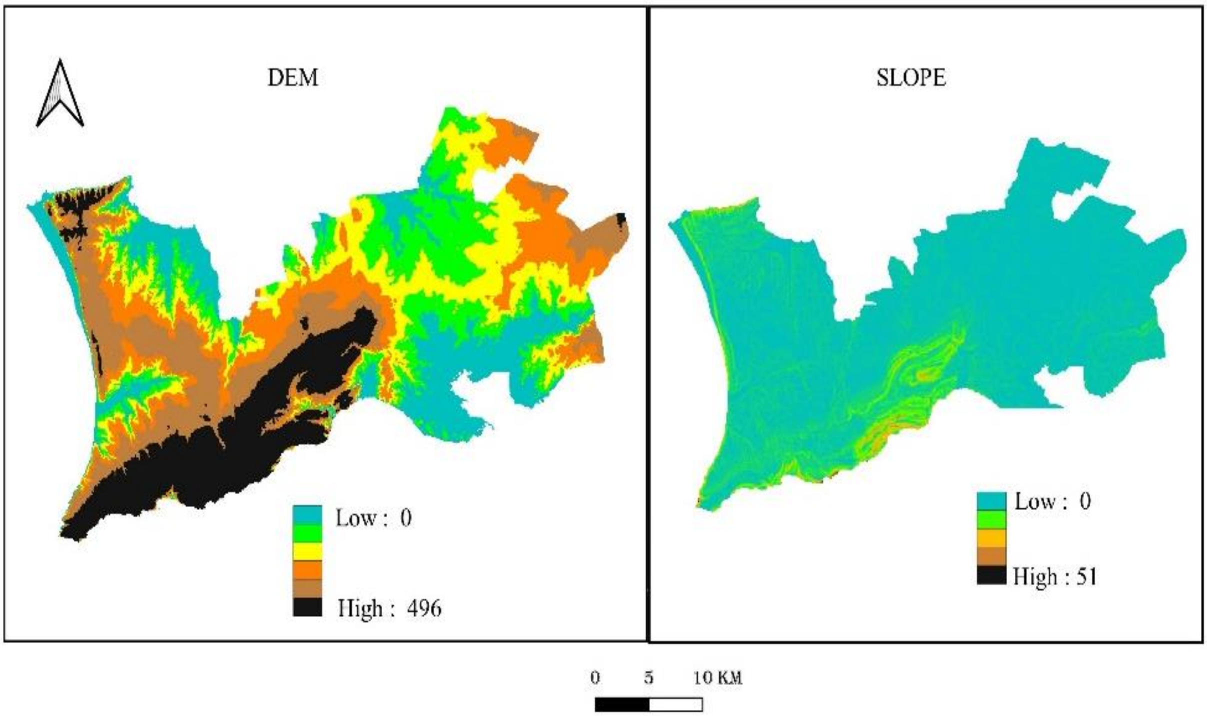


Figure 2.2: Altitude (in metres) and slope (in degree) of the area

2.2 CLIMATE

The climate of the study area is marked by the oceanic regime with warm winters and hot summers, by proximity to the Atlantic Ocean. The annual average temperature is between 15 and 17^{0}C, and the average annual precipitation falls between 233 and 1142 mm (SNIRH). Figure 2.4 represents the monthly average of Potential evapotranspiration (PET) estimated with the Penman-Monteith equation based on data series from SNIRH stations. The monthly data on temperature was retrieved from climate stations available in SNIRH. The location of the climate stations is in Figure 3.6. The average annual rainfall was presented in Figure 2.3 for some years between 1932 to 2017.

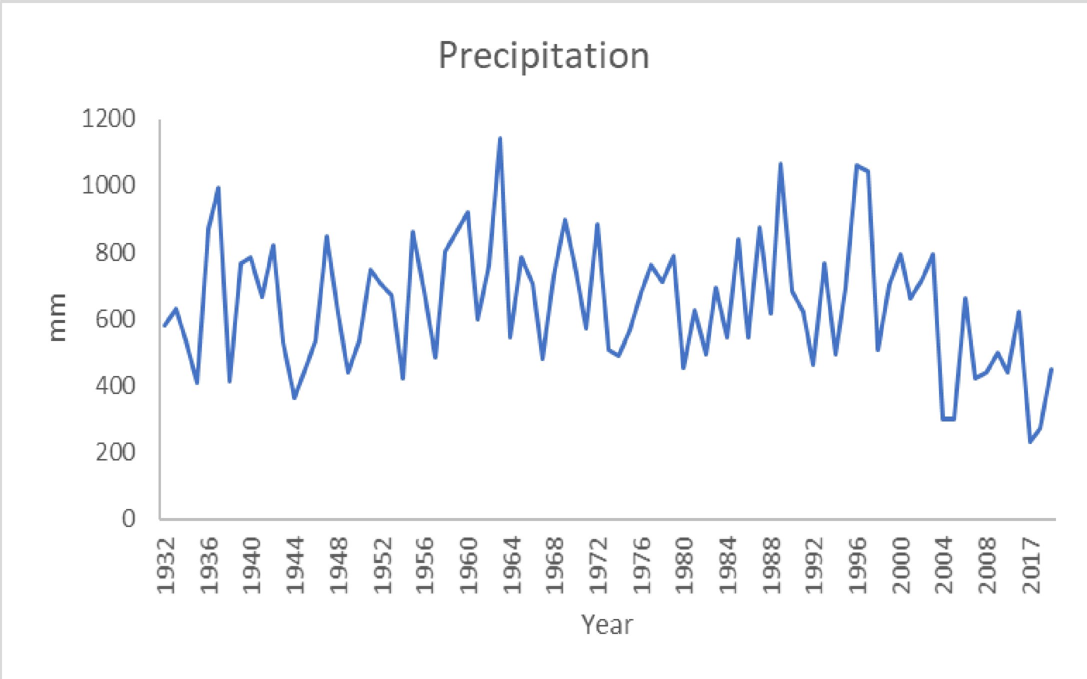


Figure 2.3: Average annual precipitation from three stations in the study area. (Data: SNIRH).

The mean annual values for potential and actual evapotranspiration, estimated with the Thornthwaite and monthly water soil balance methods, are 840mm and 485mm, respectively (Simões, 2009). According to the calculated annual average of PET using data from SNIRH, the minimum and maximum values are 630mm and 772mm, respectively.

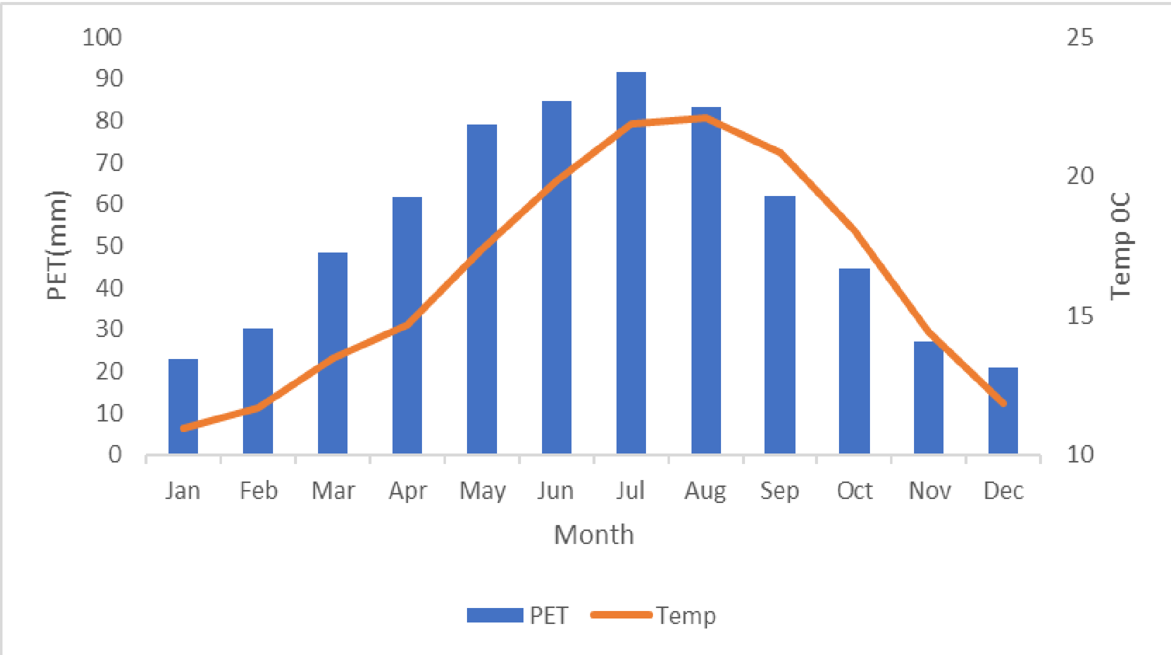


Figure 2.4: Monthly average of Potential evapotranspiration(sum) and Temperature. PET was estimated with Penman-Monteith equation, while Temperature was retrieved from SNIRH.

Table 2.1 shows the basic statistics of temperature, potential evapotranspiration, and precipitation based on data series of SNIRH within the time frame of 1932 and 2020 and the calculated PET using the Penman-Monteith method. The temperature has 25 observatory years while precipitation has 83 years, and PET was calculated for just 5 years.

Table 2.1: Statistics of the annual average of Precipitation, PET and Temperature.

Parameters	Observations	Mean	Median	Standard Deviation	Kurtosis	Skewness	Range	Minimum	Maximum
Temperature	25	16.5	16.5	0.5	-0.2	0.5	1.9	15.6	17.5
Precipitation	83	647.1	661.6	191.5	-0.2	0.2	909.6	233.2	1142.8
PET	5	675.1	653.9	57.1	3.2	1.8	142.1	630.5	772.6

2.3 HYDROGEOLOGICAL SETTING

The aquifer system in the study area is the Tagus-Sado aquifer system, the biggest aquifer system in Portugal. The area under study is located on the left bank of the aquifer (T3 – *Margem Esquerda*). The southeast part of the area, Arrábida, are not included in this aquifer. It can be classified as an unproductive fissured aquifer. The information below was retrieved from Almeida et al. (2000), available in the SNIRH database.

The dominant aquifer formations are Pliocénico, Arenitos de Ota, and Série calco-gresosa marinha which were deposited in the Tertiary period. Pliocénico formation deposited in the Pliocene epoch has the lithologies consisting of sands, with lenticular intercalations of clays, with very variable thickness. Arenitos de Ota, which was deposited in the late Miocene to early Pliocene, has its lithologies comprising of sandstones with some intercalations of clays. Série calco-gresosa marinha was deposited in the Miocene epoch, and it comprises limestone, sandstones, marls, with a thickness greater than 450m.

It is a multi-aquifer system, unconfined, confined, and semi-confined, in which lateral and vertical facies variations are responsible for insignificant changes in hydrogeological conditions. The aquifers are separated by layers of low or very low permeability (aquitards and aquiclude). On the Setúbal Peninsula, the system consists of an unconfined upper aquifer, overlying a confined, multilayer aquifer. Underlying this set, separated by thick marly formations, is a confined multilayer aquifer whose lithological support is the thick limestone formations at the base of the Série calco-gresosa marinha.

The Pliocénico have transmissivity between 100 and 3000m²/day. Arenitos de Ota has the most frequent values of transmissivity between 45 and 179m²/day. Série calco-gresosa marinha has more frequent transmissivity values between 127 and 693m²/day, and the storage coefficient is 10^{-3}.

Recharge is done by rainfall, vertical leakage between aquifers, and infiltration through water streams. The groundwater flow occurs towards the Tagus River and along with the aquifer system to the Atlantic Ocean. The hydro-chemical facies consist of Pliocénico: sodium and calcic chlorinated, calco-magnesian bicarbonate; Arenitos de Ota: sodium and calcium bicarbonate and Série calco-gresosa marinha: calco-magnesian bicarbonate.

The lithologies that were specifically identified in the five municipalities within the study area are shown in Figure 2.5. The western part which is in Palmela is dominated by limestone, sandstone, and a combination of both with claystone. The North-eastern part, which is the Almada region has various lithologies like clay, basalt, and alluvium.

Generally, the main geology of the study area comprises Sandstone, Limestone, and Conglomerate.

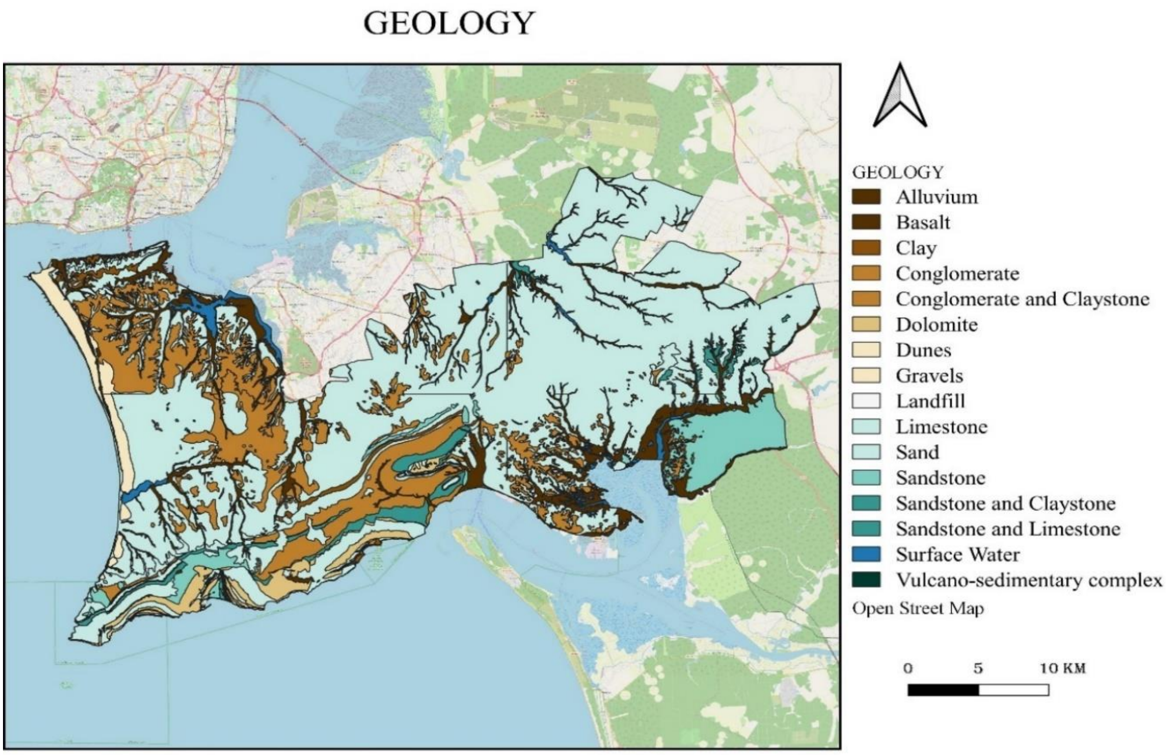


Figure 2.5: The geology of the study area

3 DATA SOURCES, PROCESSING, AND METHODOLOGIES

This chapter comprises the data sources, data processing, and the methodologies for achieving all the research objectives.

Figure 3.1 shows the schematic diagram of the research methodologies. The first part shows the demographic analysis. The source of the data used, and the different processing done to obtain the result were explained. The second part deals with data collection and analysis for groundwater use in the study area. The change in land use was discussed explicitly in the third stage. The data source and the different methodologies applied were presented. Recharge estimation and water balance analysis were done at the fourth stage. The sources of the data and the software used for this analysis were explained. The vulnerability of the groundwater to pollution was assessed at the fifth stage. This accounted for various factors which could make the groundwater to be susceptible to pollution. At the sixth stage, the analysis of the groundwater level was made to evaluate the effect of all these factors (climate, abstraction, land use and population) on the groundwater system. The data source and the statistical tool used for this analysis were presented. The final stage is about the sustainability of the groundwater resource under future climate scenarios.

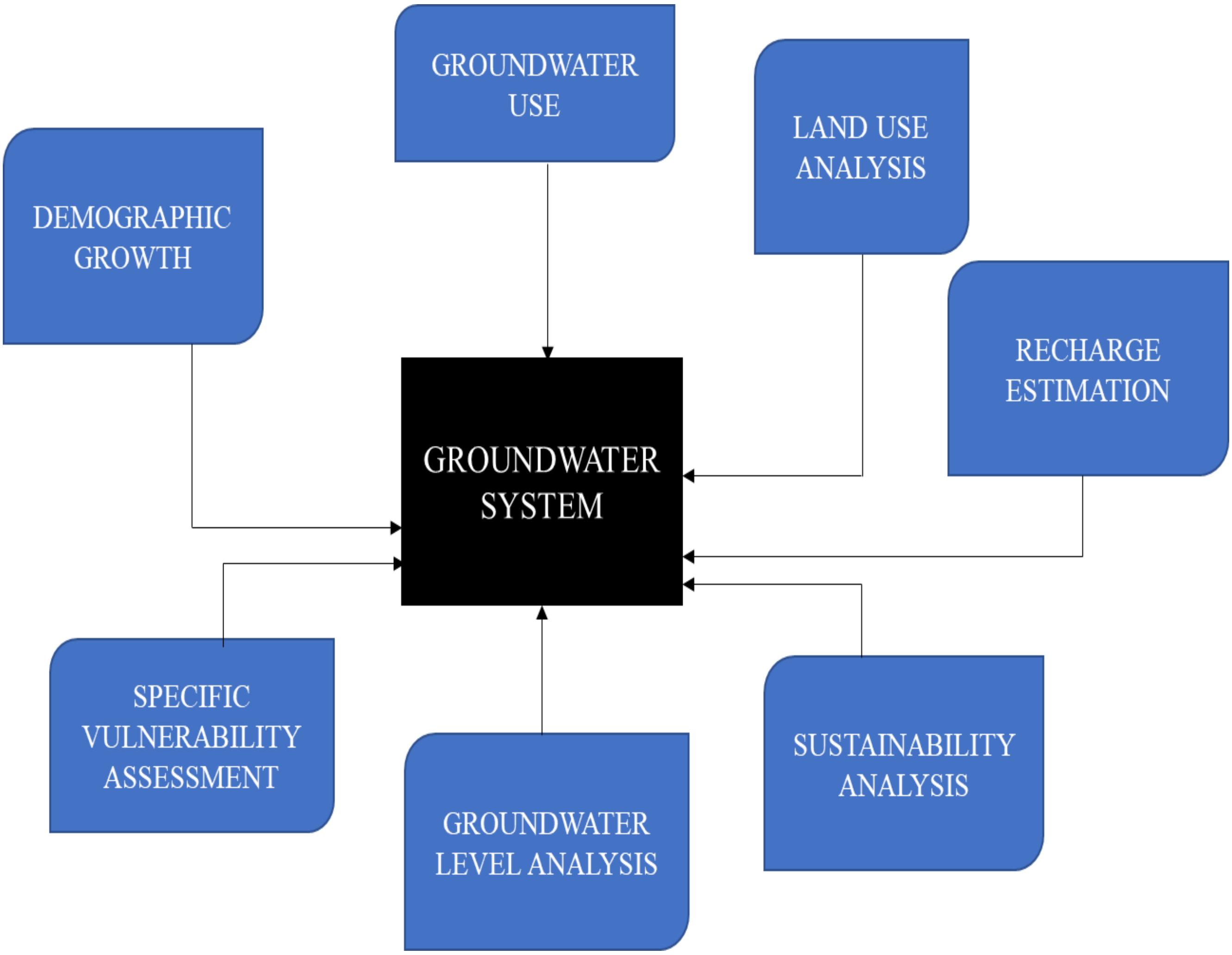


Figure 3.1: The schematic diagram of research methodology

3.1 DEMOGRAPHIC DATA AND PROCESSING

Population growth is one of the indicators of development in an area. However, the increase in population may lead to the over-exploitation of some natural resources. As regards the scope of this work, the natural resource to consider is water. More people will need more volume of water not just for their daily consumptions but also for other things. To evaluate the population changes, data on population was retrieved from the Database of Contemporary Portugal (PORDATA). Some of the functions of PORDATA include the collection, compilation, systematization, and dissemination of data on multiple areas of society for Portugal and its municipalities, and the European countries. The reported statistics derive from official and certified sources, with data production skills in the respective areas. Also, the important work of contextualized information, the so-called "metadata", is an inextricable part of the data, enabling its adequate interpretation. The data is provided as a public service to the Portuguese society, free of charge and without any cost to the user (https://www.pordata.pt/en/About+Pordata).

The reference years for this analysis are 1990, 2000, 2006, 2012, and 2018. These correlate with the years of Corine land use/cover. Table 3.1 shows the years of data available on PORDATA, the years required for this analysis, and the availability status. These data include the total data for the study area and data for each municipality.

Table 3.1: PORDATA population data and the years of availability

Available on PORDATA	Required	Status
1960	1990	×
1981	2000	×
2001	2006	×
2009	2012	✓
2010	2018	✓
2011		
2012		
2013		
2014		
2015		
2016		
2017		
2018		
2019		

To verify the correctness of this data, the unknown values were compared to those on Wikipedia [from the Portuguese National Institute of Statistics (ine.pt)] for each municipality. Both corresponded. Unfortunately, from all sources, there were no data for 1990, 2000, and 2006. Figure 3.2 shows the evolution of the population of the study area as retrieved from PORDATA.

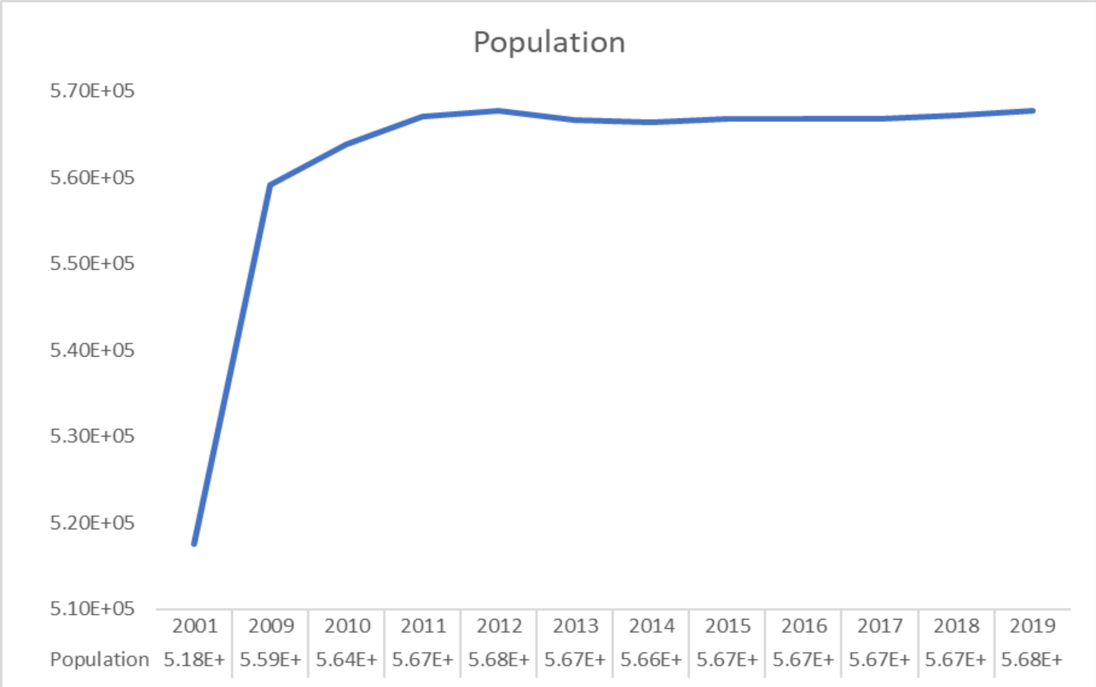


Figure 3.2: Population data of the study area from PORDATA

To overcome this challenge, the values were extracted using linear interpolation. An inbuilt function on MS Excel called FORECAST (or FORECAST.LINEAR, depending on the version of Excel) was used to find the missing records. The function works on the principle of linear interpolation. A very concise and detailed description of the function can be found in Steve (2018). This helps to get the trend of population evolution over the years. Further analysis and visualization were done with MS Excel.

3.2 GROUNDWATER USE

The increase in population and the change in land use would lead to increased water demand. Since the region depends on groundwater for all supplies, the increased water demand should cause stress on the groundwater system due to increased abstractions.

To quantify water consumption over the past decades, the Planning and Information Division, Administration of Tagus, and West Hydrographic Region were consulted. Shapefiles for the wells' information were acquired and processed in QGIS and Excel. A total of 14,620 well data were retrieved and grouped according to the municipalities and well use.

3.3 LAND-USE INFORMATION

3.3.1 CORINE LAND USE

Land use is one of the indicators of development in an area and the stress on natural processes. Understanding the change in land use can help to track urban sprawling and stress on water resources. The following steps were followed for this analysis to detect the change in land use, as shown in Figure 3.3.

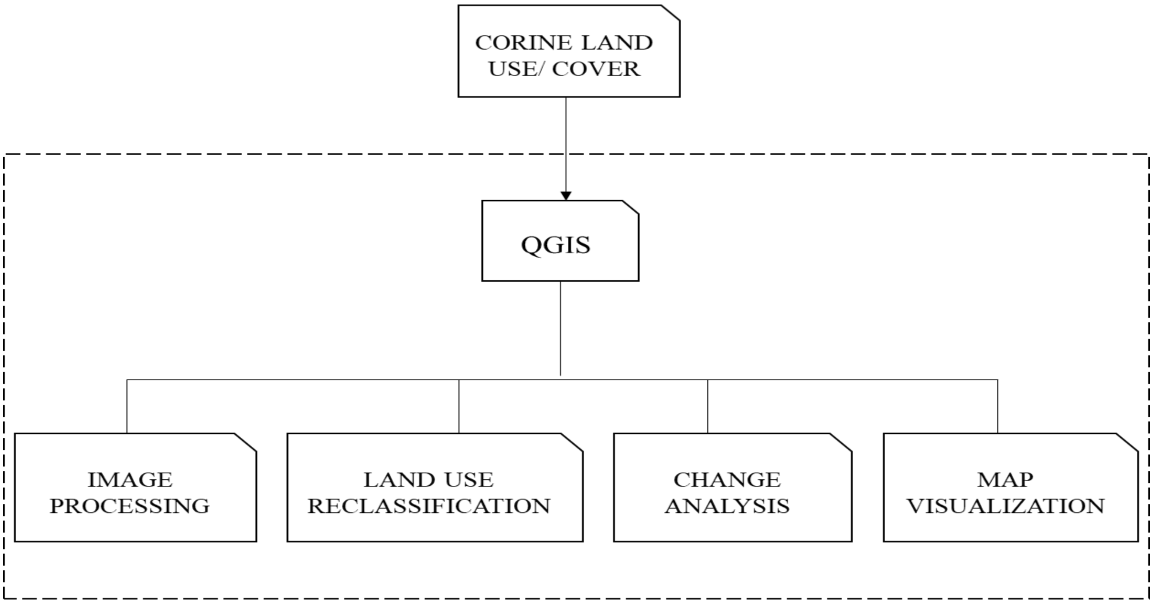


Figure 3.3: Land use classification methods

- CORINE LAND MAP: CORINE was produced by the Directorate-General for Territory (DGT) of Portugal in conjunction with the European Environment Agency (EEA) for 1990, 2000, 2006,2012 and 2018. The CORINE land cover cartographic products are created based on satellite images (e.g., Landsat, SPOT, LISS-III and RapidEye) and auxiliary information related to land use/occupation, coming from different institutions (Mar 2017). The CORINE land use/cover map of the whole of Portugal was downloaded. Table 3.2 shows the technical specifications of the land use maps. The yearly maps of CORINE were used and not the change map. Apart from the fact that the study area is large and the choice of CORINE maps does not really matter, the change map could also not be used to perform the water balance and recharge analysis with WetSpass. These maps were processed and reclassified in a GIS environment.

Table 3.2:CORINE land use technical specifications

Attributes	CORINE Land Cover
Acronym	CLC
Scale	1/100 000
Minimum cartographic unit (UMC) Data	25 hectares
model	Vectorial
Spatial representation	Polygons
Minimum distance between lines (DMEL)	100 m
Base data (spatial resolution) Production	Satellite imagery (20 m)
method	Visual interpretation
Nomenclature	Hierarchical (3 levels) 44 classes
Geometric accuracy	Better than 100 meters ≥
Global thematic accuracy	85%

- GIS: To process the land use map to suit the objectives of this research, CORINE maps were integrated into the QGIS environment. QGIS is an open-source, cross-platform desktop geographic information system application that supports viewing, editing, and geospatial data analysis. Major processing was done in this environment. The first process was setting up the coordinate reference system to fit the area of study. The maps were clipped to the extent of the study area. This helps to downscale the analysis to the exact location of interest and aid ease and accuracy in classification. The various land use land cover types were reclassified under mega classes considering the relevance to other objectives, especially water balance estimation with WetSpass-M (see section 3.4.) The classification and descriptions are shown in Table 3.3. The area of each land use was calculated in the attribute table using the inbuilt QGIS vector calculator.

Table 3.3: The description of each land use class

LAND USES	DESCRIPTION
Built up	Every artificialized areas with impervious surfaces, e.g., urban fabrics, road networks, industries.
Open Built up	Artificialized areas with green areas e.g., urban green, parks.
Agriculture	All agricultural and cropping activities
Pine	An evergreen coniferous tree which has clusters of long needle-shaped leaves. It is taken here as all the forested areas.
Permanent Pasture	Natural or seeded grassland that remains unploughed
Natural Vegetation	Naturally vegetated areas like natural herbaceous vegetation
Water Bodies	All open water bodies like sea and ocean.

Wetlands	Flooded areas or water bodies with the characteristic vegetation of aquatic plants and with unique hydric soil.
Orchards	Orchards comprise fruit- or nut-producing trees which are generally grown for commercial production.

The change of land use and land cover was estimated on Excel. The percentage of each land use was calculated as a fraction of the total study area. The results were further visualised in excel for easier interpretation. The reclassified maps of the land use were later printed with QGIS.

3.4 RECHARGE ESTIMATION AND WATER BALANCE

For the spatial estimation of recharge to determine the recharge zone and the vulnerability of the groundwater system to pollution and determine the hydrological water balance for the past and future, the following methods were applied as discussed in this section.

A hydrological software called WetSpass-M was used for this analysis. The modified WetSpass-M model is a raster-based water balance model that partitions precipitation into interception, surface runoff, evapotranspiration, and recharge for each grid cell. Distributed land use, soil texture, groundwater depth, slope, and climate data (rainfall, potential evapotranspiration, number of rainy days, wind, and temperature) are the required basic input. Four sub-cell fractions for each land-use class are defined per grid cell: vegetated cover, bare soil, open water, and impervious surface to address land-use heterogeneity within the cell (Abdollahi et al., 2017). Figure 3.4 shows the overall framework of the model.

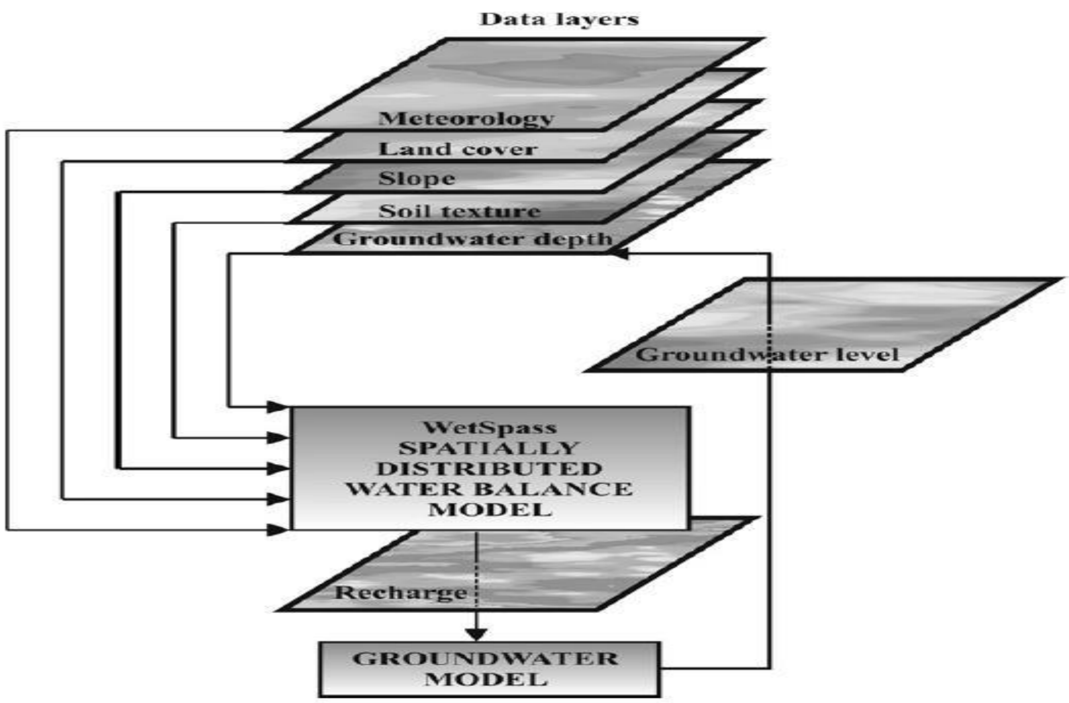


*Figure 3.4: Schematic representation of the interactive process between WetSpass-M and groundwater(*Source: Batelaan & De Smedt, 2007*).*

The model is a distributed one making the water balance computation to be performed at a raster cell level. Individual raster water balance is obtained by summing up independent water balances for the vegetated, bare soil, open water, and impervious fraction of a raster cell. The total water balance of a given area is thus calculated as the summation of the water balance of each raster cell (Abdollahi et al., 2012).

The important part of using this model is the spatial evaluation of the interplay between the major four hydrological elements. Like any other water balance tool or method, rainfall is partitioned into different components. These components include runoff, evapotranspiration, and infiltration (potential recharge). The water balance components of vegetated, bare soil, open water, and impervious surfaces are used to calculate the total water balance of a raster cell. The equations (1-3) below show the calculation of each component. Figure 3.5 shows the interplay of different components that influence water balance.

$$ET_{raster} = a_v ET_v + a_s E_s + a_o E_o + a_i E_i \quad \text{Equation 1}$$
$$S_{raster} = a_v S_v + a_s S_s + a_o S_o + a_i S_i \quad \text{Equation 2}$$
$$R_{raster} = a_v R_v + a_s R_s + a_o R_o + a_i R_i \quad \text{Equation 3}$$

ET_{raster}, S_{raster} and R_{raster} are the total evapotranspiration, surface runoff, and groundwater recharge of a raster cell, respectively, each having a vegetated, bare soil, open water, and impervious area component denoted by a_v, a_s, a_o, and a_i, respectively. (Abdollahi et al., 2012)

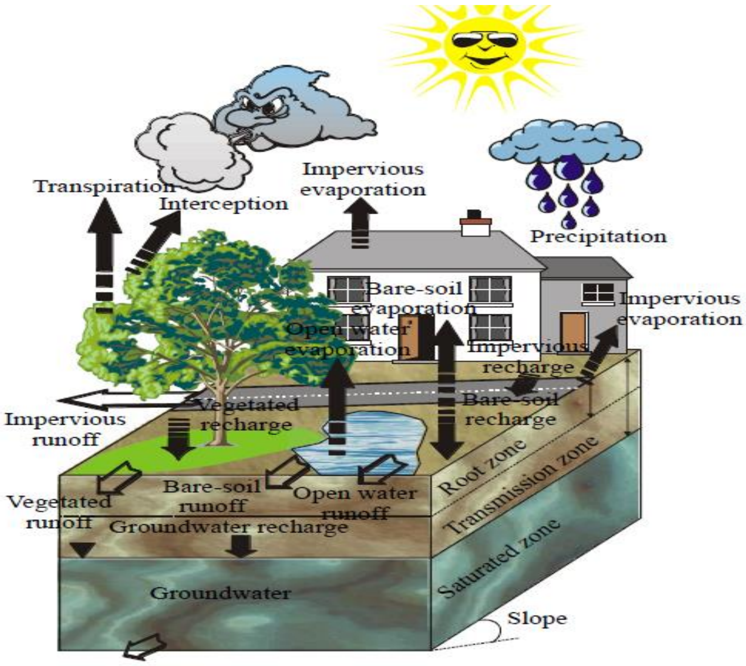


Figure 3.5: Interplay of the hydrological components(Source: Abdollahi et al., 2012)

In general, the water balance is calculated by taking precipitation as the starting point of the computation, followed by other processes like interception, runoff, evapotranspiration, and recharge in an orderly manner as shown in Equation 4.

$$P = E_T + S + R \text{ ...Equation 4}$$

P is the total precipitation, ET is the actual evapotranspiration, S is the surface runoff and R is the recharge.

The most important part of the model is the calibration and validation of the results. This can be done by comparing the output of the model to a known value. For example, the actual average evapotranspiration can be compared to the known actual evapotranspiration of the study area. However, this will require adjusting the parameters in the parameter section of the model and the parameters of the land use and soil.

To successfully setup the model, there are many input data needed. Table 3.4 shows the input data for the model.

Table 3.4: Input parameters for WetSpass-M

WETSPASS-M INPUT MAPS					
Meteorological variables	Wetspass-M Format	Spatial Variables	Wetspass-M Format	Groundwater	Wetspass-M Format
Precipitation	rain	Elevation	elevation	Depth	gwdepth
PET	pet	Slope	slope		
Wind	wind	land use/cover	land use		
Temperature	temp	Soil	soil		
Number of rainy days	RainyDaysPerMonth				

3.4.1 DATA SOURCES

3.4.1.1 METEOROLOGICAL DATA

The past climate data used for this analysis were retrieved from SNIRH. The data retrieved are precipitation, wind speed, and temperature. These parameters were further processed in Microsoft Excel. The years under consideration are 1990, 2000, 2006, 2012 and 2018, and this is concerning the CORINE land use maps. The number of rainy days per month was calculated by summing up days with rainfall greater than 0.1mm within a month.

Three meteorological stations were found within the study area. Figure 3.6 shows the location of the meteorological stations (red points). The three stations are in Almada, Palmela and Setubal.

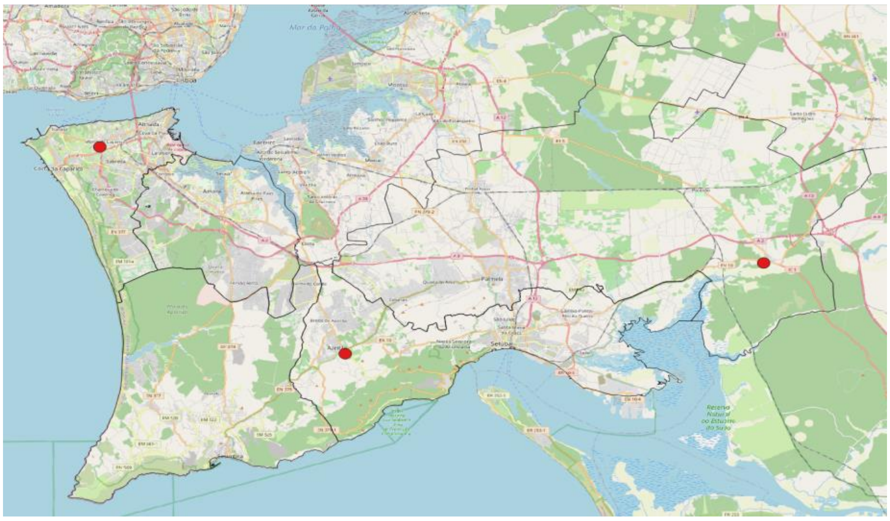


Figure 3.6: Location of the meteorological stations

The challenge was the lack of complete data for the variables needed in the time series, especially for the reference years. This challenge was overcome by filling up the missing data with the long term annual monthly average values. Table 3.5 shows the climate variables retrieved, their units and the source.

Table 3.5: Meteorological data and their sources

Variable	Unit	Source
Precipitation	mm	Portuguese National Water Resources System Information (SNIRH)
Windspeed	m/s	Portuguese National Water Resources System Information (SNIRH)
Temperature	0C	Portuguese National Water Resources System Information (SNIRH)
Potential Evapotranspiration	mm	Calculated using Penman-Monteith equation

Potential evapotranspiration is one of the critical variables for recharge estimation and water balance analysis. This variable had no observed data in the three stations. The potential evapotranspiration time series was calculated using the Penman-Monteith equation. The choice of the method (Penman-Monteith) for estimating potential evapotranspiration is based on the retrievable data and the strong likelihood of the method correctly predicting the potential evapotranspiration in a wide range of locations and climates (Moratiel et al., 2019). To estimate the potential evapotranspiration using the Penman Monteith, the relevant climate data (relative humidity, mean temperature, windspeed) were used in daily resolution. Other parameters such as latitude and longitude, Julian days and altitude were also used for the calculation. The Penman-Monteith equation is presented in Equation 5.

$$ETP_0 = \frac{\Delta \cdot E_m + \gamma \cdot \frac{90}{T} \cdot V \cdot \left[e_a^* - e_a\right]}{\Delta + \gamma \cdot (1 + 0{,}34\,V)}$$

Equation 5

ETP_o – Reference crop potential evapotranspiration (mm/d)
E_m – Evaporation due to the energy balance (mm/d)
T – Average daily air temperature (K)
V – Wind speed (m/s)
ea, ea - Vapour pressure and saturated vapour pressure (mmHg)*
Δ, ϒ – Weighting factors (hPa/K)

3.4.1.2 SPATIAL VARIABLES

As input for WetSpass-M, some spatial variables are needed for the analysis. These include the soil texture, digital elevation model, land use map and slope. As explained in the land use section (3.3.1), CORINE land use maps were used for this analysis for the years 1990, 2000, 2006, 2012 and 2018.

Portugal's soil map (shape file) retrieved from the Portuguese Directorate General for Agriculture and Rural Development (DGADR) was clipped to the study area and classified. This classification was also correlated with the soil characteristics and descriptions from INFOSOLO database (https://projects.iniav.pt/infosolo/) for a better understanding of the soil texture of the study area. The INFOSOLO database is the most comprehensive effort ever made to organize soil information in Portugal. It currently includes 9934 horizons/layers studied in 3461 soil profiles across the country (Ramos et al., 2017).

Portugal's digital elevation model (DEM) with a resolution of 30m was clipped to the study area. For the WetSpass-M simulation, the resolution was changed to 100m. Using the DEM and QGIS, the slope map of the study was created both in degree and percentage. Table 3.6 shows the spatial parameters for the model set-up.

Table 3.6: Spatial parameters and their WetSpass-M units

Parameter	Unit
Groundwater Depth	m
Elevation	m
Slope	degrees
Soil texture	-
Land use	-

3.4.1.3 GROUNDWATER DEPTH

The depth to water level is another input parameter for WetSpass-M. The depth to water level data was retrieved from the piezometric monitoring stations within the study area. More information about the location of the piezometers is found under the piezometric analysis section (see section 3.6). The depth to water level was averaged for each land use horizon year. For this analysis, only wells with depth below 16m were used.

3.4.2 GENERAL SETTING FOR INPUT DATA

The input maps for WetSpass-M were processed in the GIS environment with QGIS. Table 3.7 shows all the requirements of the input maps for WetSpass-M.

Table 3.7: Spatial requirements for WetSpass-M.

CONDITIONS	
Raster Format	ASCII (.asc)
Spatial Resolution	Must be the same
Rows and Columns	Must be the same
Coordinate System	Must be the same

All the conditions above must be fulfilled because WetSpass-M makes the calculation cell by cell.

The elevation and slope maps were converted to ASCII format from tif. This was easily done in QGIS, and the extent of the map with the resolution was the same.

The soil and land use maps required a bit of an effort to prepare because a study on the land use and soils in the region had to be done. According to the lookup tables, this involved an approach of standardization and reclassification to WetSpass-M environment, which defines the codes for each land use and soil type. Table 3.8 and Table 3.9 are the lookup tables for land use and soil, respectively. Therefore, the input maps of land use and soil contain these codes for each raster cells, according to the reclassification of the original attributes to the corresponding values of these tables. The values of the lookup tables for each land use type and soil could be modified by the user to calibrate these default values of each parameter.

Table 3.8: Lookup table for some land use types.

Code	LUSE_TYPE	RUNOFF_VEG	VEG_AREA	BARE_AREA	IMP_AREA	OPENW_AREA	ROOT_DEPTH	LAI	MIN_STOM	VEG_HEIGHT	nManing	LandFactor	AerodynResistance
1	city center build up	grass	0.2	0.3	0.5	0	0.3	2	100	0.1	0.03	0.667	225.158
2	build up	grass	0.1	0.4	0.5	0	0.3	1	100	0.1	0.02	0.5405	225.158
3	industry	grass	0.4	0	0.6	0	0.3	2	100	0.1	0.035	0.571	225.158
4	infrastructure	grass	0.6	0.1	0.3	0	0.3	2	100	0.1	0.04	0.5	225.158
5	sea harbour	grass	0.6	0.1	0.3	0	0.3	2	100	0.1	0.045	0.444	225.158
6	airport	grass	0.2	0	0.8	0	0.3	2	100	0.1	0.03	0.667	225.158
7	excavation	bare soil	0	1	0	0	0.05	0	110	0.001	0.09	0.222	692.160
10	open build up	grass	0.5	0.5	0	0	0.3	1	100	0.5	0.0945	0.38544	124.221
21	agriculture	crop	0.9	0.1	0	0	1	8	30	6	0.9865	0.3541	39.974
23	meadow	grass	0.8	0.2	0	0	0.3	4	30	2	0.947	0.2286	66.329
27	maize and tuberous p	crop	0.8	0.2	0	0	0.3	4	180	1.5	0.05	0.4	76.024
28	wet meadow	grass	1	0	0	0	0.3	2	100	0.3	0.055	0.364	152.495
29	orchard	forest	0.8	0.2	0	0	1	4	120	4	0.955	0.244	47.837
31	pine	forest	1	0	0	0	2	10	150	17	0.945	0.355	27.622

Table 3.9:Look-up table for some soil texture

Code	SOIL	FIELDCAPAC	WILTINGPNT	PAW	RESIDUALWC	A1	EVAPODEPTH	TENSIONHHT	P_FRAC_SUM	P_FRAC_WIN	Teta
1	Sand	0.11	0.04	0.19	0.02	0.52	0.05	0.02	0.08	0.01	0.09
2	loamy sand	0.14	0.04	0.19	0.04	0.50	0.05	0.04	0.08	0.01	0.11
3	sandy loam	0.21	0.07	0.12	0.04	0.40	0.05	0.15	0.08	0.01	0.24
4	silty loam	0.21	0.05	0.17	0.02	0.49	0.05	0.08	0.09	0.04	0.13
5	loam	0.17	0.06	0.14	0.03	0.46	0.05	0.07	0.10	0.02	0.11
6	silt	0.30	0.10	0.20	0.04	0.50	0.05	0.61	0.09	0.01	0.43
7	sandy clayl	0.26	0.16	0.10	0.07	0.50	0.05	0.28	0.54	0.30	0.35
8	silty clayl	0.36	0.19	0.17	0.04	0.50	0.05	0.33	0.62	0.41	0.56
9	clayloam	0.33	0.19	0.14	0.08	0.50	0.05	0.26	0.62	0.41	0.49
10	sandy clay	0.32	0.23	0.09	0.11	0.50	0.05	0.29	0.80	0.68	0.47
11	silty clay	0.28	0.10	0.25	0.06	0.42	0.05	0.18	0.20	0.45	0.25
12	clay	0.46	0.33	0.13	0.09	0.40	0.05	0.37	0.85	0.85	0.85

For the climate and groundwater depth data, spatial interpolation was done on QGIS using the Inverse Distance Weighting (IDW) method. The choice of this method was the number of points for interpolation. There were just three stations, and some parameters like potential evapotranspiration had only one point (the value was assumed to be the same in the study area).

Another scenario was created to assess the impacts of land use change only on water balance and recharge. This was achieved by taking the 30 years average values (1990 to 2020) of the climate data as constant for all the land use years. Only land use was changed.

3.4.3 MODEL CALIBRATION AND VALIDATION

The most important part of the model is the calibration and validation of the results. This can be done by comparing the output of the model to a known value. For example, the actual average evapotranspiration can be compared to known actual evapotranspiration of the study area. Nevertheless, this will require the change of the model's parameters to fit the study area condition.

Sensitivity analysis was also done to evaluate the sensitivity of the model's result to change in some of the input parameters. This was done by changing different parameters and monitor their effects on the results.

3.5 SPECIFIC VULNERABILITY ASSESSMENT

The vulnerability assessment was done to delineate the part of the study area susceptible to groundwater contamination. Since there is agricultural practices and industrialization in the study area, it was relevant to know how susceptible the groundwater is to contamination. For this, the susceptibility index (SI) method was employed according to Stigter et al. (2005).

The susceptibility index (SI), an adaptation of the DRASTIC method, was developed to evaluate aquifer vulnerability on a large to medium scale (Stigter et al., 2005). DRASTIC was developed by Aller et al. (1987) for the US EPA, with the purpose of creating a methodology that would permit a systematic evaluation of the groundwater pollution potential of any hydrogeological setting (Stigter et al., 2005). The seven hydrogeological factors that form the acronym DRASTIC are shown in Table 3.10. SI does not consider some of the DRASTIC factors which are soil media (S), the impact of vadose zone (I) and the hydraulic conductivity of the aquifer (C). SI also defined new weights to the equation based on the methodology presented in Stigter et al. (2005). The main novelty of this method was the use of the LU (Landuse) parameter, which corresponds to land use, leaving behind the concept of a purely intrinsic index based solely on natural conditions. In other words, the SI was developed to evaluate the specific risk, which considers the potential impacts of land use and possible contaminants associated with that use. Table 3.10 shows the DRASTIC parameters with the SI parameters and weights.

Table 3.10: DRASTIC, SI parameters, their meaning, and weights (Source: Stitger et al. 2005)

Letter	Meaning	Weight	Pesticide weight	SI weight
D	Depth to water	5	5	0.186
R	Net recharge	4	4	0.212
A	Aquifer media	3	3	0.259
S	Soil media	2	5	-
T	Topography	1	3	0.121
I	Impact of the vadose zone media	5	4	-
C	Hydraulic conductivity of the aquifer	3	2	-
LU	Land use	-	-	0.222

For SI, the factors are abbreviated as D, R, A, T, LU. Table 3.11 shows the definition of each parameter.

Table 3.11: SI parameters

Parameter	Definition
D	Depth to water table
R	Spatial Recharge

A	Permeable Aquifer Media
T	Slope of the study area
LU	Land use

The idea is to make a raster map for all these parameters by giving each of their values the susceptibility rating. The rating is between 10 and 100. The SI rating is simply DRASTIC rating multiplied by 10. Table 3.12 shows the values and their corresponding ratings. The ratings below are from DRASTIC method.

Table 3.12: The values of each parameter and their corresponding ratings (Source: Stigter et al., 2005)

D[a] (m)		R[a] (mm)		T[a] (%)	
<1.5	10	<51	1	<2	10
1.5–4.6	9	51–102	3	2–6	9
4.6–9.1	7	102–178	6	6–12	5
9.1–15.2	5	178–254	8	12–18	3
15.2–22.9	3	>254	9	>18	1
22.9–30.5	2				
>30.5	1				

A[ab]	
Massive shale	1–3 (2)
Metamorphic/igneous	2–5 (3)
Weathered metamorphic/igneous	3–5 (4)
Glacial till	4–6 (5)
Bedded sandstone, limestone and shale sequences	5–9 (6)
Massive sandstone	4–9 (6)
Massive limestone	4–9 (8)
Sand and gravel	4–9 (8)
Basalt	2–10 (9)
Karst limestone	9–10 (10)

[a] For SI the ratings are multiplied by 10
[b] Typical ratings between brackets

Table 3.13 shows the rating of different land use types in the SI method.

Table 3.13:Land use types and their SI ratings (Source: Stigter et al., 2005)

Land use	Rating
Agricultural areas	
Irrigation perimeters (annual crops), paddy fields	90
Permanent crops (orchards, vine yards)	70
Heterogeneous agricultural areas	50
Pastures and agro-forested areas	50
Artificial areas	
Industrial waste discharges, landfills	100
Quarries, shipyards, open-air mines	80
Continuous urban areas, airports, harbours, (rail)roads, areas with industrial or commercial activity, laid out green spaces	75
Discontinuous urban areas	70
Natural areas	
Aquatic environments (salt marshes, salinas, intertidal zones)	50
Forests and semi-natural zones	0
Water bodies	0

The raster maps allow giving a spatial variation of each parameter according to the rating given to it. These maps can then be used to calculate the vulnerability of the aquifer to pollution and to delineate the major zones of higher vulnerability. This was calculated using the SI equation (equation 6) below to make the raster map of susceptibility index.

$$SI = 0.186*D + 0.212*R + 0.259*A + 0.121*T + 0.222*LU \quad \text{Equation 6}$$

The classification was done following the classes adopted by Stigter et al.(2005).

3.6 ANALYSIS OF GROUNDWATER LEVELS

To perform a trend analysis of groundwater levels, data of monitoring wells was retrieved from SNIRH. Data from 31 wells with different depths and observation periods were found within the study area. To make an analysis between 1990 and 2020, 11 monitoring wells with more than 10 years of data were used. The location of these monitoring wells is shown in the Figure 3.7.

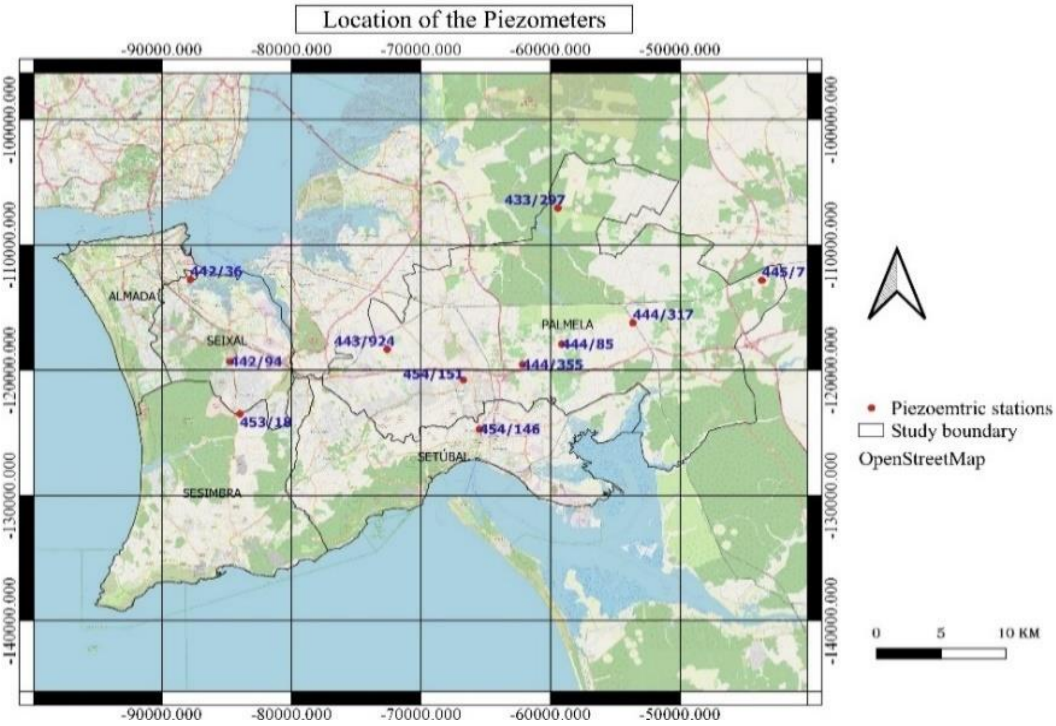


Figure 3.7: Location of the monitoring wells

A trend analysis is the evaluation of change, in this case, of the groundwater levels. In time series analysis, trend is the smooth additive component containing information about the changes in the time series. In case of working with time series with a regular variation, it is easy to find the trend by fitting the right curve.

The singular spectral analysis (SSA) is a form of principal component analysis that is used to detect periodic signals and extract the dominant frequencies in short and noisy time series. The main advantage of SSA is that it allows the reconstruction of the original record using a linear combination of the most statistically significant oscillations. Hanson et al. (2004) showed that the variability in most hydrological time series can be described in terms of the first 10 reconstructed components.

Contrary to the traditional methods of time series forecasting (both autoregressive or structural models that assume normality and stationarity of the series), SSA method is non-parametric and makes no prior assumptions about the data (Hassani, 2014). SSA can be used for a wide range of tasks: trend or quasi-periodic component detection and extraction, denoising, forecasting, change-point detection (Alexandrov, 2009).

The basic SSA method consists of two complementary stages: decomposition and reconstruction; both stages include two separate steps. At the first stage, the series is decomposed and at the second stage, the original series is reconstructed. The reconstructed series can be used for forecasting new data points.

This analysis was done in R with the RSSA package. The package works on the basic principle of SSA. The documentation of the package and other mathematical formulas have been presented in Golyandina et al. (2018). The main concern for the success of SSA is the choice of the window length (L) for decomposition of the time series and the singular value decomposition (SVD) subgroup elements for the reconstruction of the series. By changing these two parameters, one can change the output of the time series. To select the window length, many works have been done suggesting the rules to follow. Dickinson et al. (2014) suggested that the window length should be at least one-fifth of the entire data points. Another author suggested the selection of window length half of the total series (Hassani, 2014). The window length can be defined by user in the package, but the default value is 50% of the total observation. For this analysis, the default value was used since changing the window length did not affect the output of the analysis. This is because the series is not complex and only one source contributes to its variation. The subgroup elements for reconstructing the series were determined from the eigenvalues.

The kind of plot of Figure 3.8 would be created after the decomposition of the series. This can be used to determine the trend and the seasonality. For Figure 3.8, the first two components were taken as the trend. The other components with upward and downward variations were taken as the seasonality. The other parts with steady eigenvalues (20-50) were taken as noise.

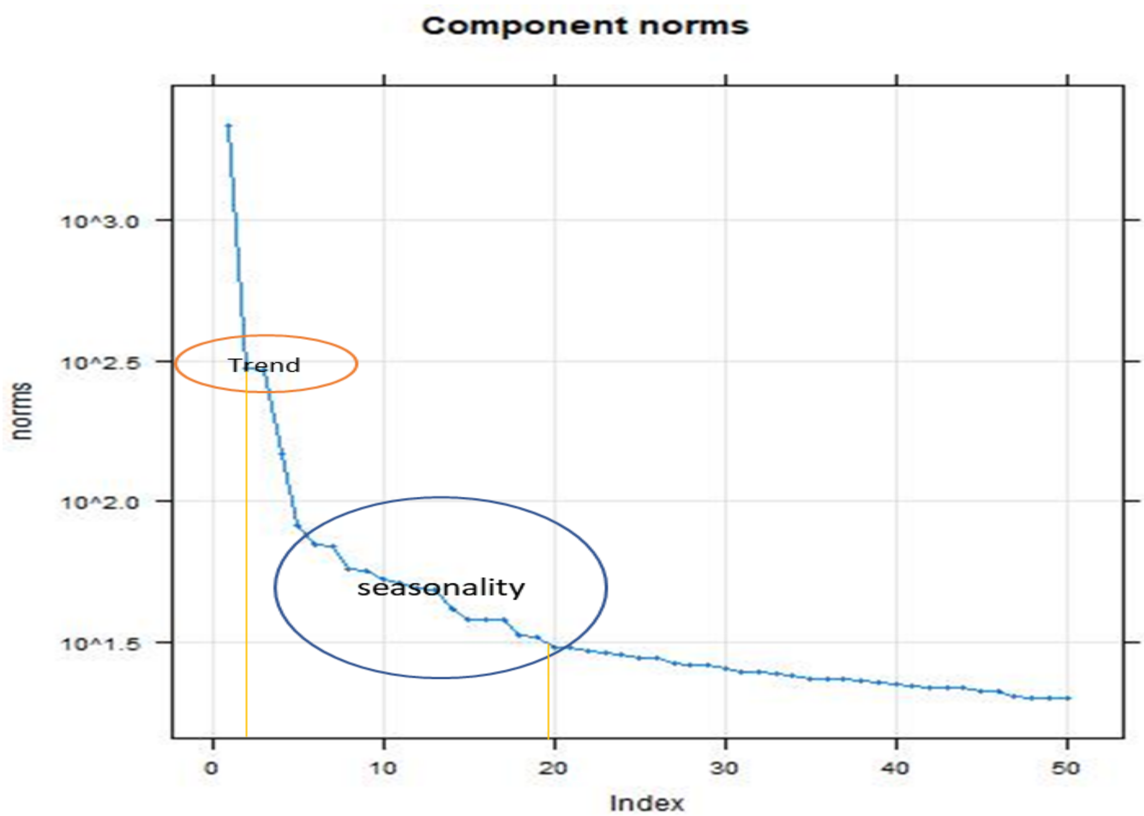


Figure 3.8: The eigenvalues and components

The R code with clear explanation of each step can be downloaded from the following link in GitHub: https://github.com/Ayodejiojo1/mycodes/blob/main/RSSA.R

3.7 SUSTAINABILITY ASSESSMENT

This was done to assess the state of water balance and recharge in the study area to the middle of the century (2041-2070). For this analysis, the average climate data for the 30 years was calculated using the modeled data from IPMA. The modeled 30 years (1971-2000) average historical data and the modeled RCP scenarios (4.5 and 8.5) data (2041-2070) were downloaded from IPMA (ipma.pt) climate portal. These data have no spatial variation i.e., a single value was assumed for entire study area. These two (historical and future) data were compared to calculate the percentage change between the modeled past and the future. Table 3.14 shows the modelled data from IPMA. This change in the modeled data was then applied to the 30years (1990 – 2020) actual average climate data retrieved from SNIRH to calculate the future data used for this analysis. Other spatial variables like DEM, slope, and soil were unchanged. The land use of 2018 was fixed for the future analysis. And a static groundwater depth of 10m was assumed in the three years. This was done because groundwater level did not have effect on the model's result. The sensitivity analysis performed with groundwater depth of 5m, 10m, and average of groundwater level data retrieved from SNIRH gave the same results.

Table 3.14: The 30 years average climate data from SNIRH and modelled historical and future averages from IPMA.

	SNIRH (1990-2020)	Modelled Historical (1971-2000)	Modelled future (2041-2070)	
			RCP4.5	RCP8.5
Rain(mm)	586	716.6	677.8	669.1
PET (mm)	675	1235.9	1299.0	1320.2
Wind(m/s)	1.3	4.3	4.3	4.3
Temperature (0C)	16	15.3	16.6	17.2

4 RESULTS AND DISCUSSION

This chapter presents and explicitly discusses the results of all the analysis done to achieve the objectives of this research.

4.1.1 DEMOGRAPHIC GROWTH

The five municipalities have experienced a considerable change in population in the past decades. This can be attributed to the migration of people from the rural areas to urban areas. Almada has the highest number of people living within her boundary. This is followed by Seixal, Setubal, Palmela, and Sesimbra in an orderly manner. Almada is a more residential area, and it has experienced a significant increase in built up area over the years. Figure 4.1 shows the evolution of population for the five horizons (1990, 2000, 2006, 2012, 2018) representing four (4) decades.

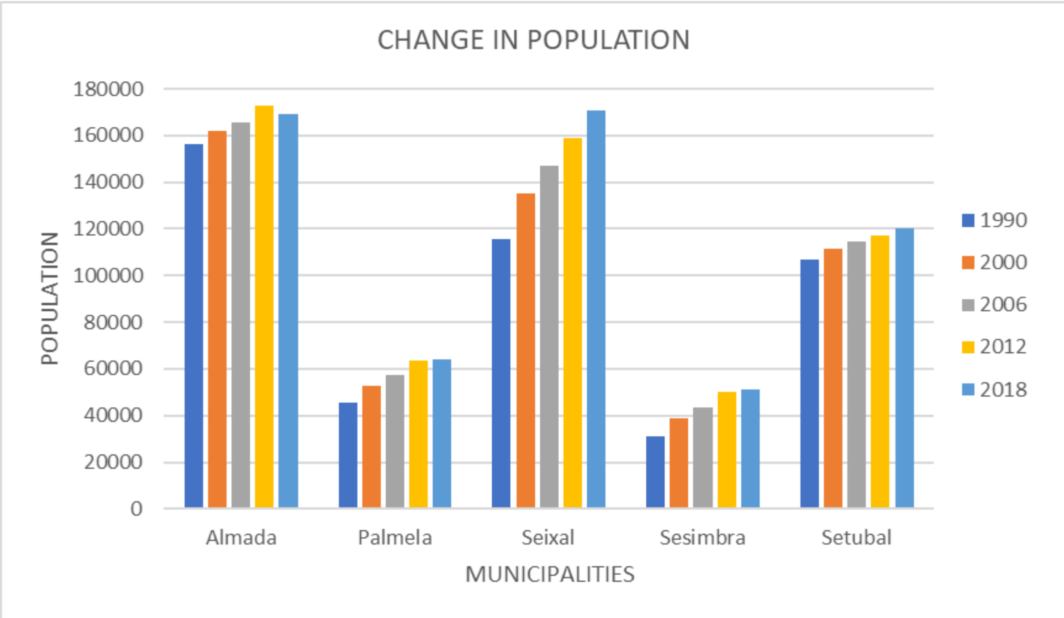


Figure 4.1: Evolution of population in each municipality

In Almada, the population in the year 2000 increased by over 4% of that in 1990. This growth in population progressed until 2018 when there was a relatively decrease in population. Population increased in 2006 and 2012 by 2.2% and 4.3% of year 2000 and 2006 respectively. In 2018, the population curve experienced a drop relative to 2012 by -2.21%.

Contrary to Almada that experienced a drop in population in the year 2018, the population progressively increased all through the years under review in other municipalities. In Palmela, the population of year 2000 is about 16.5% higher than in 1990. This became progressive as the population in 2006, 2012 and 2018 is 8.5%, 10.7% and 1.1% higher than the population in 2000, 2006 and 2012 respectively. In Seixal, the population in the year 2000 is about 17.2% higher than 1990 population. This became progressive as the population in 2006, 2012 and 2018 is 8.8%, 8.1% and 7.5% higher than the population in 2000, 2006 and 2012 respectively. In Sesimbra, the population of year 2000 is about 25% higher than in 1990. This became progressive as the population in 2006, 2012 and 2018 is 12%, 15% and 3% higher than the population in 2000, 2006 and 2012 respectively. In

Setubal, the population of year 2000 is about 4% higher than in 1990. This also became progressive as the population in 2006, 2012 and 2018 is 3%, 2% and 2% higher than the population in 2000, 2006 and 2012 respectively. Generally, in all municipalities, the change in population between 2012 and 2018 is lowest. Table 4.1 shows the evolution of population in each municipality.

Table 4.1: Population evolution in each municipality

Population						
Year	Almada	Palmela	Seixal	Sesimbra	Setubal	Total
1990	156226	45427	115391	31085	106943	455072
2000	162224	52914	135244	38983	111682	501048
2006	165823	57407	147156	43723	114526	528634
2012	172890	63553	159068	50092	117369	562972
2018	169070	64222	170979	51421	120213	575906

4.1.2 WATER CONSUMPTION

To assess the variation of groundwater, use and the respective licenced abstraction volume in the years under consideration, the existing wells abstract were studied. From the assessment and according to the data provided by Planning and Information Division, Administration of Tagus, and West Hydrographic Region (ARH Tejo), between the years 1990 and 2018, it is observed that there has been a very demand of groundwater. The major consumption of water is the agricultural sector especially in the municipality of Palmela.

Private and public well data was obtained, as shown in Figure 4.2 which shows the location of the wells within the study area. After processing in QGIS and MS Excel, there was a total of 14,620 wells constructed in the study area from 1970 to 2018. The absence of wells in the southeast area, is related to the low population density, as it corresponds to a nature protected area.

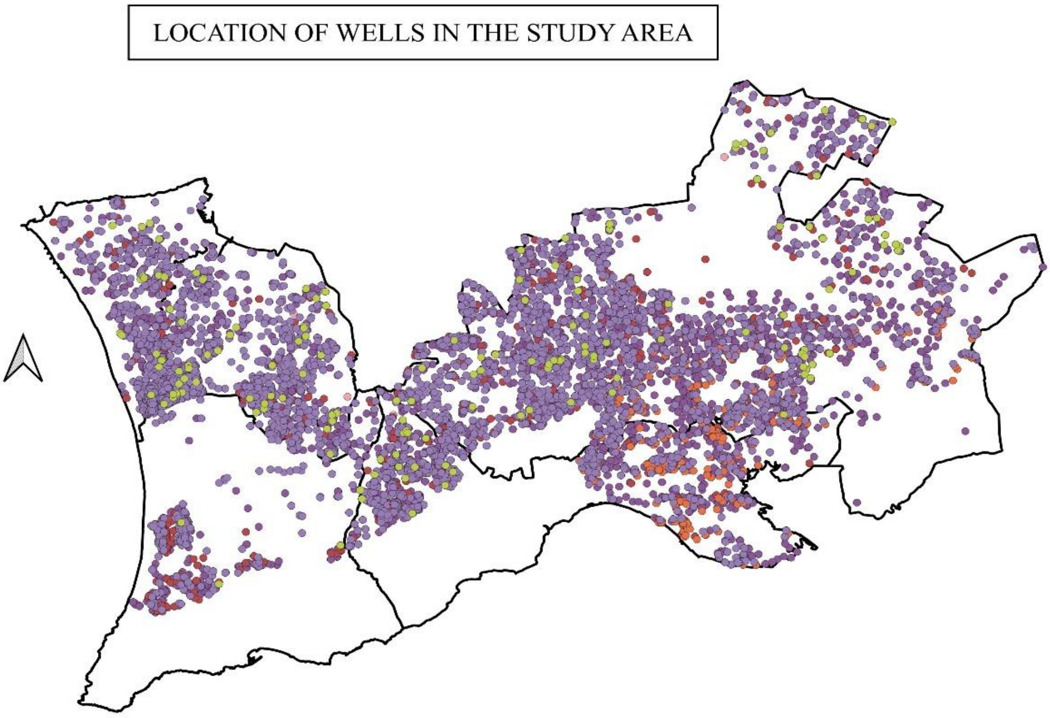


Figure 4.2: Location of the wells in the study area.

As shown in Figure 4.3, 47% of the wells were constructed in Palmela, related to agriculture use (about 15 wells/km^2). The least number of wells which constitute on 7% are in Sesimbra because of the less favourable local hydrogeological conditions of the area (about 5 wells/km^2).

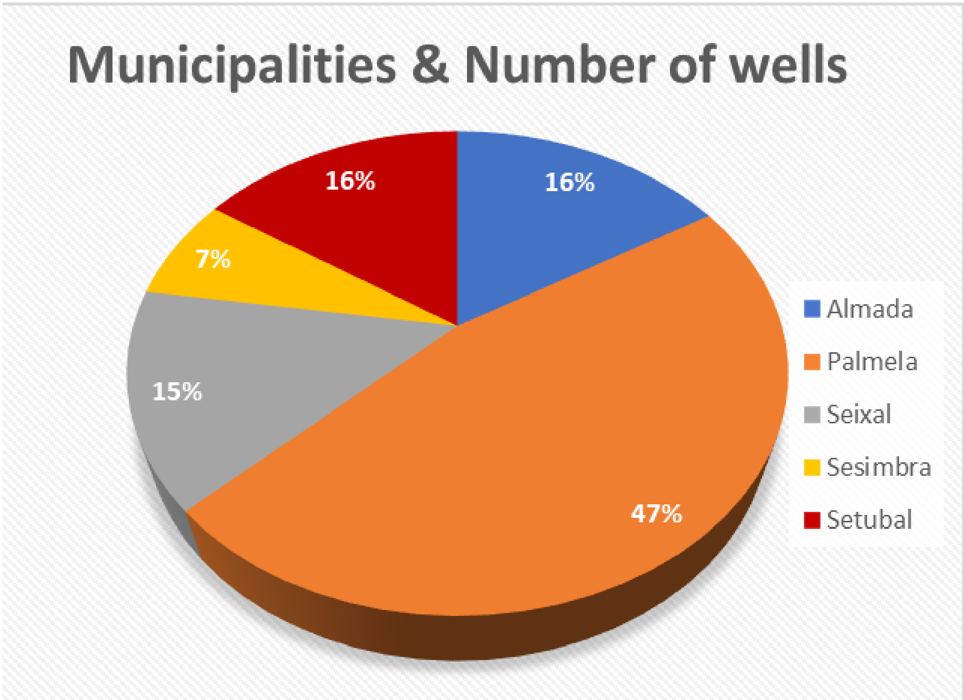


Figure 4.3: The percentage of wells in each municipality from 1970 to 2018

The wells are used for different purposes which include irrigation, industrial, human consumption, and multiple uses. Some wells, whose use were not recorded on the licence were classified as others. About 71% of the wells are used for irrigation purpose while just 3% are used for industrial purpose as shown in Figure 4.4.

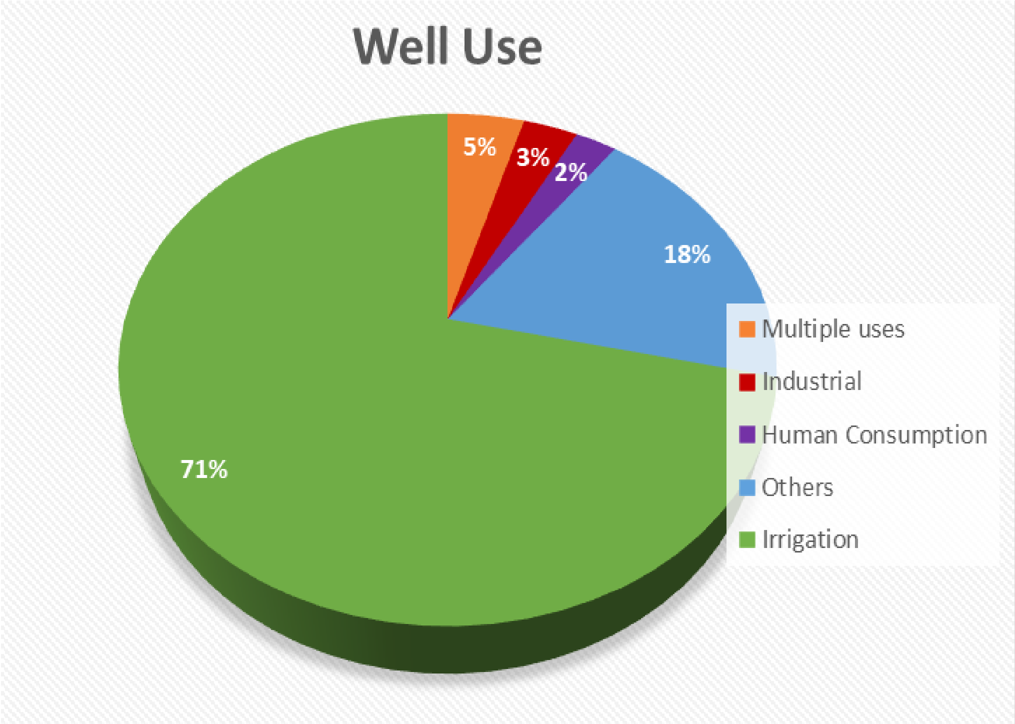


Figure 4.4: The percentage of each well use from 1970 to 2018

It was observed that majority of the wells were licenced in 2007 and after. This occurred because it was mandatory for people to licence their wells in 2007 (Law 54/2005, 15 November 2005 and Decree-Law 226-A/2007, 31^{st} May). This shows that many unregistered and illegal wells had been abstracting water prior to 2007.

4.2 LAND USE CLASSIFICATION

The classification of land use was done to identify the different land use and land cover within the study area. Nine land use was recognised within the overall boundary of the study area. This will be explained for the whole study area and specifically for individual municipality. The classification of the land use was done with accordance to the input for WetSpass-M to achieve one of the objectives of this thesis. The definitions of the land use classes are given in Table 3.3. The total study area is about 995.7km^2

The land use classes in 2018 has a little deviation from other years. This is because the methodology adopted by CORINE in making the 2018 map is quite different from the other 4 years. Nine (9) land use classes were identified in 1990, 2000, 2006 and 2012. Eight (8) were identified in 2018. Orchard was not one of the land-use classes in 2018.

Figure 4.5 shows the land use classes in the five years and all the five municipalities. The major land use classes that have significant change over the period under study are pine, agriculture, built-up, and natural vegetation.

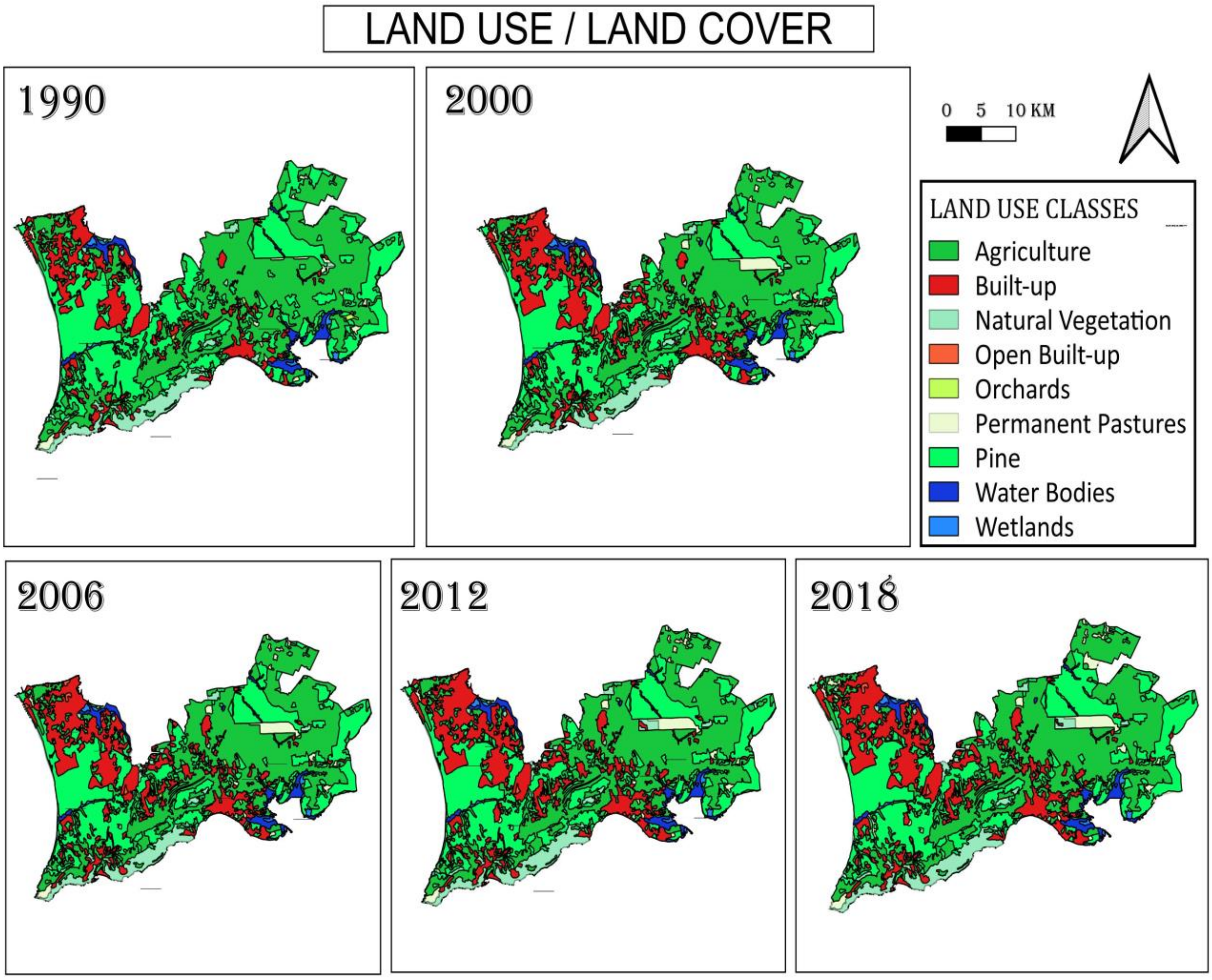


Figure 4.5: Land use change

The built-up area increased considerably from 12.53% in 1990 to 19.22% in 2018. The built-up area was 19.39% in 2012 and the reduction in 2018 can be attributed to the method adopted in creating the CORINE land use map of this year. Table 4.2 shows the area occupied by each land use class in the reference years.

Table 4.2: Area of each land use

	Area km^2				
Land Use	1990	2000	2006	2012	2018
Wetlands	8.68	8.65	8.65	8.66	8.66
Water Bodies	25.13	25.33	25.33	25.33	23.31
Built-up	124.78	169.80	186.45	193.02	190.28
Pine	353.72	315.62	308.38	304.57	308.44
Open Built-up	1.49	2.82	3.05	1.64	2.17
Agriculture	418.92	402.68	391.95	386.51	372.83
Permanent Pastures	10.11	18.90	19.30	19.97	26.28
Natural Vegetation	51.04	51.56	51.94	55.33	57.87
Orchards	1.78	0.31	0.60	0.62	-

The agriculture and pine areas decreased over the years from 42.07% and 35.53% in 1990 to 37.67% and 31.16% in 2018 respectively. Pine also increased from 2012 to 2018 from 30.595% to 31.16% respectively. Wetlands and Water Bodies were almost constant from

1990 to 2018 while Orchards, permanent pastures, open built-up and natural vegetation also undergo a considerable change from 1990 to 2018. Figure 4.6 shows the land use classes and the percentage of land they occupy from 1990 to 2018.

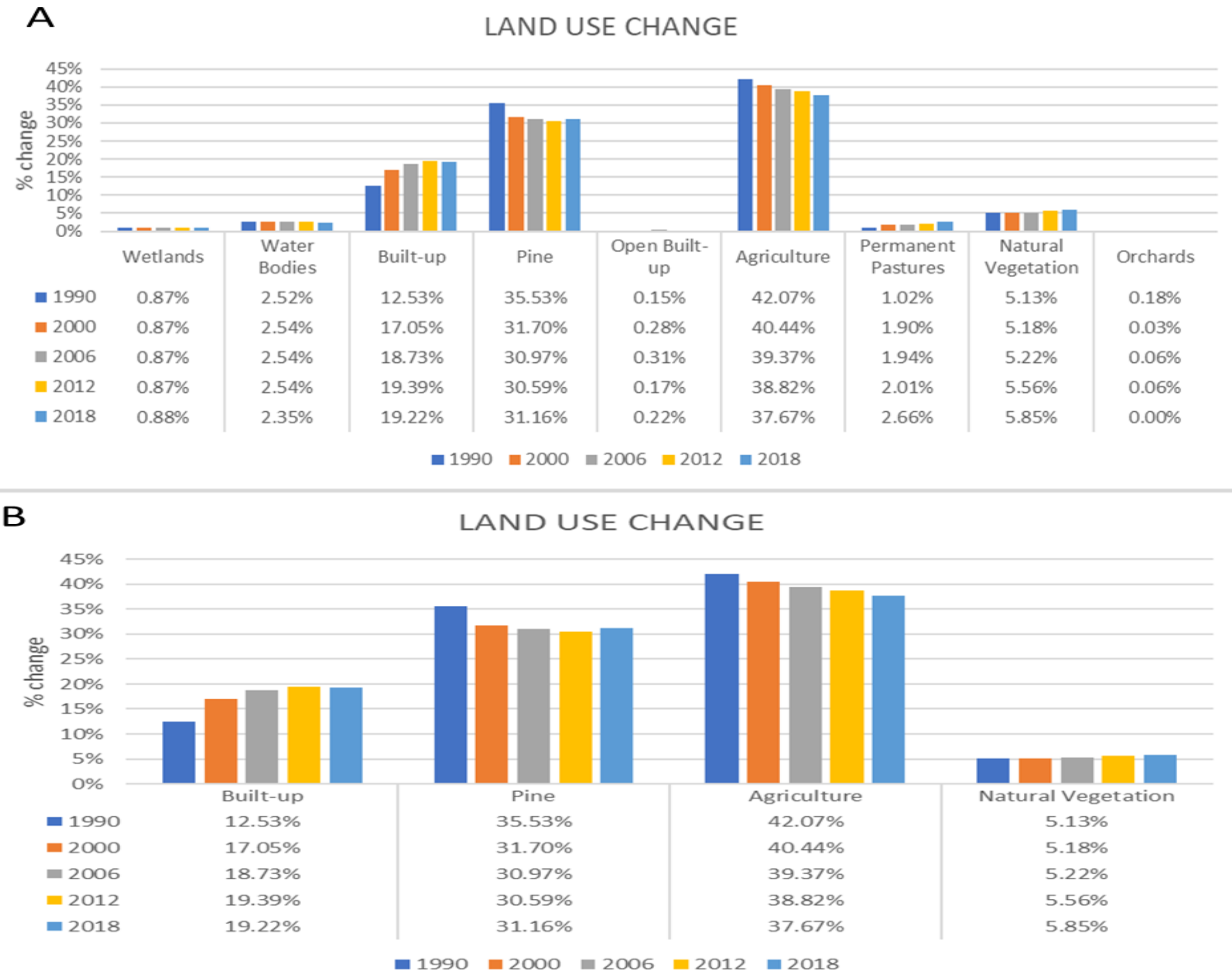
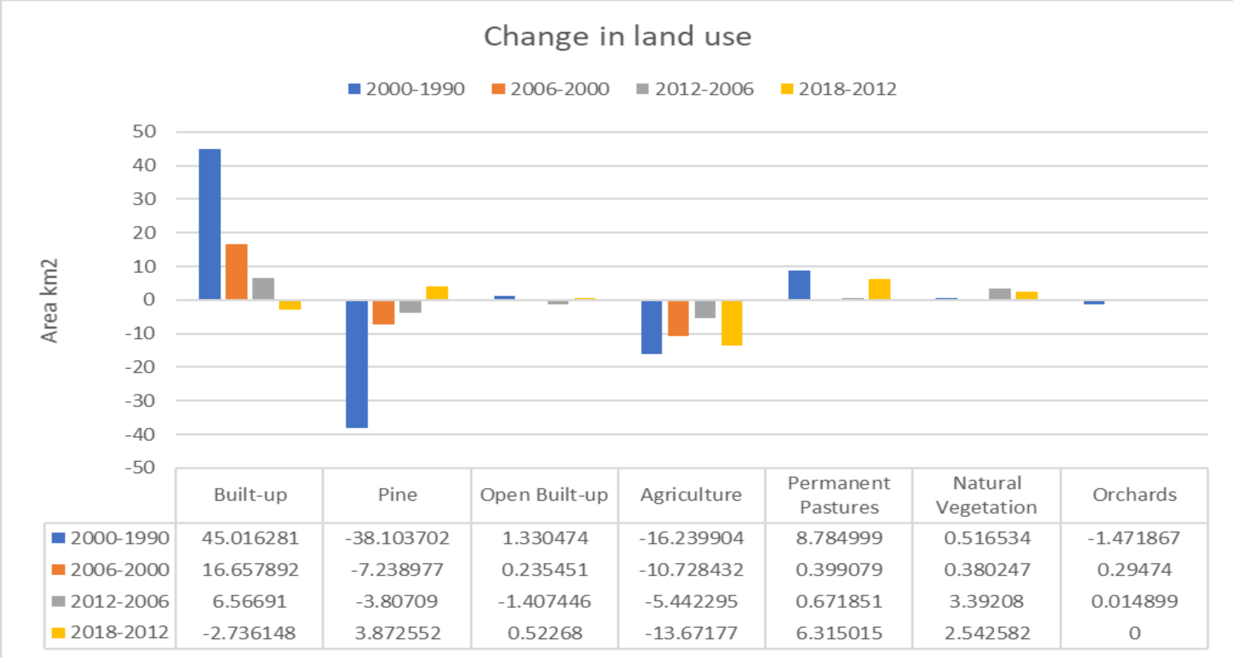


Figure 4.6: Evolution of each land use. A shows all the land use classes while B shows the four dominant land use classes.

To show the change in area of each land use in the study area between two consecutive years under study, a plot of difference in area between years was plotted for the main land use that underwent considerable change. From the plot (Figure 4.7), how each land use area has changed progressively from year to year can be seen.



	Built-up	Pine	Open Built-up	Agriculture	Permanent Pastures	Natural Vegetation	Orchards
2000-1990	45.016281	-38.103702	1.330474	-16.239904	8.784999	0.516534	-1.471867
2006-2000	16.657892	-7.238977	0.235451	-10.728432	0.399079	0.380247	0.29474
2012-2006	6.56691	-3.80709	-1.407446	-5.442295	0.671851	3.39208	0.014899
2018-2012	-2.736148	3.872552	0.52268	-13.67177	6.315015	2.542582	0

Figure 4.7: Difference in land use for two successive years

To downscale the analysis and see how each land use has changed locally in each municipality, land use change was assessed for each municipality. This gave a better insight into the major activities done in each municipality in the past decades. The built-up area which was taken as the impervious surface was also correlated with the population in each municipality to show the interplay and dependency of these factors.

4.2.1 ALMADA

This municipality has a total area of about 70km^2. It is the most industrialised of the five municipalities. There has been an evolution of built-up area over the past decades. The built-up has increased from 44.87% in 1990 to 59.25% in 2018. Agriculture has reduced from 28.03% in 1990 to 14.80% in 2018, accounting for almost half of the agricultural area in 1990 being replace by other land use in 2018. This area has majorly been replaced with artificialized area. Pine also experienced a reduction from 20.84% in 1990 to 14.52% in 2018. The other land use that has considerable change is Natural vegetation which increased from 3.18% in 1990 to 6.25% in 2018. Others are wetlands, water bodies, open built-up, orchards and permanent pastures. The reduction in agricultural and pine area has a significant implication on groundwater recharge. The built-up area is said to be impervious leading to increase in bare soil evaporation and surface runoff. This suggests that the recharge of groundwater would have reduced considerable with the reduction in area of land use that facilitates infiltration of rainfall. From Figure 4.8, the change in land use between 1990 and 2018 is very pronounced at the northern part of the study area as most of the agricultural and forested (green colour) areas have been replaced by built-up (red colour).

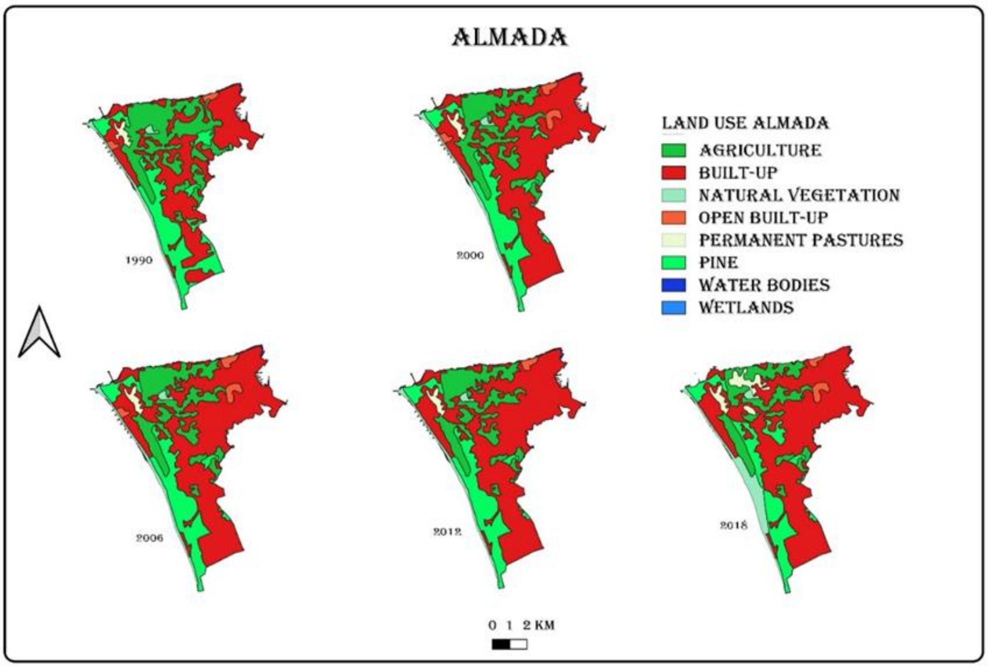
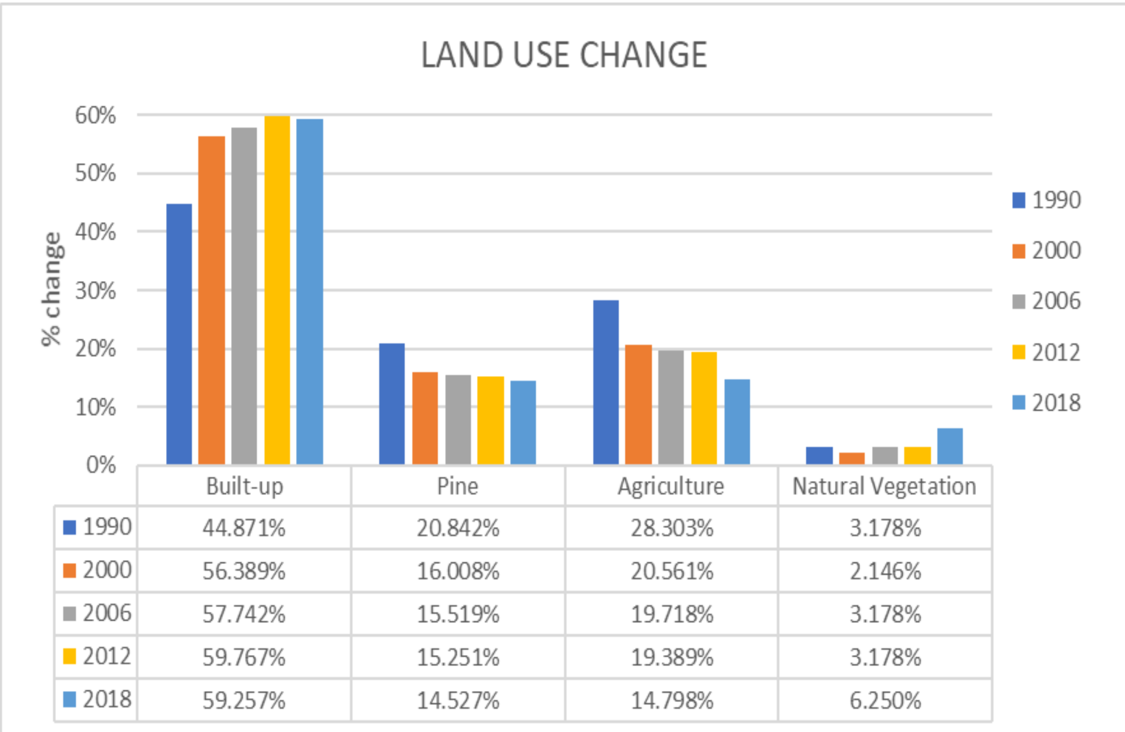


Figure 4.8: Land use classes of Almada

Figure 4.9 shows the changes in the dominant land use in Almada.



	Built-up	Pine	Agriculture	Natural Vegetation
1990	44.871%	20.842%	28.303%	3.178%
2000	56.389%	16.008%	20.561%	2.146%
2006	57.742%	15.519%	19.718%	3.178%
2012	59.767%	15.251%	19.389%	3.178%
2018	59.257%	14.527%	14.798%	6.250%

Figure 4.9: Plot of the dominant land use in Almada

A relationship between the impervious surface and population was made to see how these parameters have changed over the years. Figure 4.10 is the plot showing the result. Table 4.3 shows the correlation matrix between the parameters. There was a positive correlation between them. Impervious surface increased with the growing population.

Table 4.3:Correlation matrix of imperviousness and population.

	Imperviousness (%)	Population
Imperviousness (%)	1	
Population	0.899	1

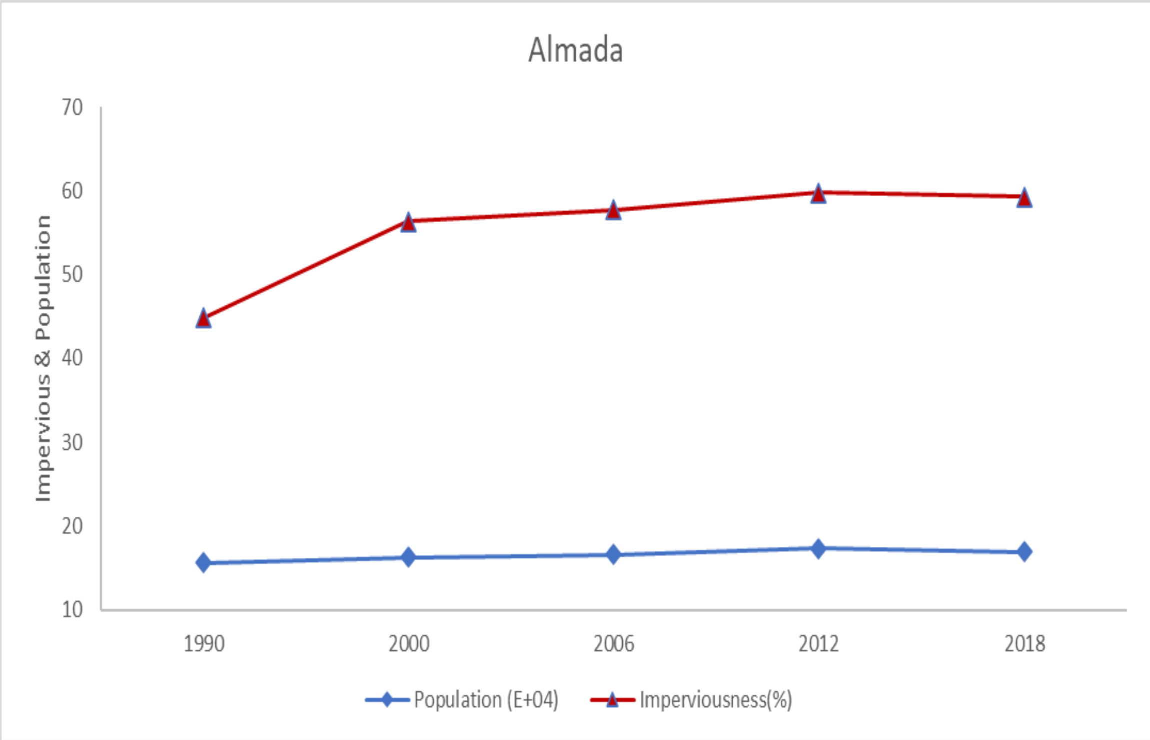


Figure 4.10: Relationship between impervious surface, and population

4.2.2 PALMELA

The total area is about 463km^2. Palmela has most of her land used for agriculture and pine. Though, in the past decades, there has been a progressive increase in the built-up area from 2.96% in 1990 to 7.02% in 2018. Generally, agriculture has the greater share of the land-use area but has also experienced a constant decline from 59.68% in 1990 to 55.85% in 2018. Except for the sharp reduction from 33.83% in 1990 to 29.23% in 2000, the area occupied by Pine has remained fairly the same over the past decades. Permanent pasture has also progressively increased from 1.19% in 1990 to 4.21% in 2018. Others are wetlands, water bodies, open built-up, orchards, and natural vegetation. Palmela is one of the recharge zones within the study area. The only issues the municipality is likely to face is the overexploitation of groundwater for agricultural purpose and the risk of groundwater pollution due to agriculture. It is also important to point out that since the water abstracted is majorly used for irrigation, there will also be a fast replenishment of the shallow aquifer from the irrigated water. Unfortunately, this does not necessarily affect the deeper aquifer from where the groundwater is abstracted. The major challenge will be a risk of groundwater quality at shallow depth especially nitrate concentration. From Figure 4.11, Palmela's land is mainly used for agriculture. And there has been an expansion of built-up area from 2.96% 1990 to 7.01% 2018.

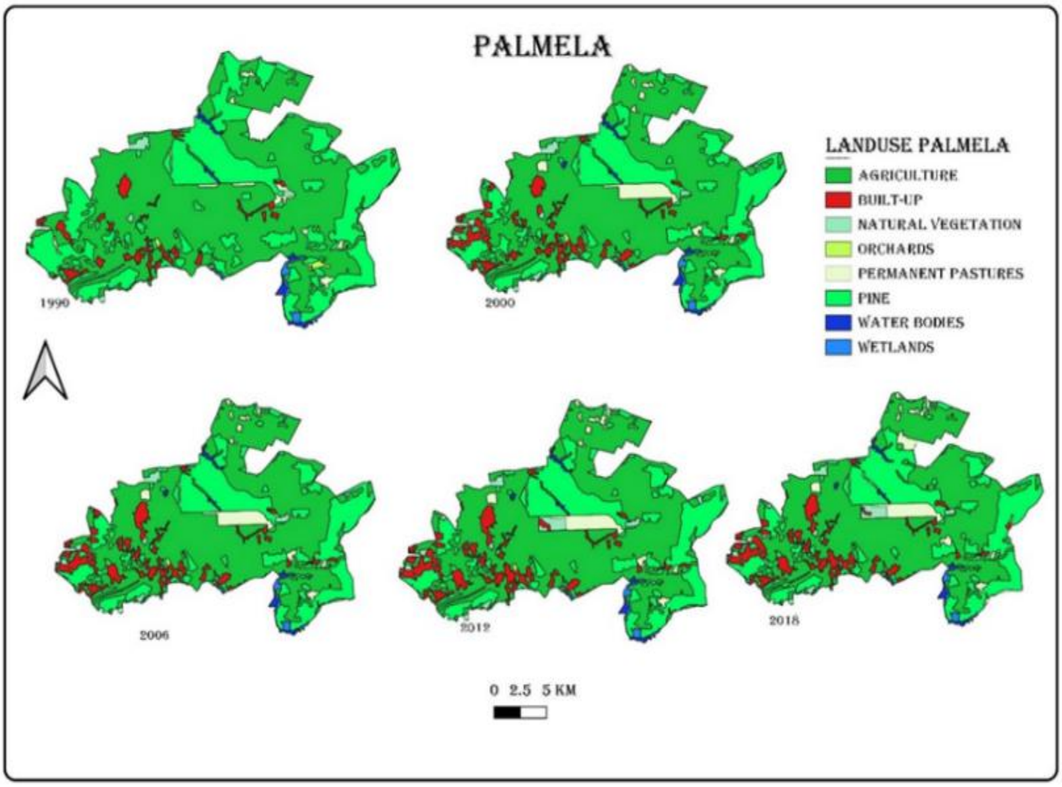
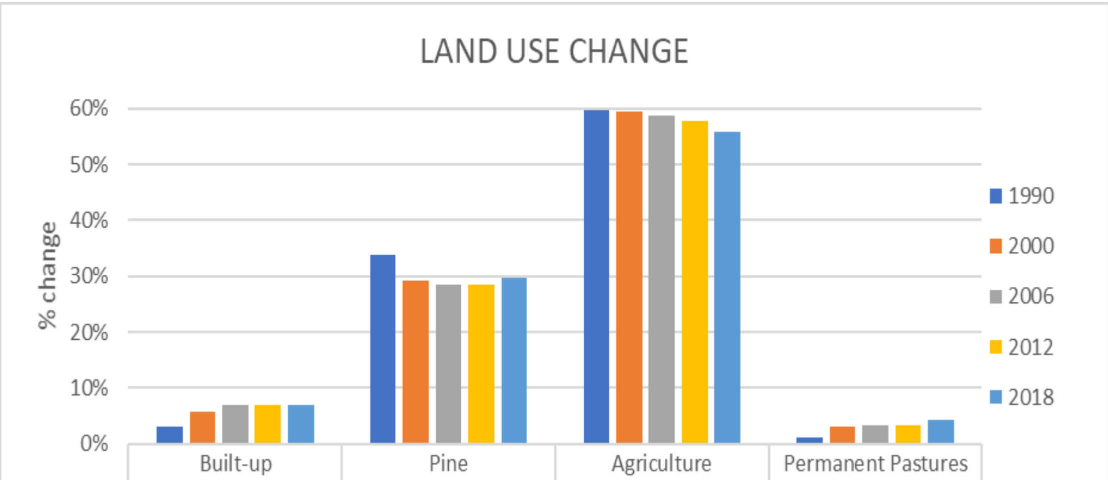


Figure 4.11: Land use of Palmela

Figure 4.12 shows the plot of the percentage change in the dominant land use classes in the study area.



	Built-up	Pine	Agriculture	Permanent Pastures
1990	2.958%	33.833%	59.679%	1.193%
2000	5.692%	29.231%	59.413%	3.109%
2006	6.824%	28.550%	58.769%	3.195%
2012	7.026%	28.464%	57.831%	3.327%
2018	7.018%	29.579%	55.845%	4.210%

Figure 4.12: Plot of the change in dominant land use

A relationship between the impervious surface and population was created to assess the change in these parameters over the years (Figure 4.13). As shown in Table 4.4, there exists a positive correlation between the two parameters. Population grows as the impervious surface increased.

Table 4.4: Correlation matrix between imperviousness, population, and abstraction in Palmela

	Imperviousness	Population
Imperviousness	1	
Population	0.93	1

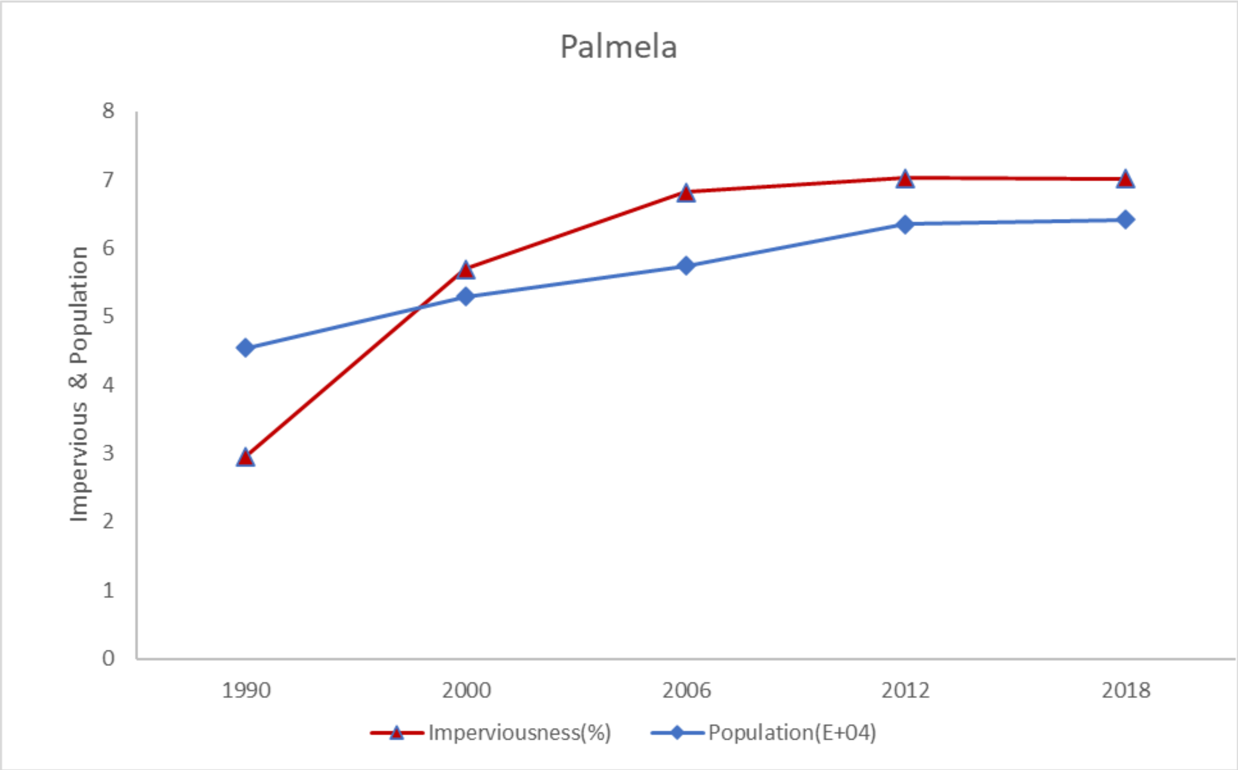


Figure 4.13: Relationship between impervious surface and population.

4.2.3 SEIXAL

The total area is about 95.5km^2. The major land use in this municipality is built-up, pine and agriculture. There are many artificial surfaces in this area as the built-up area has increased from 37.19% in 1990 to 53.89% in 2018. The pine and agriculture reduced in the area over the years from 37.96% and 12.7% in 1990 to 27.89% to 7.56% in 2018, respectively. The other land use that has experienced a fair reduction in area is the natural vegetation. The higher the area of urban fabrics also means the lower the recharge. Others are wetlands, water bodies, open built-up, orchards, and permanent pastures. As shown in Figure 4.14, the built-up area has significantly expanded especially towards the western part.

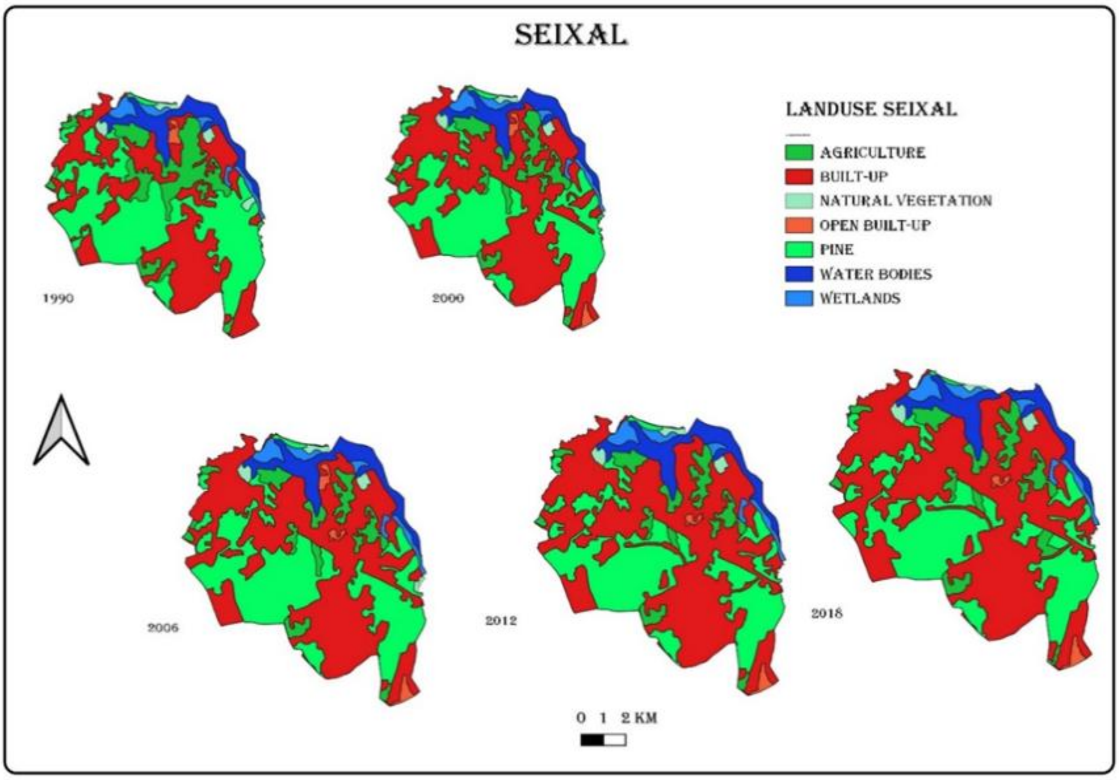


Figure 4.14: Change in land use in Seixal

Figure 4.15 shows the change in the major land use over the years.

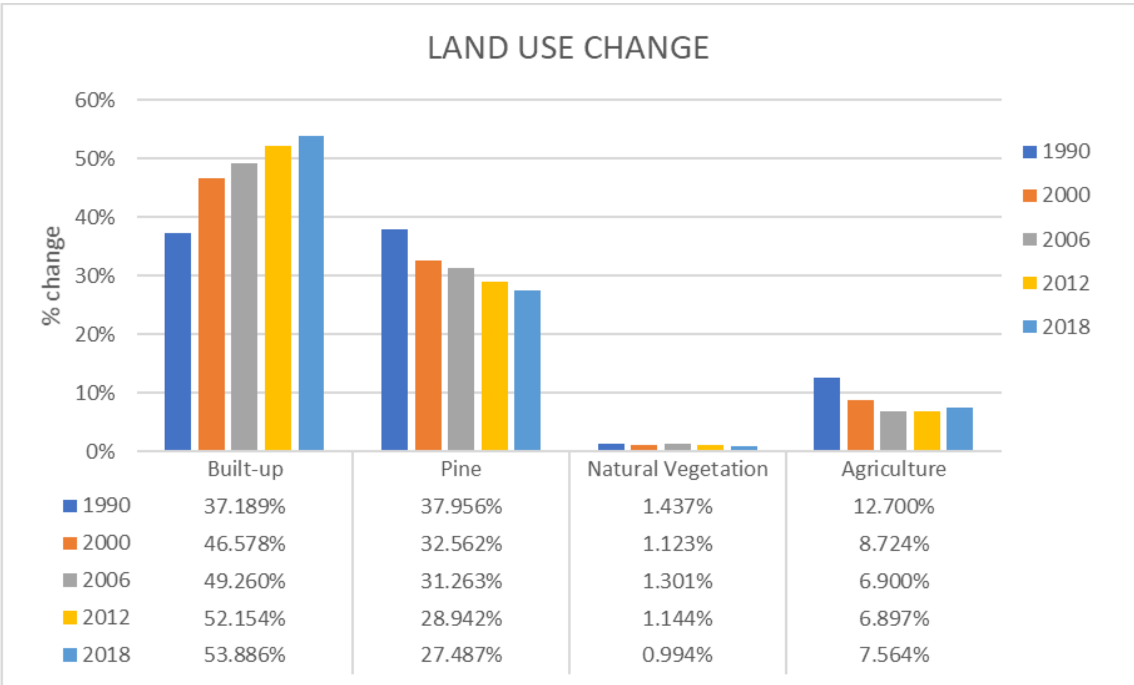


Figure 4.15: The plot of change of dominant land use classes in Seixal.

A relationship between the impervious surface and population was made to see how these three factors have changed over the years (Figure 4.16). From Table 4.5, there exists a positive correlation. Impervious surface increased with population growth.

Table 4.5: Correlation matrix of imperviousness, and population in Seixal

	Imperviousness	Population
Imperviousness	1	
Population	0.97	1

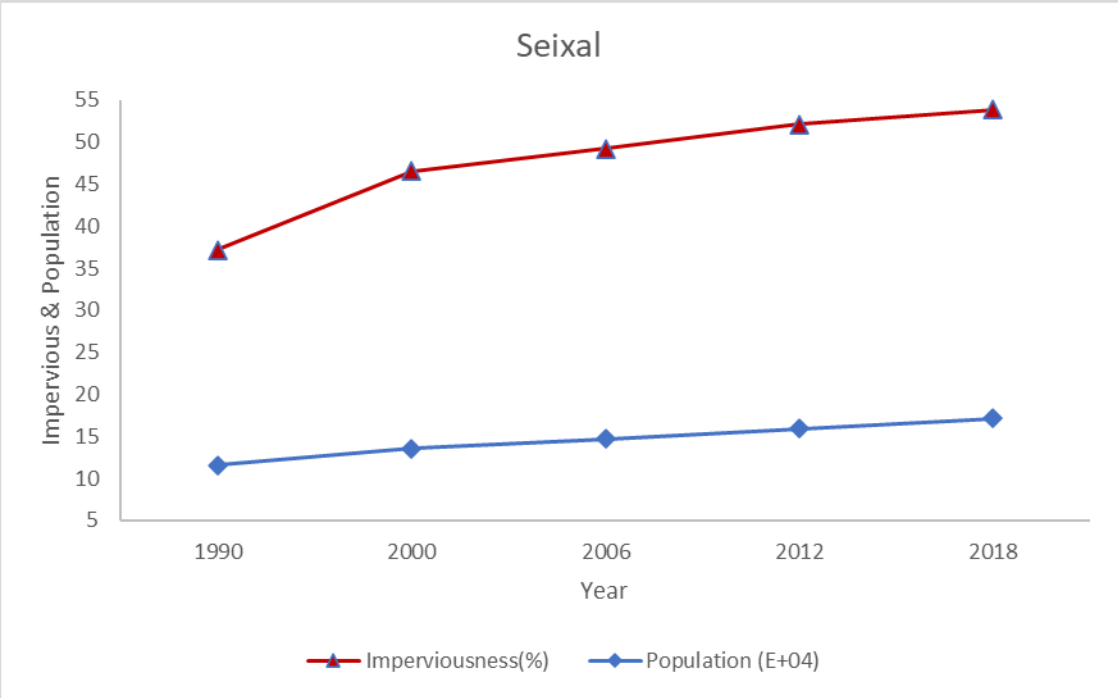


Figure 4.16: Relationship between impervious surface and population

The increased of impervious surface has a strong effect on groundwater recharge. The reduction of the pervious surface leads to reduction in infiltration of water and ultimately, a reduction in groundwater recharge.

4.2.4 SESIMBRA

The total area was about 195km^2. The major land use is Pine. Pine constitutes about 51.35% of the area in 1990 and declined to 50.27% in 2018. This can be attributed to the increase of built-up area from 11.39% in 1990 to 15.69% in 2018. The agricultural area also reduced from 21.65% in 1990 to 18.50% in 2018. Natural vegetation has a substantial but almost constant are which constitutes average of 12.50% of the area. Others are wetlands, water bodies, open built-up, orchards and permanent pastures. The type of land use in this municipality really promotes groundwater recharge. From Figure 4.18, the main land use is pine with artificial areas extending at the southern part of the region as shown in Figure 4.17.

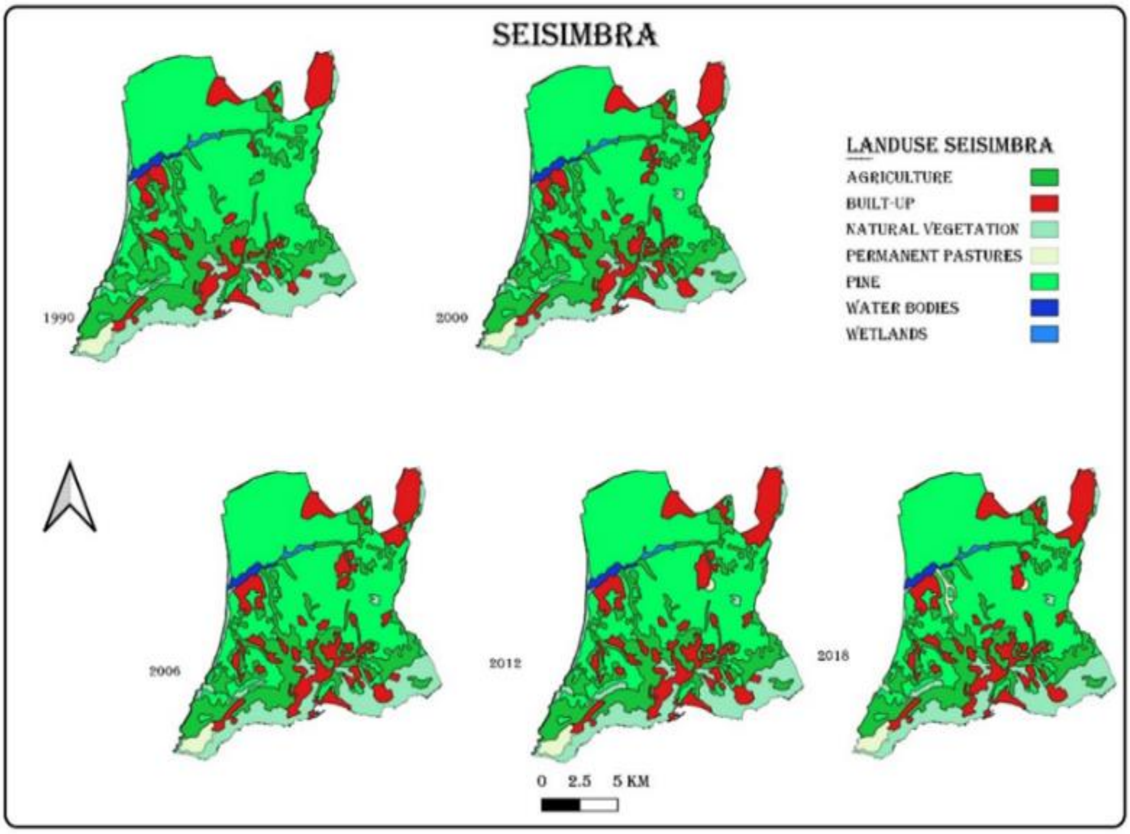
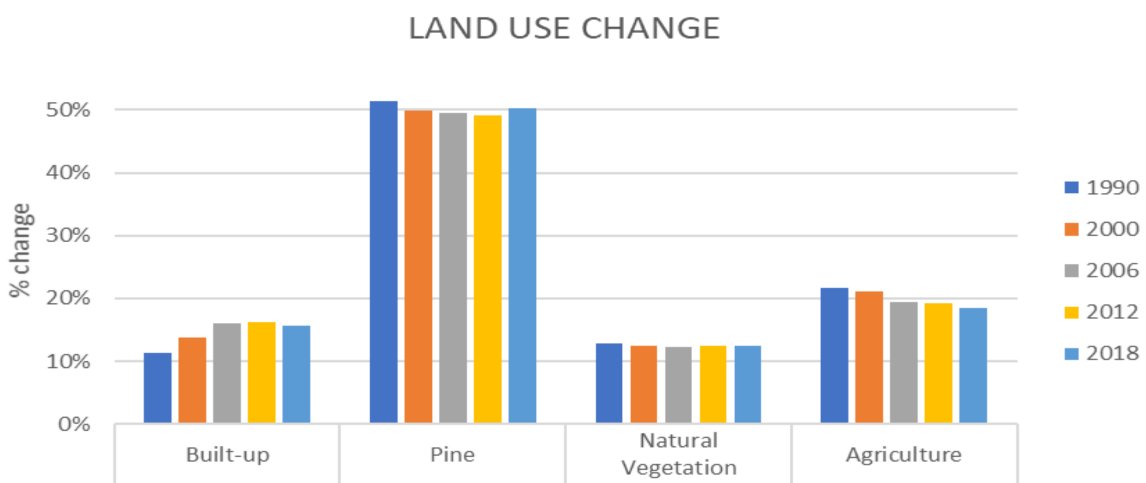


Figure 4.17: Land use of Sesimbra



	Built-up	Pine	Natural Vegetation	Agriculture
1990	11.396%	51.347%	12.835%	21.650%
2000	13.789%	49.848%	12.477%	21.108%
2006	15.968%	49.556%	12.330%	19.368%
2012	16.224%	49.147%	12.482%	19.220%
2018	15.693%	50.274%	12.383%	18.501%

Figure 4.18: The plot of dominant land use classes in Sesimbra

A relationship between the impervious surface and population was made to see how these parameters have changed over the years as shown in Figure 4.19. From Table 4.6, there exists a positive correlation. Impervious surface increased with the rise in population.

Table 4.6: Correlation matrix between imperviousness, and population.

	Imperviousness	Population
Imperviousness	1	
Population	0.93	1

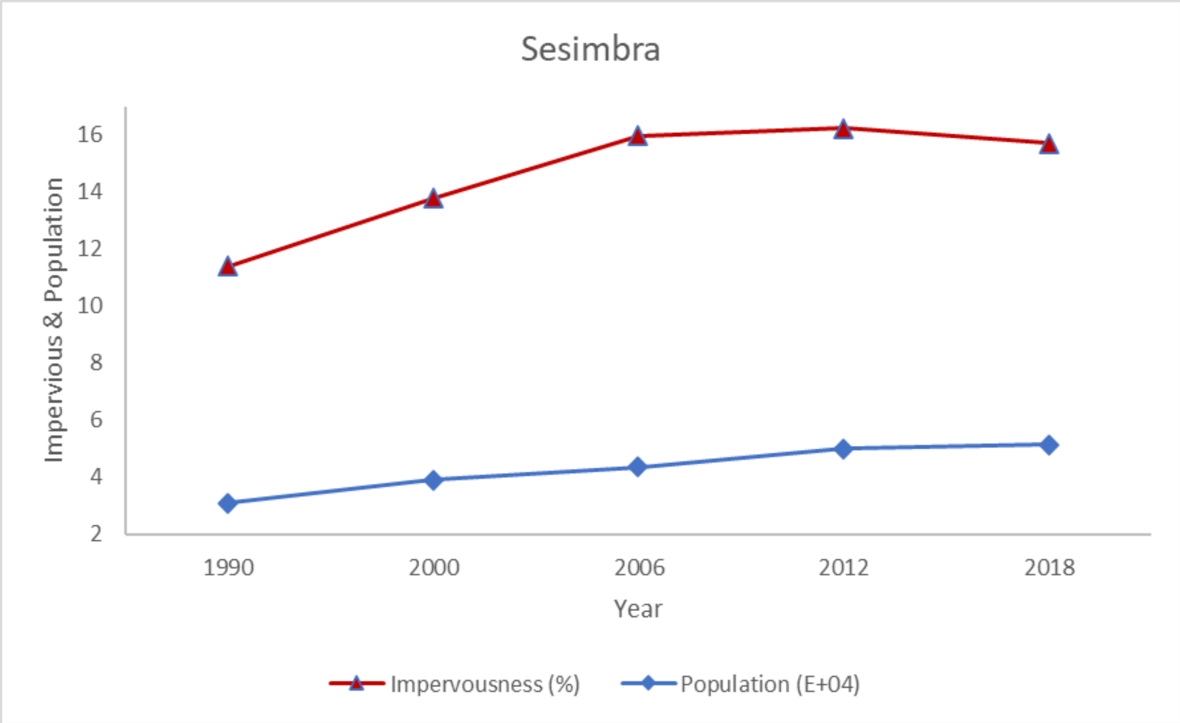


Figure 4.19: Relationship between impervious surfaces, and population.

4.2.5 SETUBAL

The total area is about 171.9km^2. The major land use that significantly changed in Setubal are built-up, pine, natural vegetation, and agriculture. Others are wetlands, water bodies, open built-up, orchards and permanent pastures. The built-up area increased from 12.71% in 1990 to 21.23% in 2018 while pine and agriculture reduced from 26.8% and 39.74% in 1990 to 22.6% and 35.7% in 2018, respectively. The built-up area really concentrated in one part of the study area. Relatively, the agriculture and pine take the greater percentage of the area and with significant area occupied by natural vegetation, which has remained fairly the same at an average of 11.21%, groundwater recharge is still expected to be at a substantial quantity. There may be a risk of water quality because of agricultural practices. Figure 4.20 shows the evolution of the land use for the years and Figure 4.21 shows the plot of the percentage change in the dominant land use classes.

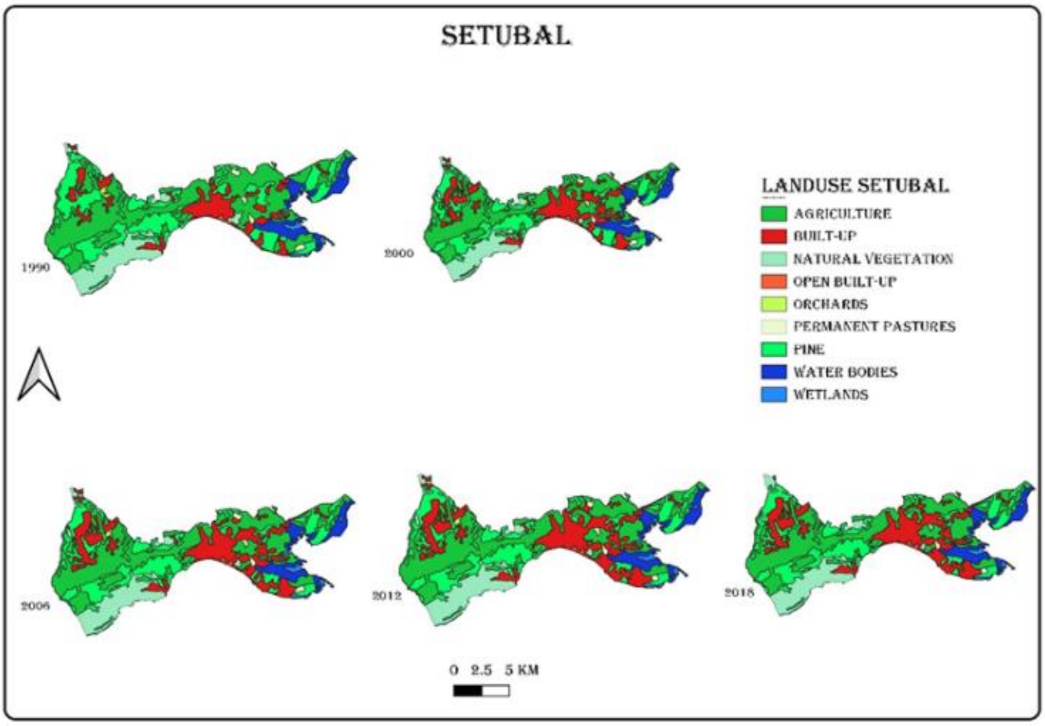
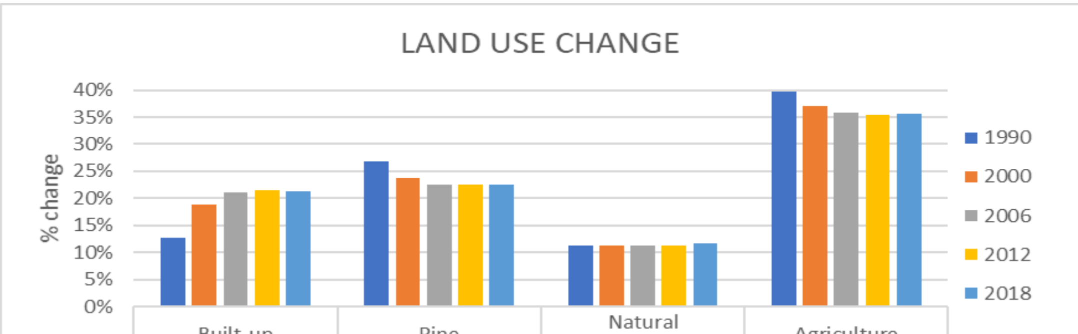


Figure 4.20: Land use change of Setubal



	Built-up	Pine	Natural Vegetation	Agriculture
1990	12.71%	26.80%	11.28%	39.74%
2000	18.90%	23.70%	11.17%	37.00%
2006	21.03%	22.58%	11.17%	35.82%
2012	21.58%	22.46%	11.21%	35.49%
2018	21.23%	22.60%	11.71%	35.70%

Figure 4.21: Plot of the dominant land use classes

A relationship between the impervious surface, and population was made to see how these factors have changed over the years (Figure 4.22). From Table 4.7, there exists a positive correlation between the three. Impervious surface increased as population grows.

Table 4.7: Correlation matrix between imperviousness, and population.

	Imperviousness	Population
Imperviousness	1	
Population	0.958	1

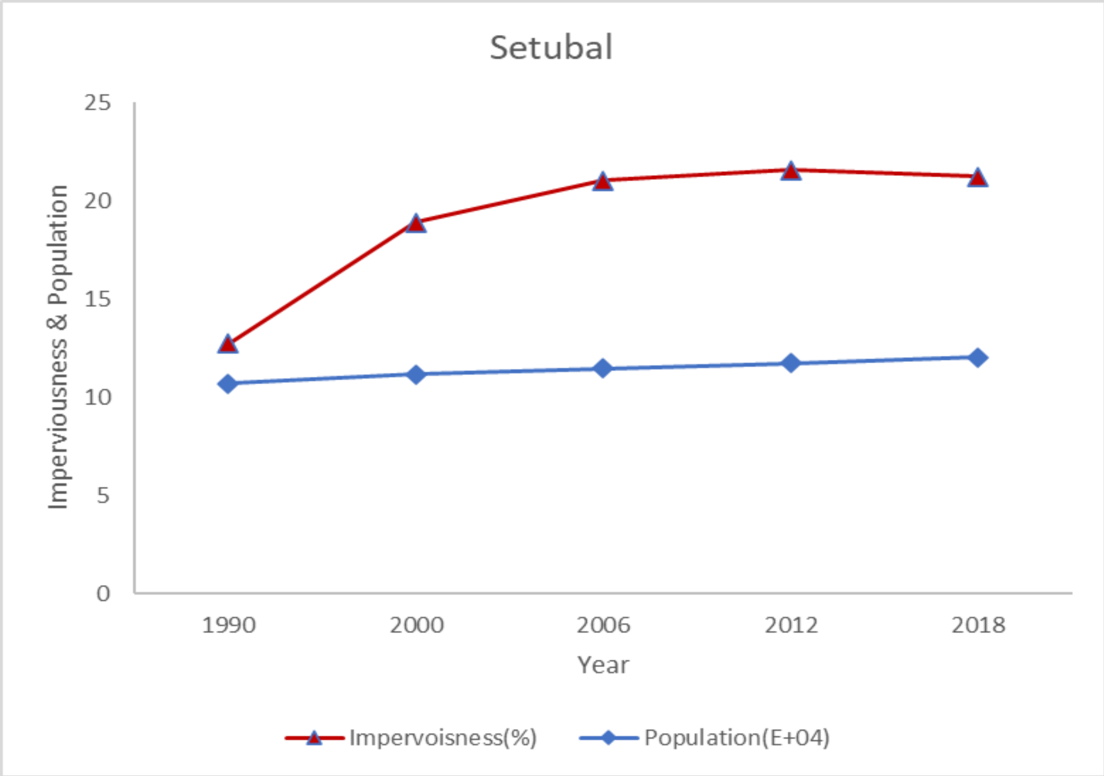


Figure 4.22: Relationship between impervious surfaces, and population.

4.3 RECHARGE ESTIMATION AND WATER BALANCE

In this section, the results of the water balance from WetSpass-M are presented. Two scenarios were assessed in this section. The first is the change in water balance from 1990 to 2018 and the spatial recharge estimation with the delineation of major recharge zones under a varying climates and land use. The second is the impact of land-use change on recharge assuming that the climate variables are fixed.

4.3.1 IMPACTS OF LAND USE AND CLIMATE ON WATER BALANCE

4.3.1.1 SPATIAL VARIABLES

Before presenting the results of the analysis and the water balance, it is important to present the input data for WetSpass-M and the process of calibration. For the meteorological data, the spatial variations of these variables were used to create a map for the model. Three meteorological stations were found within the study area as explained in the previous chapter. The stations are in Almada, Setubal, and Palmela as shown in Figure 4.23.

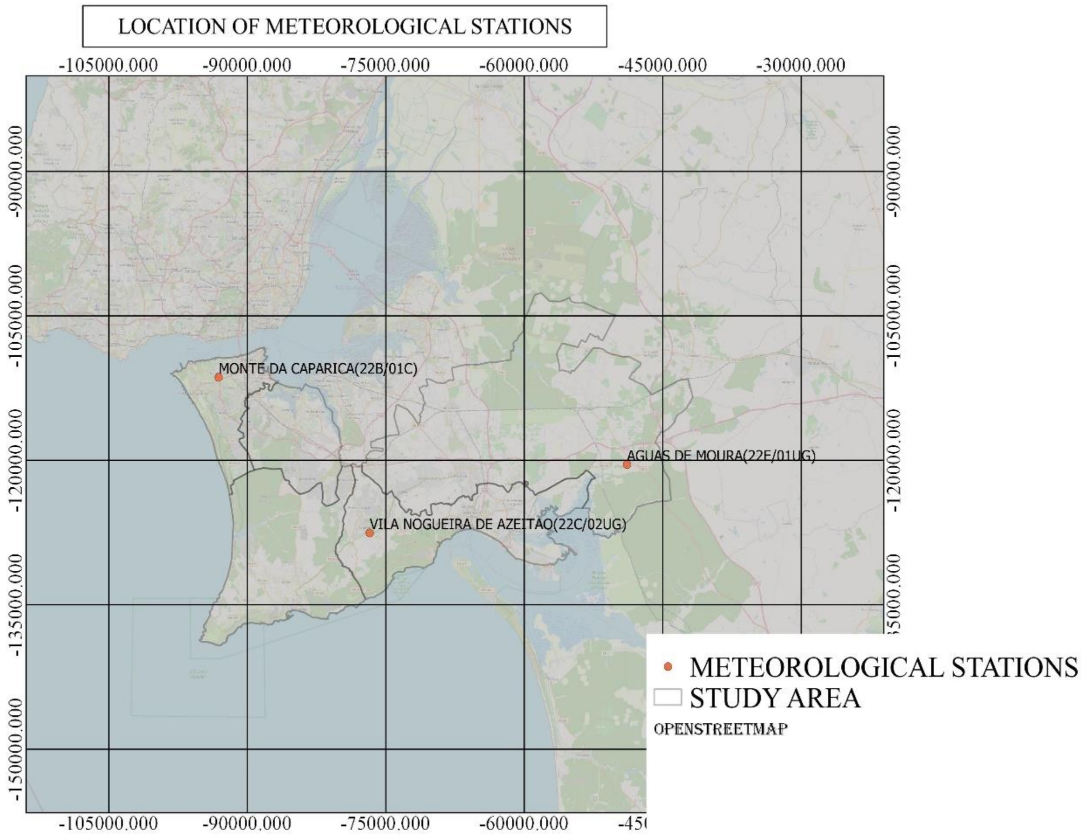


Figure 4.23: Location of the meteorological stations

The meteorological data needed for this analysis are wind speed, temperature, potential evapotranspiration, and precipitation. Windspeed and precipitation had a spatial variation as values were recorded in the three stations. Estimated potential evapotranspiration (Penman-Monteith) was a point data that was assumed to be the same in the study area.

In 1990 (Figure 4.24), precipitation had a little variation in the study area. The value in Almada (Northwest) was lower than in other part of the area. The highest value of precipitation was recorded in the meteorological station at Palmela (Northeast). This would affect the spatial water balance. Windspeed varies significantly in the study area. The wind speed increased from the east to the west. All these have implications on the spatial water balance of the area.

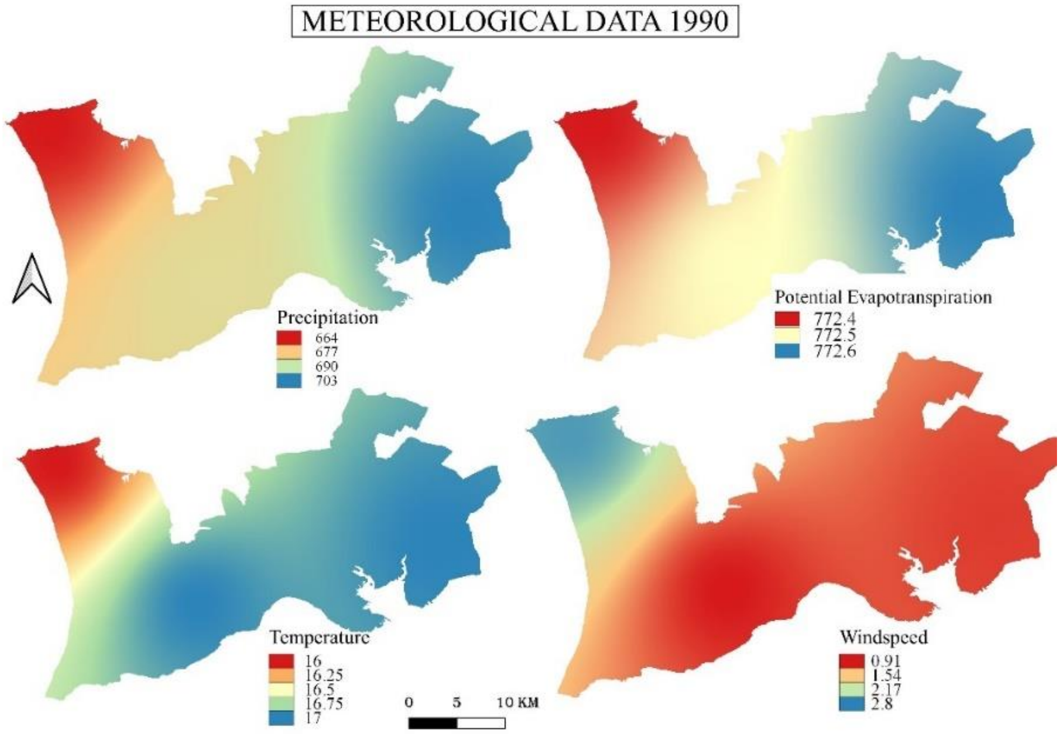


Figure 4.24: Spatial variation of meteorological data in 1990

In 2000 (Figure 4.25), the spatial variation of precipitation was the same with that of 1990 decreasing from the east to the west. The spatial variation of windspeed in 2000 is different from that of 1990. The windspeed increased from the west to the east. The potential evapotranspiration of 2000 was less than that estimated in 1990 by 12.4%. The temperature in both years remain at the same range.

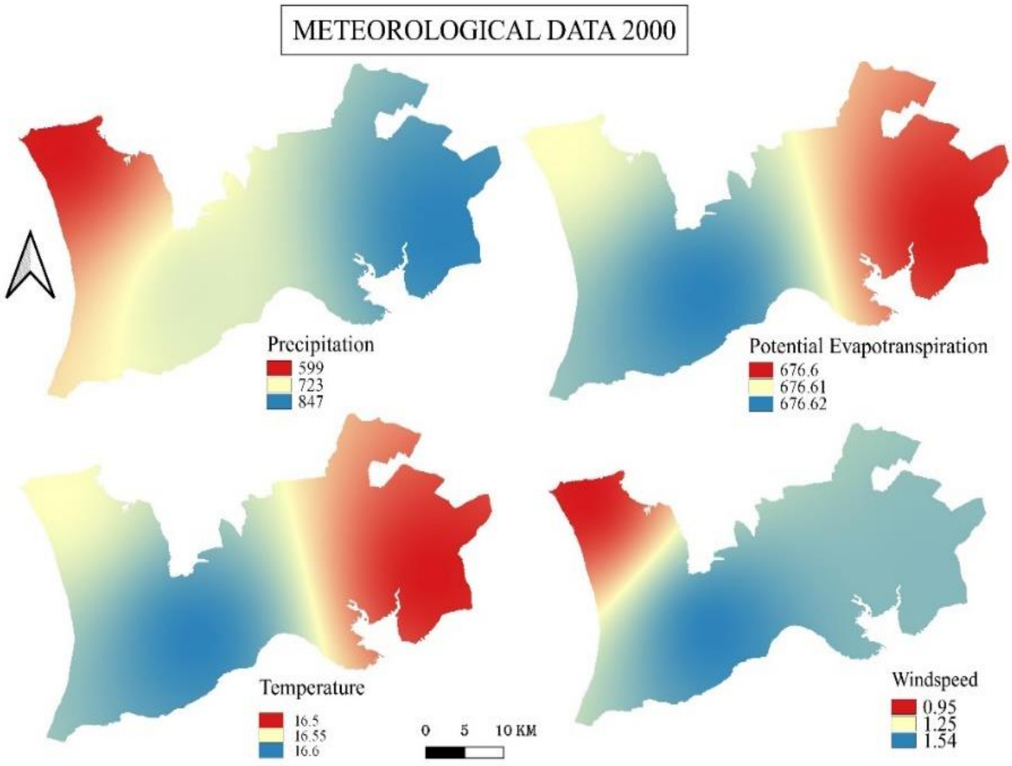


Figure 4.25: Spatial variation of meteorological data in 2000

The spatial variation of precipitation in 2006 (Figure 4.26) opposed that observed in 1990 and 2000. The precipitation reduced from west to east. The estimated potential evapotranspiration reduced by 3.3% from 2000 to 2006. The spatial variation of wind also shows that wind speed increased from east to west.

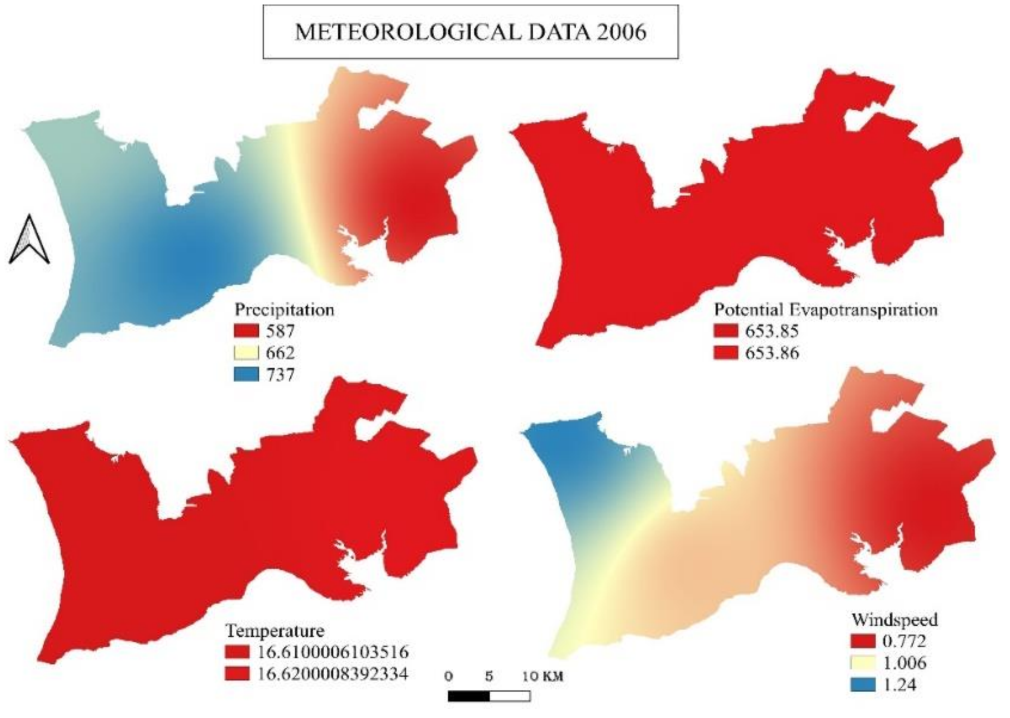


Figure 4.26: Spatial variation of meteorological data in 2006

2012 and 2018 (Figure 4.27 and Figure 4.28) had a peculiar value of precipitation. The precipitation registered in these years is dramatically smaller compared to the other years. The average precipitation in 2012 and 2018 are smaller by 56.3% and 57.3% respectively of the value recorded in 2006. This high variation in precipitation was confirmed by checking the observed values in close meteorological stations to the study area. The values were also compared to the observed values for close years like 2011, 2013, 2014 and 2019. From the two sources, the precipitation values are in a similar range. The values were also validated by the observed precipitation data for those years on the Portuguese Institute of the Sea and Atmosphere database (ipma.pt) and the values are in the same range.

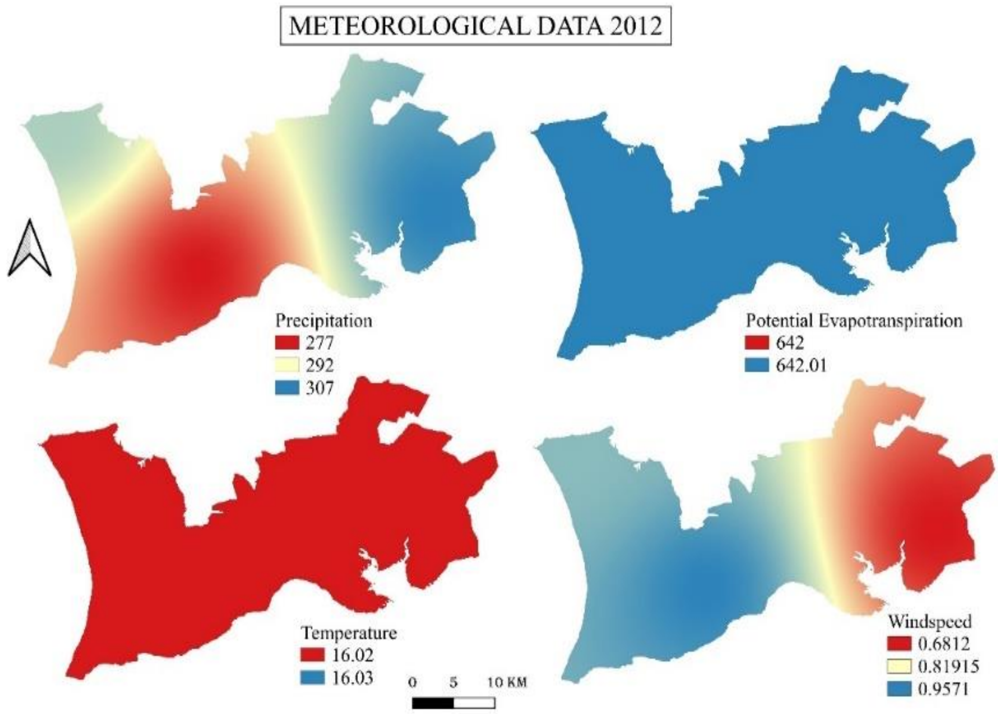


Figure 4.27: Spatial variation of meteorological data in 2012

There was generally lower precipitation in those years in the study area. Estimated potential evapotranspiration is also diminished by 1.8% and 3.5% respectively with respect to that estimated in 2006. Also, the temperature remains generally in the same range and on the average, the windspeed increased from the east to the west.

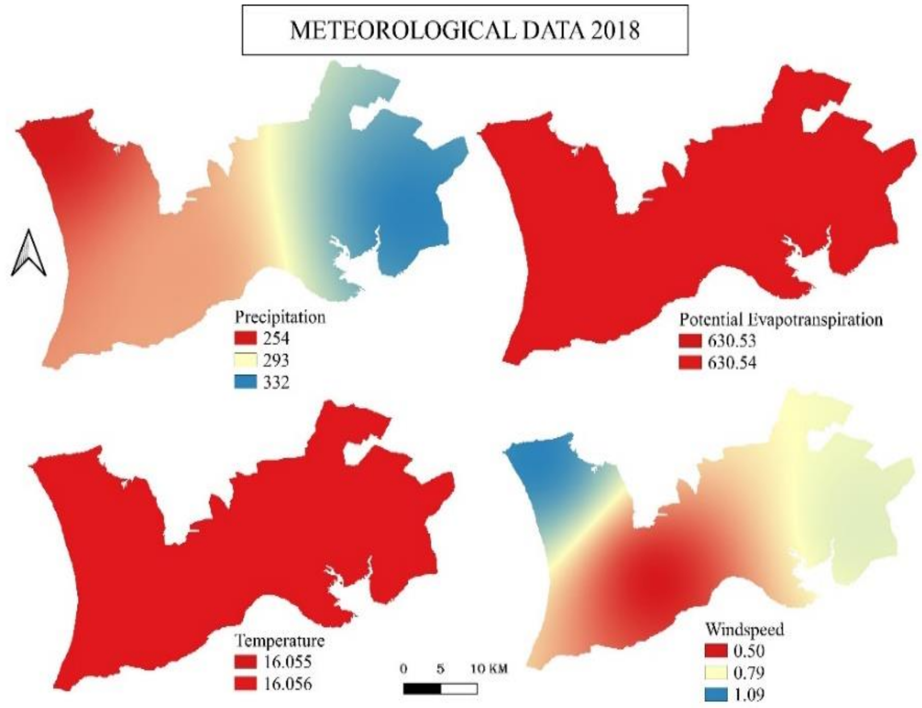


Figure 4.28: Spatial variation of meteorological data in 2018

The spatial variations in all these meteorological parameters had a very significant impact on the spatial water balance. For example, where there is higher precipitation and higher potential evapotranspiration, it is expected that the actual evapotranspiration would be higher. Also, windspeed always has a direct impact on surface runoff and actual evapotranspiration (Zhang et al., 2016). Table 4.8 shows the climate data from each meteorological station.

Table 4.8: Table showing the meteorological data at the stations.

	Windspeed(m/s)			**Precipitation(mm)**			**Average Temp(^{0}C)**	**PET (mm)**
Year	VILA NOGUEIRA DE AZEITAO (22C/02UG)	ÁGUAS DE MOURA (22E/01UG)	MONTE DA CAPARICA (22B/01C)	VILA NOGUEIRA DE AZEITAO (22C/02UG)	ÁGUAS DE MOURA (22E/01UG)	MONTE DA CAPARICA (22B/01C)	VILA NOGUEIRA DE AZEITAO (22C/02UG)	VILA NOGUEIRA DE AZEITAO (22C/02UG)
1990	2.66	0.91	1.04	684.10	703.90	664.90	17.25	772.63
2000	1.54	1.42	0.96	598.69	847.20	743.00	16.60	676.62
2006	1.25	0.77	0.94	694.40	587.00	737.80	16.62	653.86
2012	0.90	0.68	0.96	298.31	306.97	276.90	16.02	642.02
2018	1.10	0.84	0.50	253.65	331.80	276.90	16.06	630.55

The other variables used for this work are elevation, slope, land use, groundwater depth, and soil texture. Land use and groundwater depth changed over the years, but the elevation, slope, and soil texture remained constant. The land use classes had been discussed explicitly earlier. And the topography had been explained in section 2.1.

The groundwater depth in each monitoring stations were averaged for each reference year (1990,2000,2006,2012, and 2018). For this analysis, fourteen (14) wells with depth less than 16m were used. Generally, the shallowest groundwater in the study area is about 8m deep. Figure 4.29 shows both the temporal and spatial variation of groundwater depth in the study area.

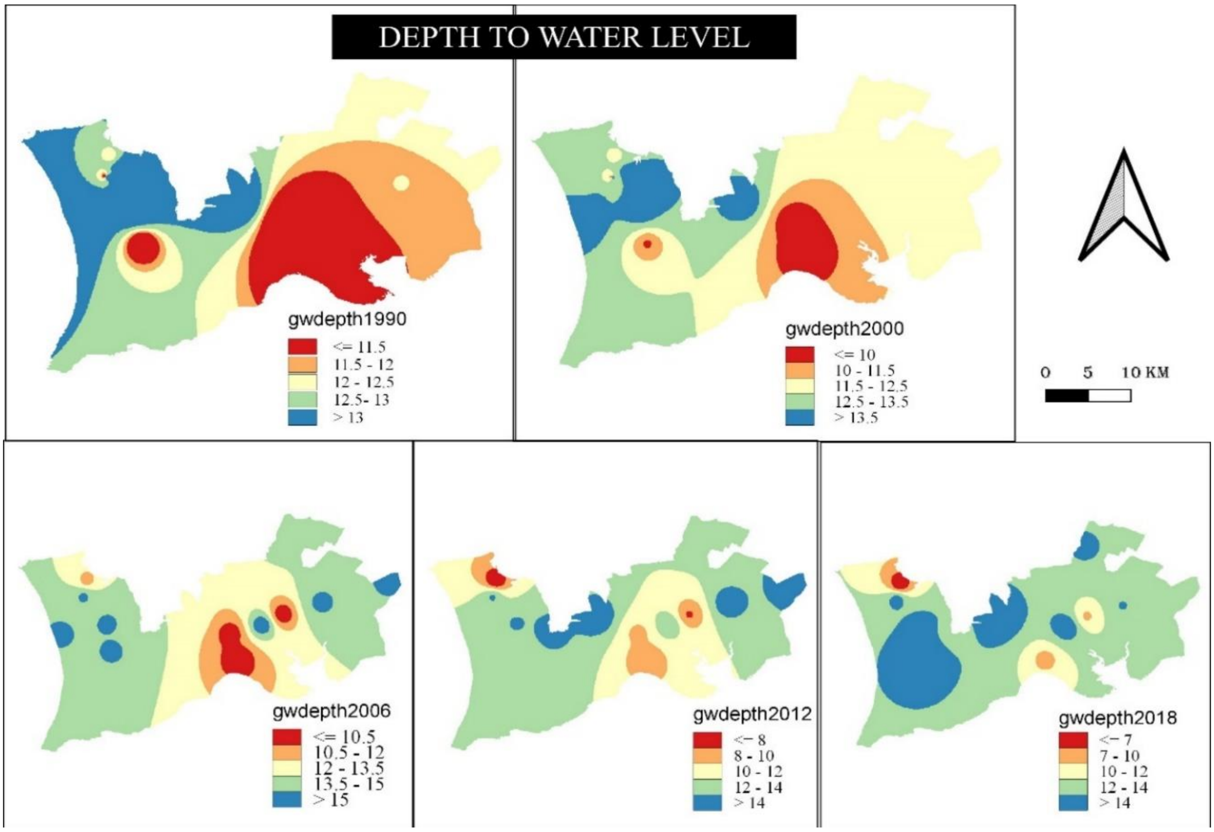


Figure 4.29: Spatial variation of groundwater depth (in meters) for the reference years

The reclassified soil map of Portugal (Figure 4.30) showed that there are five soil classes in the study area. The classification was correlated with the soil classes of INFOSOLO and some of the soil properties of the soils were extracted from INFOSOLO website. Five soil texture classes were identified within the study area. The five classes were converted to the input format for WetSpass-M.

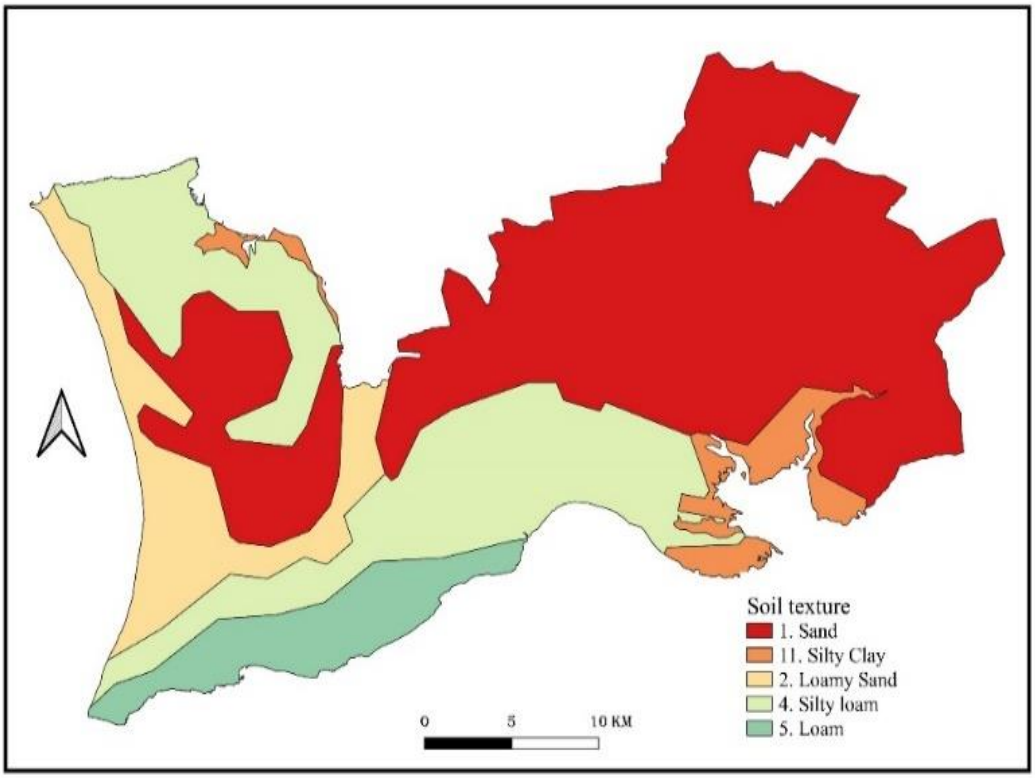


Figure 4.30:Soil texture of the study area with the corresponding WetSpass-M codes

The soil texture in the region of Palmela is Sand and this has a very high implication on downward movement of water because of the larger pore spaces and interconnectivity of grains. Since, the area is majorly used for agriculture, the irrigated water is expected to move downward fast as recharge. This would create a risk of groundwater pollution. The southern part of the area where the land use is predominantly natural vegetation has a soil texture of Loam. Loam generally has a high-water retention capacity and considerably moderate infiltration rates, and this could enhance groundwater recharge. Other soil textures in other regions include Silty Clay, Silty Loam and Loamy Sand. All these soil types have implication on runoff and infiltration, and ultimately on groundwater recharge.

4.3.1.2 SENSITIVITY ANALYSIS

To better understand the results from WetSpass-M, sensitivity analysis was done to know the response of the model to each parameter. Some parameters are fixed for the model, for example, the meteorological data. They cannot be changed since they are observed values, but they have effect on the output. The higher the rainfall and lower the potential evapotranspiration, the higher the runoff and recharge. Table 4.9 shows the parameters used for sensitivity analysis and the results they significantly affected. Ultimately, the effects of a parameter on one of the hydrological components is felt on other components. The table only marks the components that were more affected by the change of each parameter. The soil characteristics are many key factors of the soil like the wilting point, filed capacity, available water etc. Changing these parameters affect the result of recharge and runoff.

Table 4.9: Model parameters and their effects on output variables

Parameters	Runoff	Actual Evapotranspiration	Recharge
Soil Characteristics	✓		✓
Land Characteristics	✓	✓	✓
Groundwater depth			
RainyDaysPerMonth	✓	✓	✓
"a" Interception	✓	✓	✓
Alfa coefficient		✓	
LP coefficient	✓		✓
Average Intensity	✓		✓
Slope Factor	✓	✓	✓
Land Factor	✓	✓	✓
Soil Factor	✓	✓	✓

The land characteristics show the different factors of the land use types. These include the bare soil fraction, vegetated fraction, impervious fraction, leaf area index etc. Changing these parameters affect the result of the model. For example, vegetated land would lead to less runoff than bare land.

To check the effects of depth to water level on the result of the model, raster maps of groundwater depth of 5 and 10m were used to run the model. Both produced the same result as that produced by the annual average value of the piezometers located within the study area. This could be since the water level was not shallow enough to intersect with the plant roots. For this, piezometers with measurement of depth to water level of less than 16m was averaged over each year and interpolated to create the input maps.

The number of rainy days per month influences the result. For example, if rain falls consistently over a concentrated period within the year, it causes more runoff because the rain does not have time to infiltrate. With a more spaced rainy days, there can be a higher chance of infiltration and evaporation.

The interception is one of the model's global parameters of the model which are basically used for calibration. It has a very high effect on runoff and evapotranspiration (and the interception result if needed).

The alfa coefficient plays a major influence in evapotranspiration. Generally, the higher the value, the higher the evapotranspiration.

LP coefficient determines the soil moisture content. The runoff and recharge are very sensitive to this parameter.

Average intensity is about the rain intensity. This parameter affects surface runoff and recharge. According to IPMA, the average rain intensity in Portugal is 2 – 6mm.The soil, land and slope factors are the local parameters of WetSpass-M which are changed for calibration. For example, because land use changed over the years, it was given a high factor as a driver of water balance.

4.3.1.3 CALIBRATION

The model was calibrated using the value of actual evapotranspiration and recharge. The process entailed changing each key parameter until the reference value of actual evapotranspiration and recharged were attained. The calibration was done for 1990 and validated for other years. Due to the peculiarity of the precipitation observed in 2012 and 2018, the calibration parameters were different. It is important to note that calibrating the model was a little difficult because of the differences in all the meteorological parameters from year to year. The value of the actual evapotranspiration for 1990 was calibrated taking the values reported in Agência Portuguesa do Ambiente (2012) to be an average of 460mm/year and the recharge was validated with values reported in Ribeiro & da Cunha (2010) to be between 11-20% of the total precipitation.

These values are average values and were used as the reference for the calibration of the model and this does not imply that the exact values must be attained for the calibration. The calibrated parameters in 1990 were used for other years and the results were reliable.

The calibrated land use and soil table will be presented in the appendix later in this report. The calibrated global and local parameters of the model area presented in Table 4.10

Table 4.10: Calibrated parameters for WetSpass-M

Year	Slope	Land	Soil	a	alfa	Intensity	LP
1990-2018	0.2	0.4	0.4	5	2.5	1	0.95

To reach an optimum value, the soil was calibrated with a very high moisture with a factor of 0.95. This really helped to reduce surface runoff and increase the aquifer recharge. The long-term average value of the rain intensity reported by IPMA was taken into consideration but for the calibration of this model, an intensity of 1mm/hr produced the best result and was taken as the calibrated rain intensity.

4.3.1.4 WATER BALANCE

After the calibration of the model, the water balance for each year was calculated using the four hydrological components. The water balance is driven majorly by precipitation and partitioned into other components depending on the temperature, soil condition, land use, slope, windspeed and other factors. Table 4.11 shows the change in water balance for the years under evaluation. It is important to note the values below represent the average values from the spatial maps generated by WetSpass-M. The spatial variation is driven by the spatial variation of all input variables. From Table 4.11, the average recharge in 1990 was twice higher than that of 2000. This shows a very significant difference in recharge between the two years. The recharge for the last two years was lower than others. This was not far expected as the precipitation in those two years was very low.

Table 4.11: Water balance under land use and climate

Year	AET	Runoff	Recharge	Total	%Recharge	Average Precipitation
1990	402	141	140	683	20	684
2000	487	213	68	768	9	730
2006	465	156	76	697	11	673
2012	110	131	62	303	20	294
2018	108	133	60	301	20	287

To explain the relationship between the climate variables and the hydrological components, a spatial correlation matrix for each year was made with all the raster maps

(Table 4.12 to Table 4.16). From the correlation matrices, there was no significant correlation between the hydrological components and some of the meteorological data. For example, in 1990, there was no clear correlation between the spatial variation of some of the components. From all the matrices, there seems to exist a significant positive correlation between windspeed and actual evapotranspiration.

But it should be noted that there was a correlation between runoff, recharge, and actual evapotranspiration. For instance, there was always a negative correlation between runoff, actual evapotranspiration, and recharge. This was not far expected as the increase in one of the components leads to a corresponding decrease in the others.

Table 4.12: The correlation matrix of 1990 parameters

1990	AET	Precipitation	Recharge	Runoff	Temp	Wind
AET	1.00	-0.00	-0.04	-0.65	0.07	-0.08
Precipitation	-0.00	1.00	0.44	-0.20	0.83	-0.77
Recharge	-0.04	0.44	1.00	-0.56	0.36	-0.34
Runoff	-0.65	-0.20	-0.58	1.00	-0.23	0.22
Temp	0.07	0.88	0.36	-0.23	1.00	-0.99
Wind	-0.08	-0.77	-0.34	0.22	-0.99	1.00

Table 4.13: Correlation matrix of 2000 parameters

2000	AET	Precipitation	Recharge	Runoff	Temp	Wind
AET	1.00	0.34	-0.19	-0.58	0.03	0.46
Precipitation	0.34	1.00	0.31	0.09	-0.63	0.69
Recharge	-0.19	0.31	1.00	-0.36	-0.47	-0.04
Runoff	-0.58	0.09	-0.36	1.00	-0.05	0.06
Temp	0.03	-0.63	-0.47	-0.05	1.00	0.13
Wind	0.46	0.69	-0.04	0.06	0.13	1.00

Table 4.14:Correlation matrix of 2006 parameters

2006	AET	Precipitation	Recharge	Runoff	Temp	Wind
AET	1.00	0.57	-0.55	-0.27	-0.56	0.41
Precipitation	0.57	1.00	-0.64	0.39	-0.98	0.71
Recharge	-0.55	-0.64	1.00	-0.58	0.67	-0.59
Runoff	-0.27	0.39	-0.56	1.00	-0.43	0.45
Temp	-0.56	-0.98	0.67	-0.43	1.00	-0.83
Wind	0.41	0.71	-0.59	0.45	-0.83	1.00

Table 4.15: Correlation matrix of 2012 parameters

2012	AET	Precipitation	Recharge	Runoff	Temp	Wind
AET	1.00	-0.01	-0.28	0.08	nan	0.05
Precipitation	-0.01	1.00	0.18	0.12	nan	-0.93
Recharge	-0.28	0.18	1.00	-0.88	nan	-0.31

Runoff	0.08	0.12	-0.88	1.00	nan	0.01
Temp	nan	nan	nan	nan	nan	nan
Wind	0.05	-0.93	-0.31	0.01	nan	1.00

Table 4.16: Correlation matrix of 2018 parameters

2018	AET	Precipitation	Recharge	Runoff	Temp	Wind
AET	1.00	0.05	-0.23	0.06	nan	0.02
Precipitation	0.05	1.00	0.30	0.25	nan	0.10
Recharge	-0.23	0.30	1.00	-0.76	nan	-0.12
Runoff	0.06	0.25	-0.76	1.00	nan	0.21
Temp	nan	nan	nan	nan	nan	nan
Wind	0.02	0.10	-0.12	0.21	nan	1.00

From the correlation matrices, it was discovered that the meteorological parameters did not play the major role in the spatial variation of these hydrological components. The major drivers of spatial variation are runoff, actual evapotranspiration, and recharge, apart from precipitation, which was the component to be partitioned, was land use and soil texture. For example, runoff is expected to be higher in impervious surfaces and evapotranspiration should be higher in forested areas.

This land use and soil will also be the major driver in groundwater pollution. For example, the agricultural areas will have more recharge because of the soil type and irrigation activities. This also exposes the groundwater to pollution in these areas due to the application of fertilizers.

4.3.1.5 WATER BALANCE ERROR

The average water balance error of the study area was created to see how the variation of the land use and climatic components of the study area could cause a spatial imbalance in water balance. Figure 4.31 shows the water balance error map.

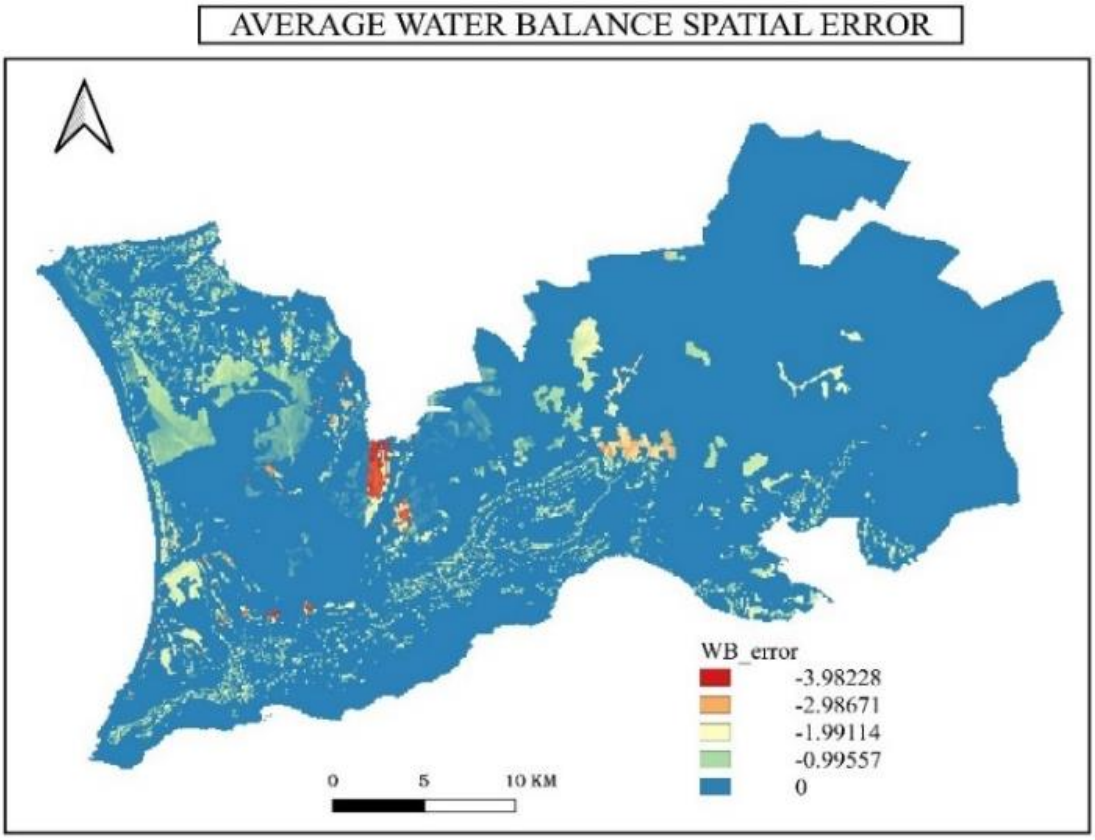


Figure 4.31: Spatial water balance error

The result shows that the model gave a very accurate estimation of water balance in most parts of the study area. The imbalance as shown in Figure 4.31 was mostly in built-up areas, but the values were very small (< 4mm). This could be due to high runoff in many built up areas. But generally, the model result is at an acceptable range and the error is minimal.

4.3.1.6 SPATIAL AND TEMPORAL VARIATION OF HYDROLOGICAL COMPONENTS

The spatial and temporal variation of the hydrological components was assessed for the years under consideration. This was done by finding the difference in the raster maps for successive years. The results of the main components have been presented below.

4.3.1.6.1 RUNOFF

Generally, the change in the water balance components from year to year can be attributed to land use, precipitation, number of rainy days per month and the rain intensity. For example, if the rainfall concentrates within a particular month and days, it causes much runoff especially when the intensity is high. But steady and spread rainfall can enhance recharge and evapotranspiration. The spatial change in runoff, though not following a consistent trend, can be seen to increase from 1990 to 2006 in the built-up areas. There was high spatial runoff in 2012 and 2018 though those years had a lower precipitation. The reason for the high runoff variation is the rainfall intensity and the number of rainy days per month. The rainfall was concentrated in some months leading to higher runoff. Figure 4.32 shows the evolution of the difference in runoff between two reference years.

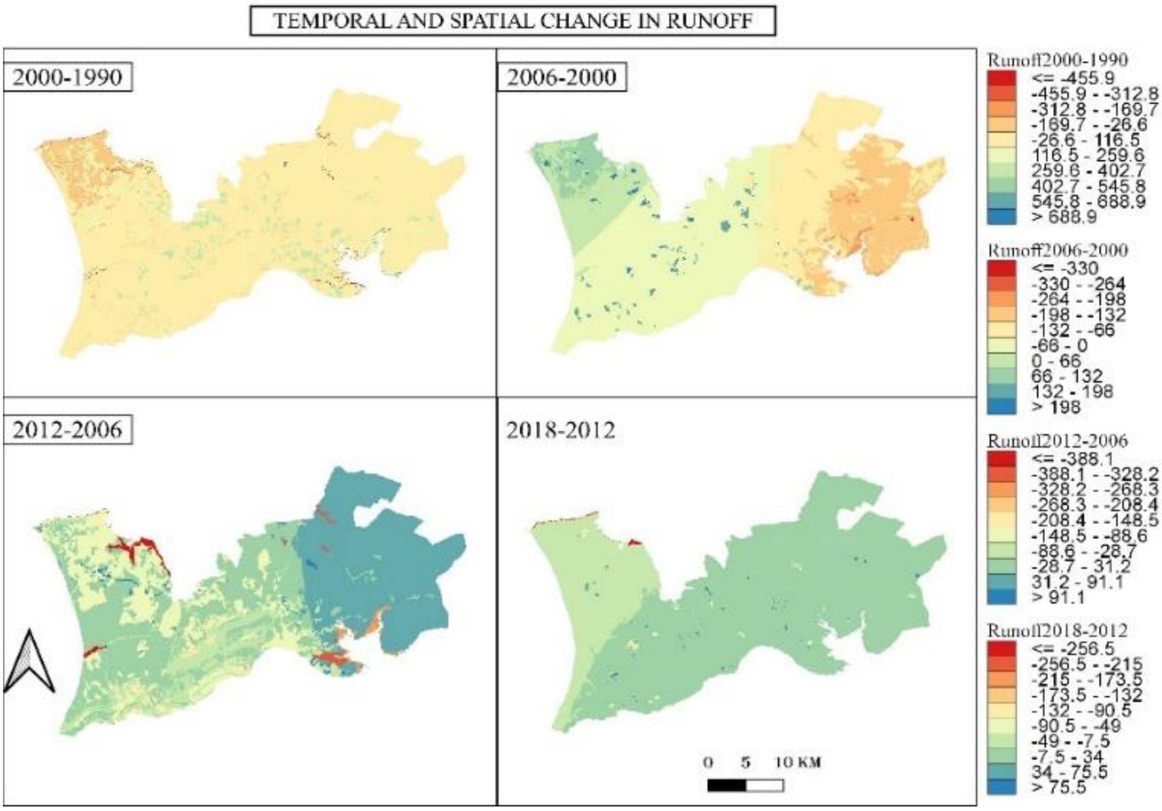


Figure 4.32: Spatial and temporal change in runoff

4.3.1.6.2 ACTUAL EVAPOTRANSPIRATION

Spatial evapotranspiration was specifically driven by the windspeed. The areas with lower windspeed tend to have a lower actual evapotranspiration. From the figure below, between 1990 and 2000, there existed a strong reverse in windspeed variation. The northwestern part of the study area (Almada) had a higher evapotranspiration in 1990 due to a very high windspeed. Both the other parts had a relatively lower evapotranspiration in 1990. The reverse was the case in 2000 with higher evapotranspiration in other regions but lower in the northern part where there existed a lower windspeed. This trend was found in other years. From the map, there was a strong correlation between windspeed and evapotranspiration. Figure 4.33 shows the evolution of the difference in AET between two reference years.

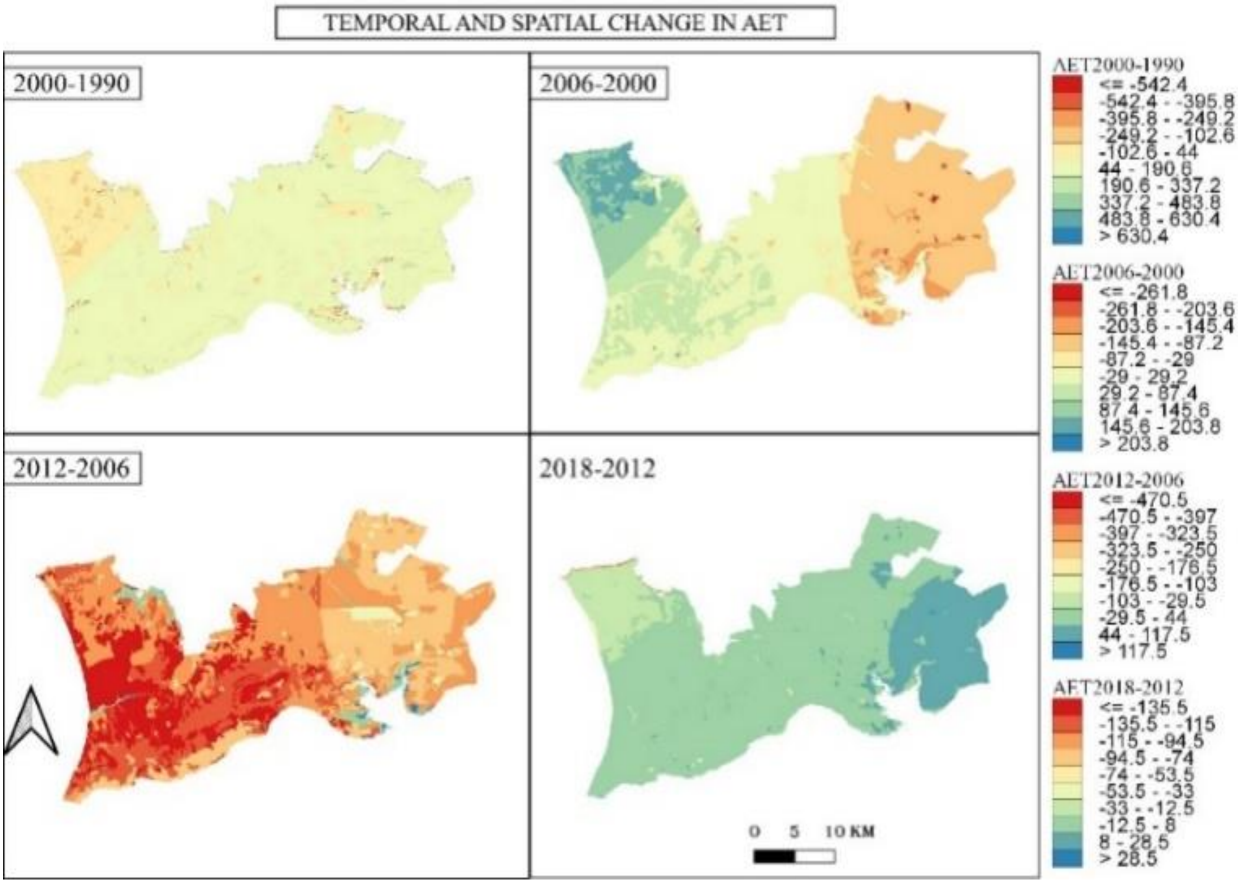


Figure 4.33: Spatial and temporal variation of actual evapotranspiration

4.3.1.6.3 RECHARGE

For the groundwater resource management, recharge is the main component of concern. This is because for the replenishment of groundwater resource, recharge must be enhanced. The increase in other hydrological components especially runoff and actual evapotranspiration have significant effect on the quantity of recharge. In 2000, there was a lower recharge which could be attributed to the high actual evapotranspiration and runoff due to a drastic increase of impervious surface and strong variation in windspeed. Figure 4.34 shows the evolution of the difference in recharge between two reference years.

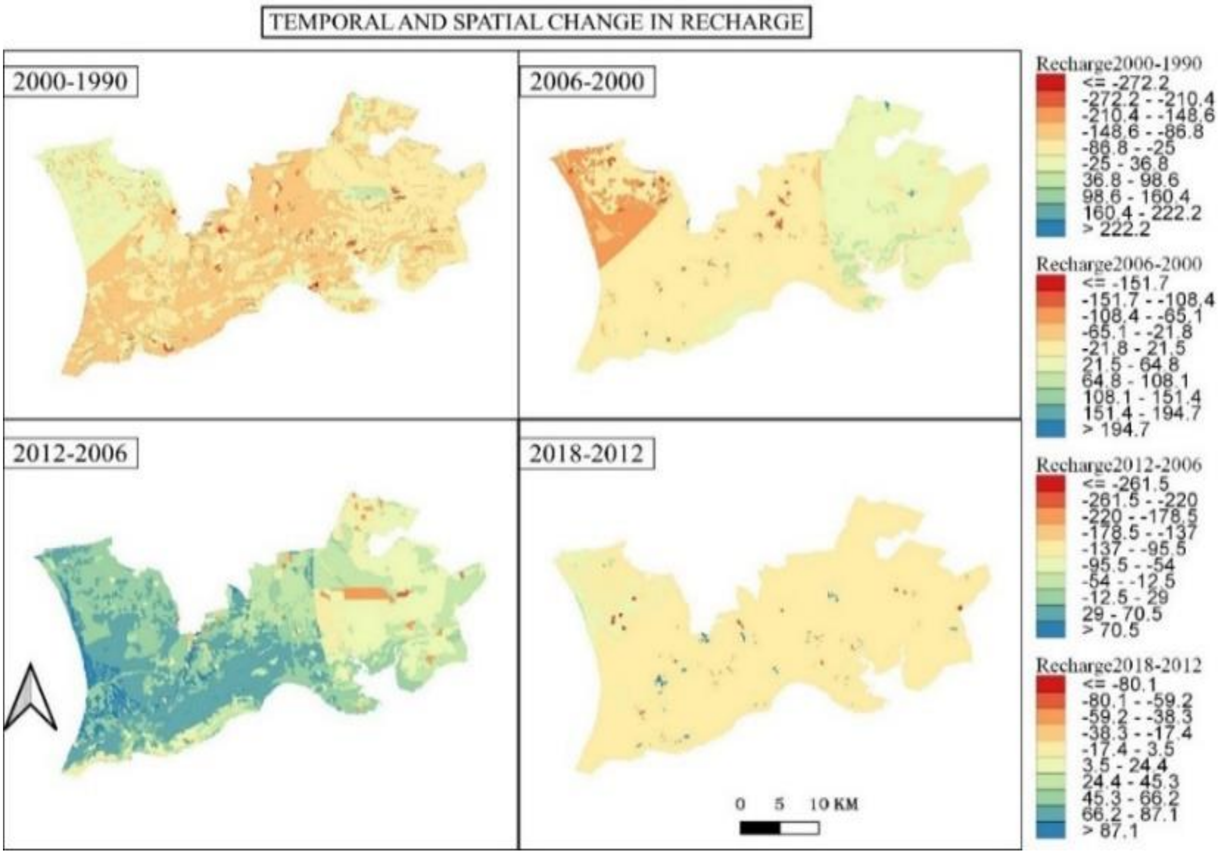


Figure 4.34: Spatial and temporal variation of recharge

4.3.2 IMPACTS OF LAND USE CHANGE ON WATER BALANCE

The same model setup was used as explained in section 4.3.1. The distinction is the assessment of the impact of land use only without considering the variation in climate. For this, the average of the climate data from 1990 to 2020 was used and assumed to be constant for all the land use years. Table 4.17 shows the climate variables and the average values used for creating the raster maps for this analysis.

Table 4.17: Average values of climate data

Variables	Value	Unit
Wind	1.3	m/s
Temperature	16	^{0}C
PET	675	mm/yr.
Rain	586	mm/yr.

The model was calibrated as explained in section 3.4.3. Table 4.18 shows the water balance and evolution of recharge.

Table 4.18: Water balance under changing land use

Year	Recharge	AET	Runoff	%Recharge
1990	106.1	354.0	125.6	18.11%
2000	105.3	349.2	135.7	17.84%
2006	104.1	347.5	138.7	17.63%
2012	104.1	347.0	139.7	17.62%
2018	105.1	345.0	132.9	18.03%

From the result, the land use has an impact on the overall recharge and water balance. The impact was more evident on runoff and actual evapotranspiration especially between 1990 and 2000. This was due to the increase of built-up areas leading to impervious surface and thereby increasing runoff. And the reduction of pine and agriculture led to reduction of actual evapotranspiration. Recharge reduced from 1990 to 2000. There was an increase in recharge between the year 2012 and 2018. This was due to the extension of the natural vegetation which served as one of the land-use types that enhances recharge. Also, the reduction of built-up area leading to lesser runoff. It should be noted that these are average values from the spatial variation of each water balance component for the whole area. If the analysis is downscaled to each municipality, there would be a more significant impact of land use. For example, there should be a very significant impact of land use on water balance in the region of Almada where built-up areas have significantly extended over the years.

The recharge map of 2018 was created to check the zones with the highest recharge. This helps to know the major recharge zones which can be protected from urbanisation and pollution. The result shows that the maximum recharge zones are in Palmela which is used for agricultural purpose. This also has implication on groundwater quality. Other area with maximum recharge is the southern part of the study area with natural vegetation. As expected, the lowest recharge occurred in built-up areas. If urbanisation continues to sprawl, the recharge will be lower leading to water scarcity in the future since the region depends on groundwater for various consumptions. Figure 4.35 shows the recharge zones in the study area from the 2018 recharge map.

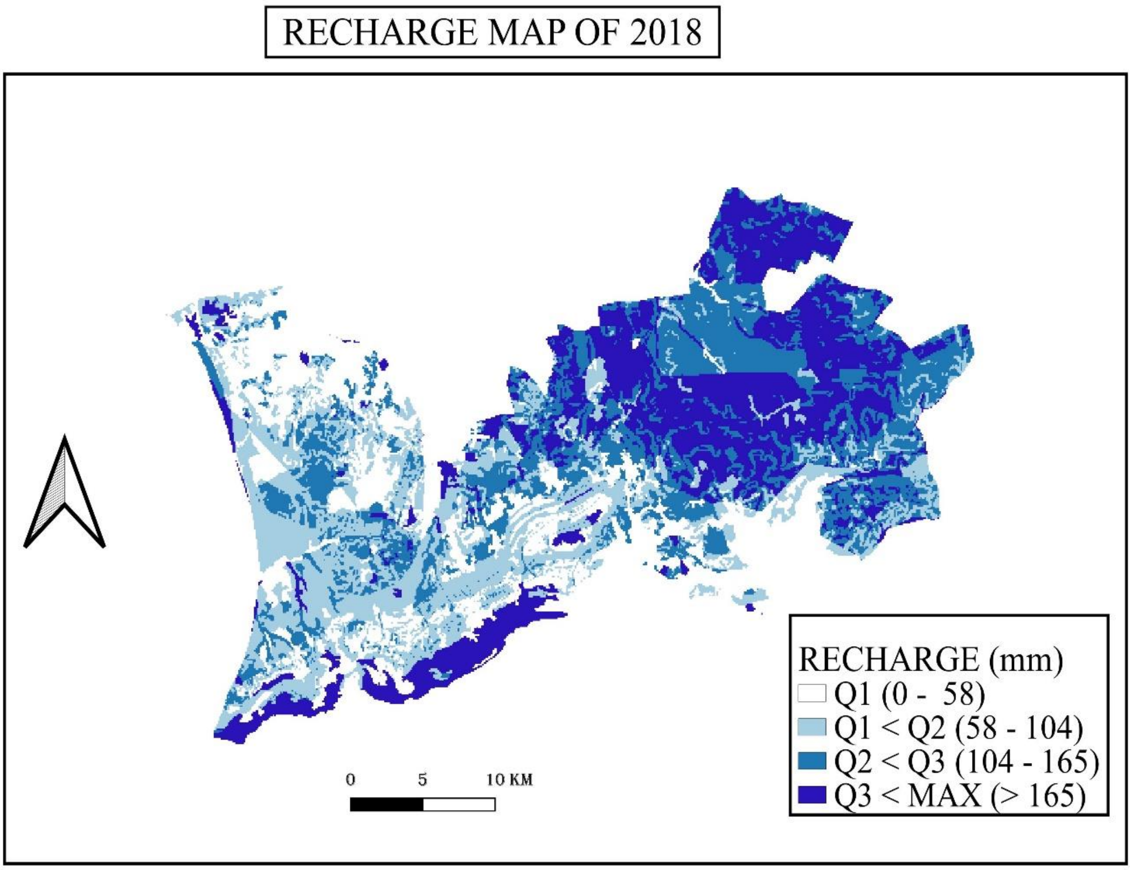


Figure 4.35: Recharge map of 2018 with the recharge zones classified in quantiles.

4.4 SPECIFIC VULNERABILITY ASSESSMENT

The vulnerability of the aquifer to pollution was assessed for the years 1990 and 2018. This was done using the susceptibility index (SI). As mentioned before, SI is a modified method of DRASTIC. The raster maps needed for this analysis are the groundwater depth, geology, recharge, topography, and land use. All these were rated according to the SI rating as described in the methodology. The geology of the area makes the aquifer very susceptible to contamination. The major hydrogeology of the area is limestone and sandstone which have high porosity (and permeability) and fast downward movement of water. The depth to water level was taken for all wells irrespective of their depths. There was a very low contamination risk based on the well depth because most of the wells are deeper than 10m. The most susceptible wells are shallow wells with depth less than 1.5m. Except for the southern part of the study area, the topography of the region is generally flat making most areas at risk of contamination. For the land use, agriculture and industrial areas pose more risk than other land use types. Since the pollution in this case comes from the surface source, the recharge will play a key role in groundwater contamination. The higher the recharge, the riskier the groundwater is to contamination. The classification of the vulnerability was done following the methodology of Stigter et al., 2005. The result for 1990 (Figure 4.36) shows that most of the study area has a moderate to high contamination risk. The most susceptible region, with very high vulnerability, is Palmela where agriculture is practiced. Because of the use of fertilizers and other chemicals, it is not far expected that the risk of contamination from agricultural areas will be high.

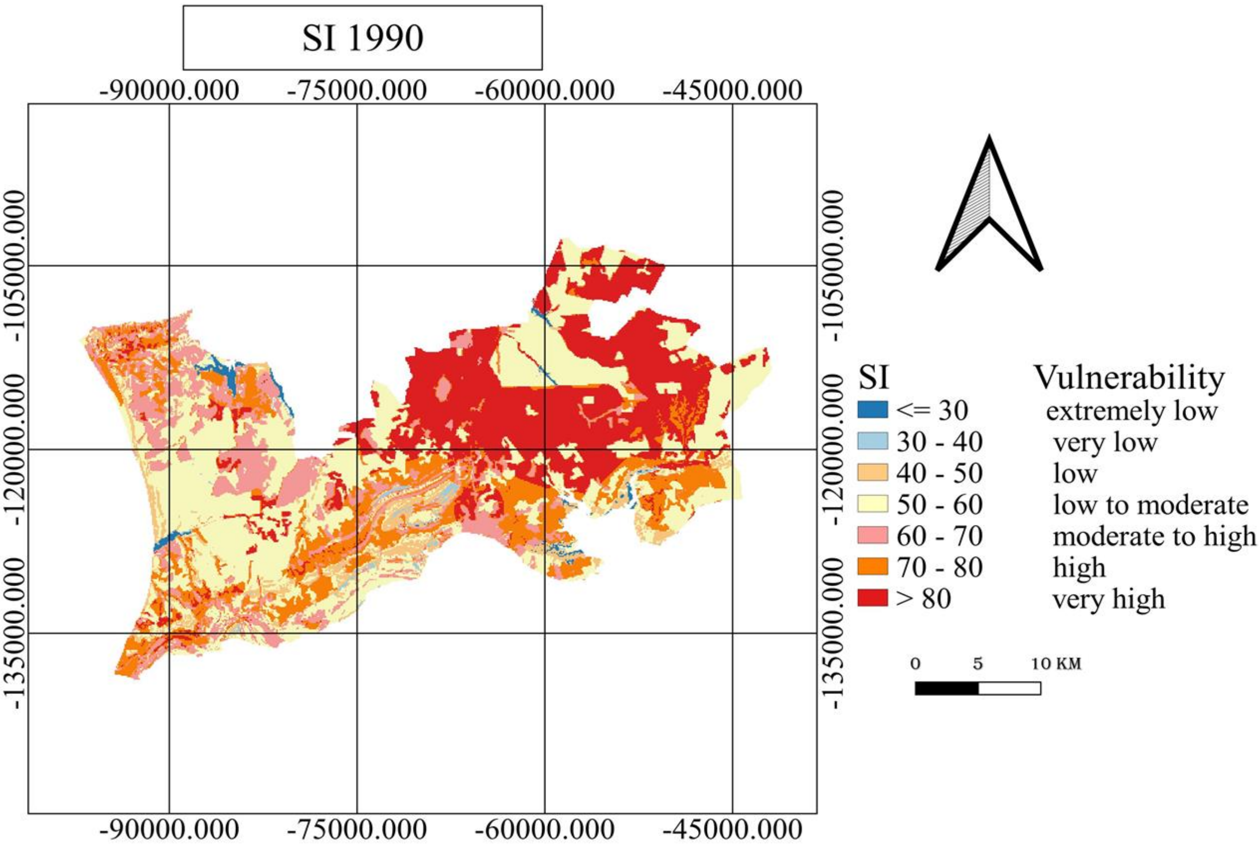


Figure 4.36: SI map of 1990

The result of 2018 (Figure 4.37) shows a lower risk of contamination as compared to 1990. This is because the recharge in 2018 was lower than 1990. Since the major variables that changed are the land use, groundwater depth and recharge, the reduction of recharge and agricultural areas led to a less susceptibility of groundwater to pollution.

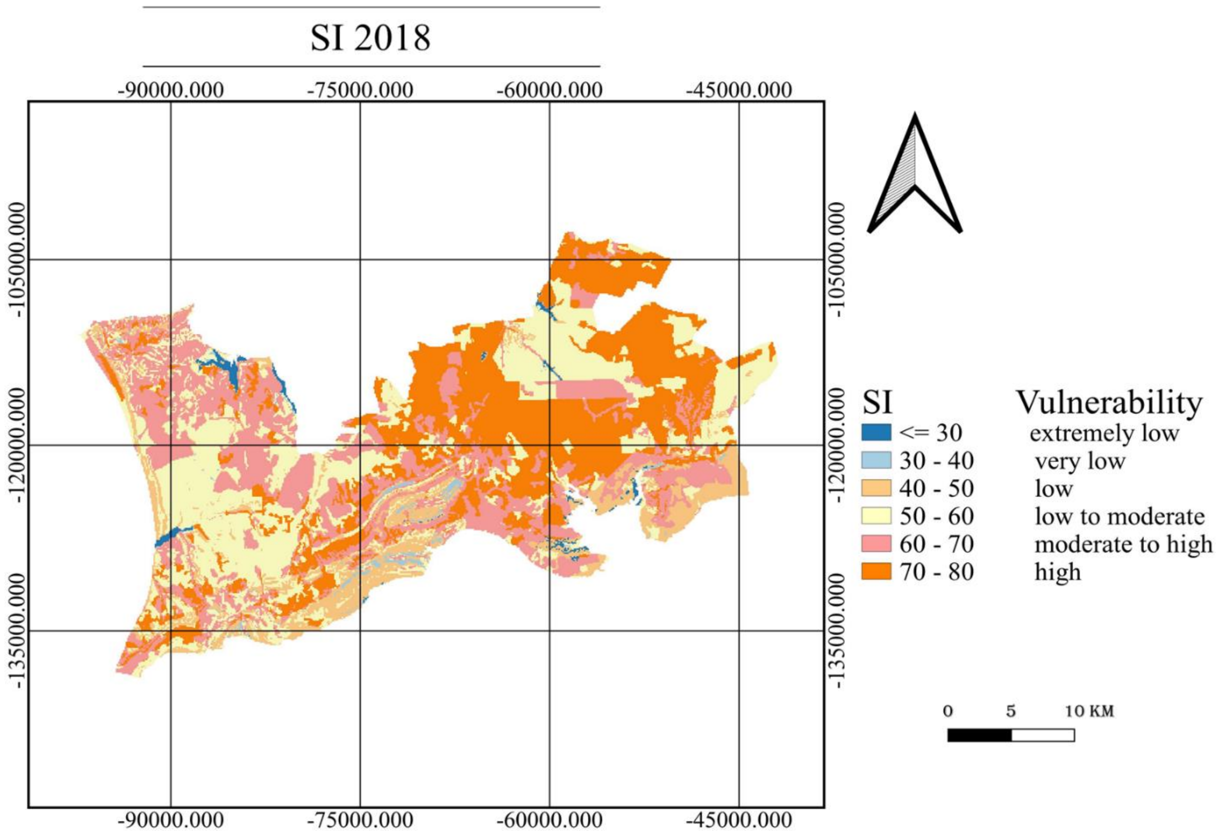


Figure 4.37: SI map of 2018

4.5 GROUNDWATER LEVEL ANALYSIS

The piezometric time series are the principal source of information concerning the effect of hydrological and anthropogenic stresses on the groundwater system (Ribeiro et al., 2015). To assess the effects of all these factors discussed so far on the groundwater level, a piezometric trend analysis was done using singular spectrum analysis (SSA) to study the variation of water level over the years. For this, the piezometers with recording within the years under analysis and with at least ten (10) years data were used irrespective of the groundwater depth. Figure 4.38 shows the location of the piezometric stations. Most of the observation points are in Palmela as shown in. This is not far expected as most of the wells in the study area are also in this region.

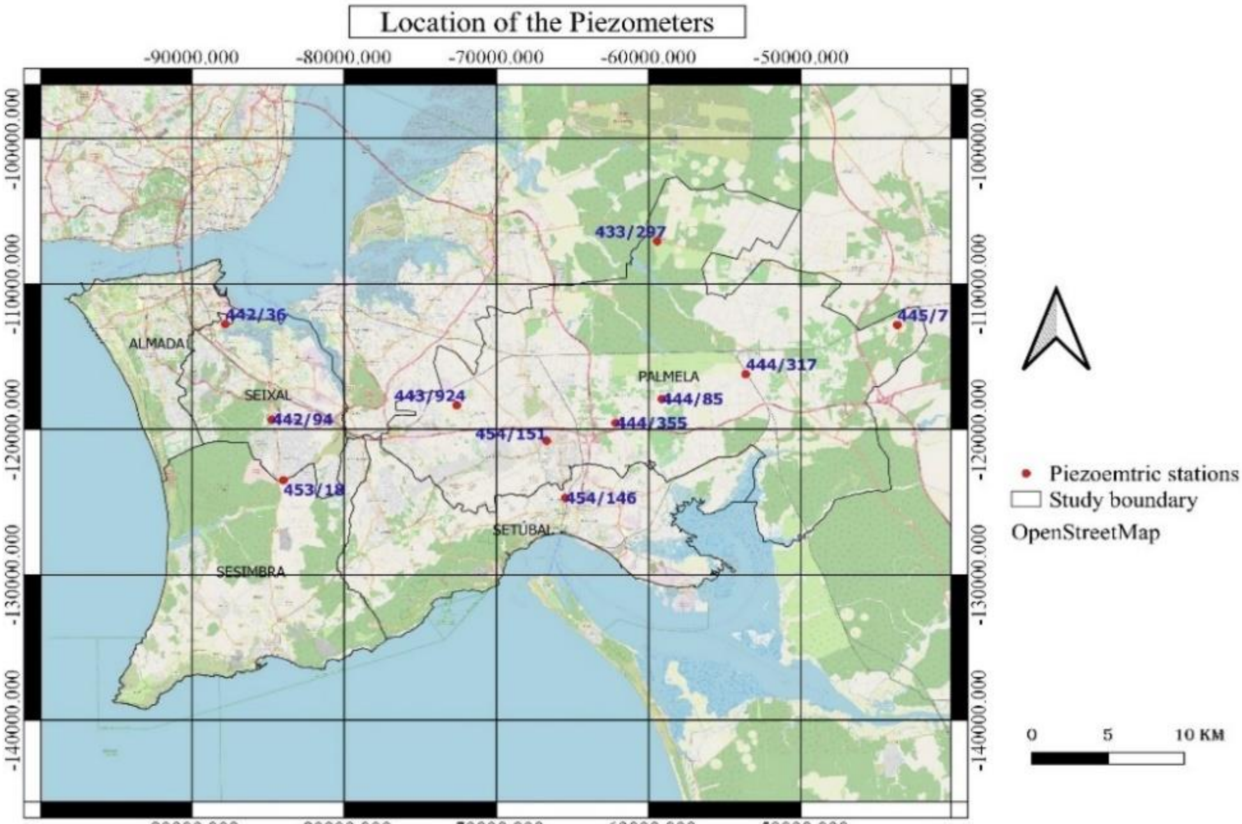


Figure 4.38: Location of the piezometric stations

Figure 4.39 shows the average groundwater depth at each monitoring station. The shallowest has a depth of about 8m and some are as deep as 50m.

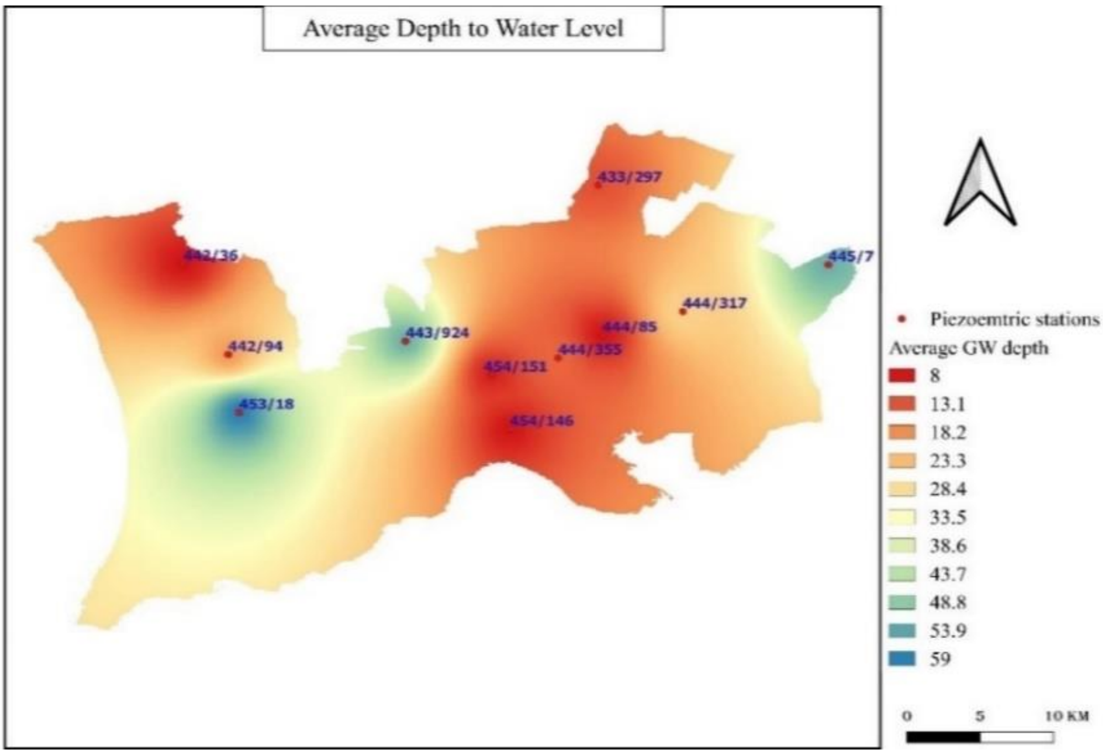


Figure 4.39: Average groundwater depth at each station

Eleven (11) piezometers were used for this analysis. The deep wells are located far away from the coastal areas and the years of observation of the wells vary but within the years under consideration.

Table 4.19 shows the statistics of the original time series. Generally, the series follow a good initial trend with less intra and interannual variations. Even from the skewness values, only one of the wells (433/297) has a negative skewness. But generally, the idea is to see the variation especially the upward and downward trend over the period and be able to relate to anthropogenic and climatic conditions. Also, SSA was performed to check if many components contribute to the variation of the series.

Table 4.19: The descriptive statistics of the original series. The negative value shows that the piezometric surfaces are below sea level

STATISTICAL ANALYSIS OF ORIGINAL SERIES										
Well	Observations	Mean	Median	Skewness	Range	Minimum	Maximum	Q1	Q3	IQR
433/297	142	14.51	14.72	-1.27	5.68	10.42	16.1	13.97	15.13	1.17
442/36	167	21.82	22.70	-0.63	10.92	15.42	26.34	19.8	24.2	4.40
442/94	628	-2.56	-2.68	0.45	9.39	-7.95	1.44	-3.5	-1.96	1.54
443/924	600	7.48	7.99	-0.75	9.23	1.26	10.49	6.02	9.26	3.24
444/85	154	29.46	29.39	-0.36	9.91	22.8	32.71	28.39	30.53	2.14
444/317	584	17.09	18.50	-0.57	9.15	11.3	20.45	13.55	18.5	4.95
444/355	202	15.84	16.21	-0.70	4.89	12.65	17.54	15.02	16.68	1.66
445/7	225	24.11	24.52	-0.86	7.11	19.1	26.21	23.06	25.17	2.11
453/18	168	11.10	11.13	0.63	5.15	9.05	14.2	10.47	11.7	1.23
454/146	158	11.62	11.61	0.08	5.73	8.78	14.51	10.91	12.22	1.31
454/151	155	140.37	140.27	-0.09	6.27	137.18	143.45	139.35	141.55	2.20

Singular spectrum analysis is a non-parametric method that was done to break the time series into different components that contribute to its variation, remove the noise from the series, and extract the seasonality in the variation of the series. This analysis was done in R as explained in the methodology.

The variation of piezometric level in the study area can be attributed to the influence of climatic factors like precipitation, human activities in terms of land use e.g., irrigation, and water abstractions due to increased demand. For all the observations, the major component that contribute to the series variation is surface recharge either from rainfall or irrigation on agricultural land.

The piezometer 433/297 has a stable trend over the years (Figure 4.40). Though there exist some intra annual (seasonal) variations. The upward and downward intra annual trend could be because of the seasonal variation of precipitation and irrigation. Groundwater could have relatively fast response due to relatively shallower depth, the soil type (sand), geology (sandstone), and the slope (low). This monitoring well is also located at the north of Palmela where the exploitation has been relatively lower and most of the wells are used for irrigation.

Figure 4.40: The figure showing the groundwater level trend, seasonality, and residuals of well 433/297

The piezometer 442/36 shows a steady upward trend from 2000 to 2006 and a very high upward trend from 2007 (Figure 4.41). Though the series shows a progressive and steady downward trend from 2016. Considering the urbanisation of the region where the monitoring well is located and the abstractions over the years, it is difficult to explain this behaviour.

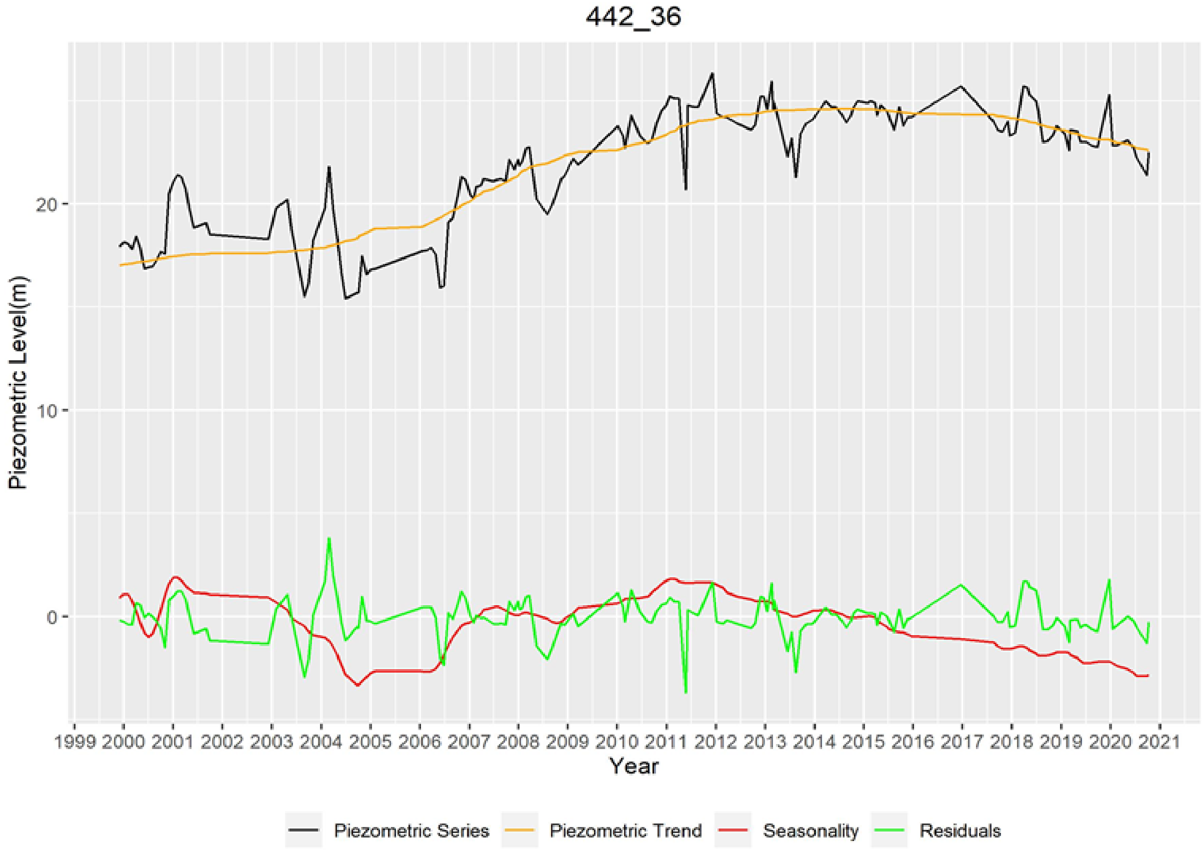


Figure 4.41:The figure showing the groundwater level trend, seasonality, and residuals of well 442/36

The piezometer 443/924 has a step trend (Figure 4.42). There was a progressive downward trend from 1990 to 2003 and a very sharp fall in the piezometric level followed by an almost steady series. The piezometric level has decreased by about 2.6m from 1990 to 2018. There has seriously been an exploitation of groundwater and increase urbanisation in this region. Closer patten was in well 442/94.

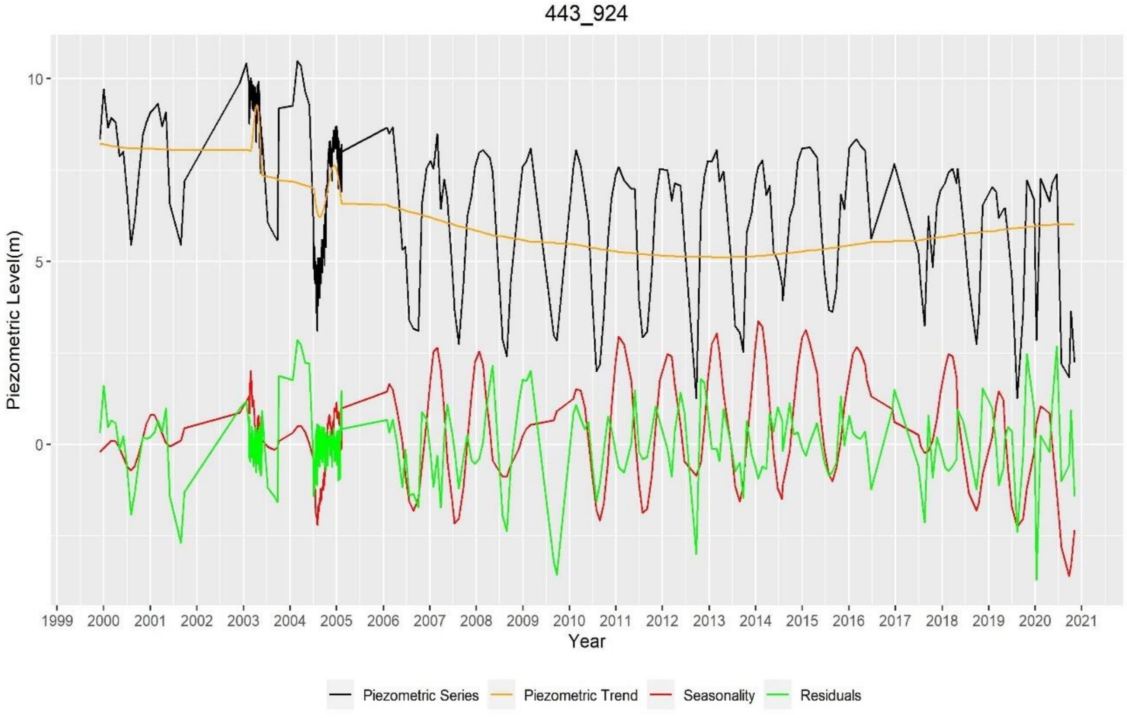


Figure 4.42:Figure 4.46: The figure showing the groundwater level trend, seasonality, and residuals of well 443/924

The piezometer 454/151 has a very stable trend (Figure 4.44) for all the years though it is located at the centre of Palmela. This could be explained by the depth of groundwater level, which is relatively shallow (8m average), and the recovery from irrigation. Figure 4.43 has an intra-annual variation.

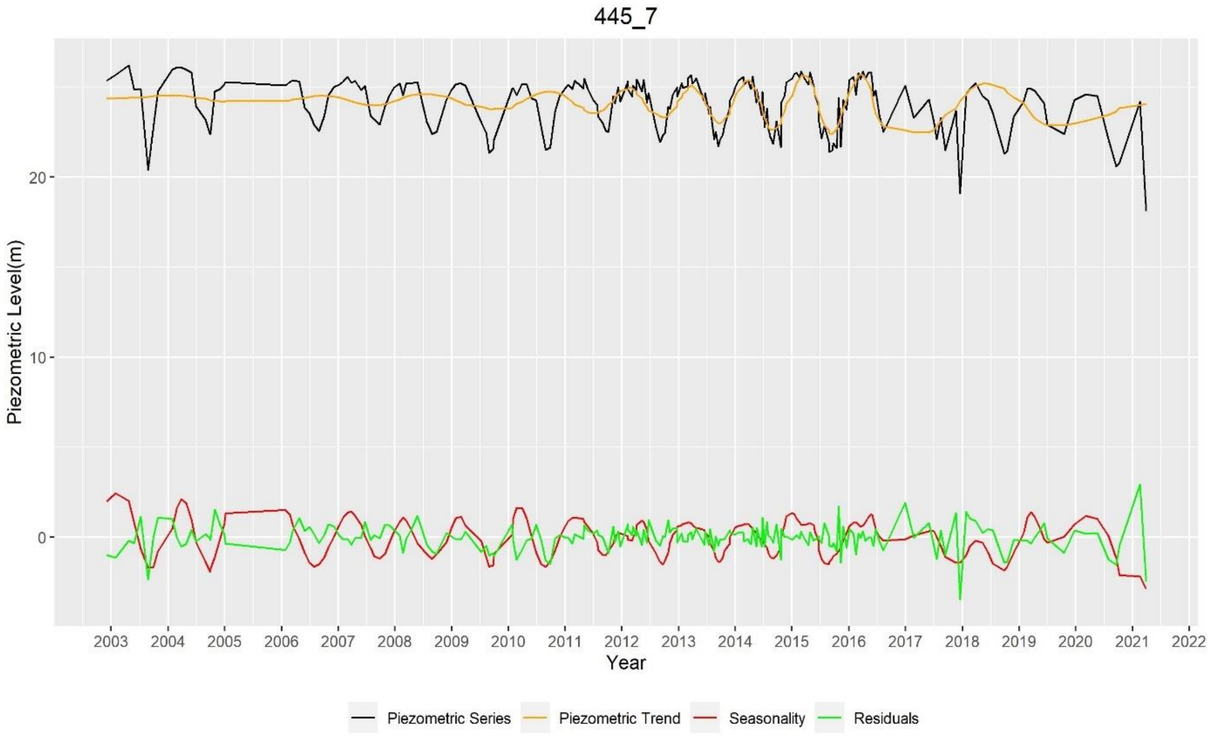


Figure 4.43:The figure showing the groundwater level trend, seasonality, and residuals of well 445/7

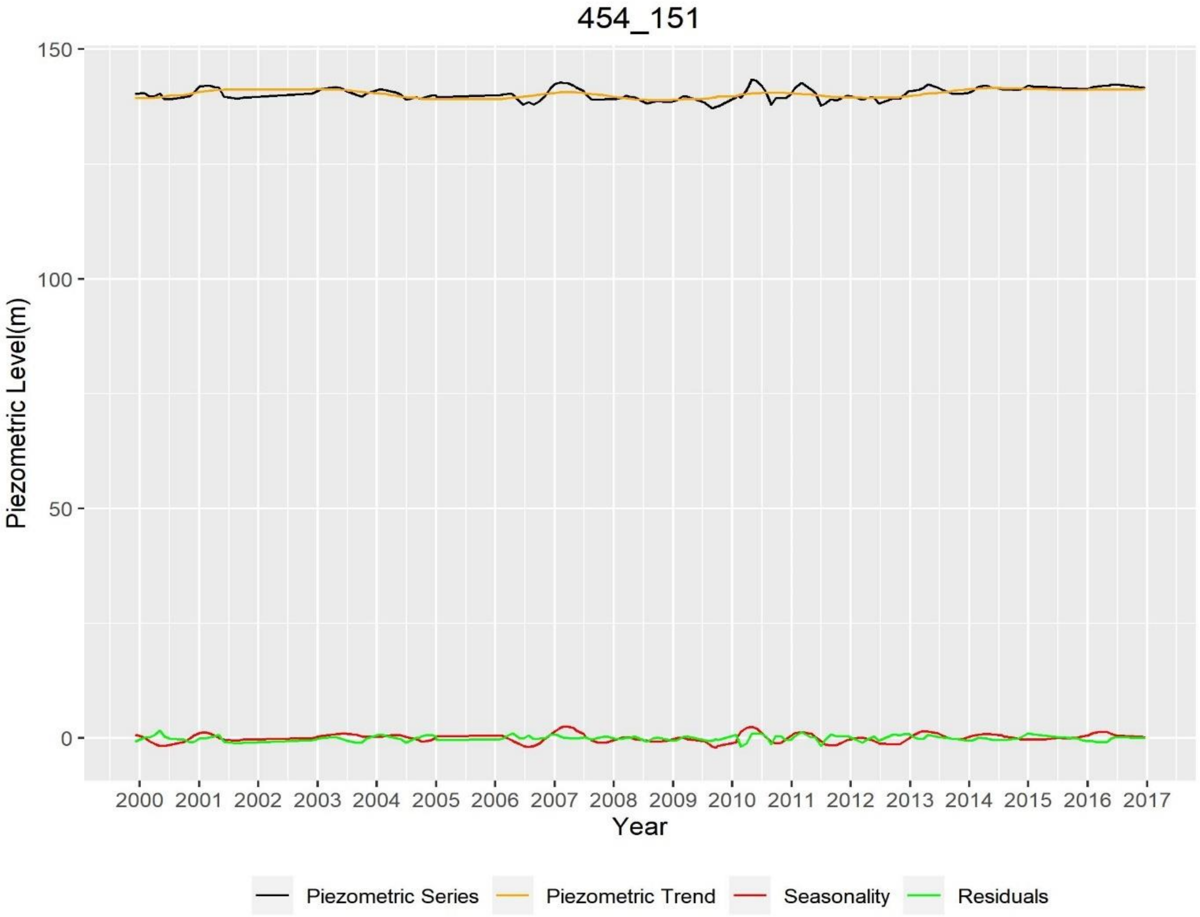


Figure 4.44:The figure showing the groundwater level trend, seasonality, and residuals of well 454/146

The piezometers 444/355 and 444/317 followed a similar pattern. In 444/355, the upward trend was observed from 2009 to 2015 with groundwater level rising by about 3m. There was interannual variation during this period, but this was followed by a progressive downward trend from 2015. The level has dropped by about 4m in 2020 (Figure 4.45).

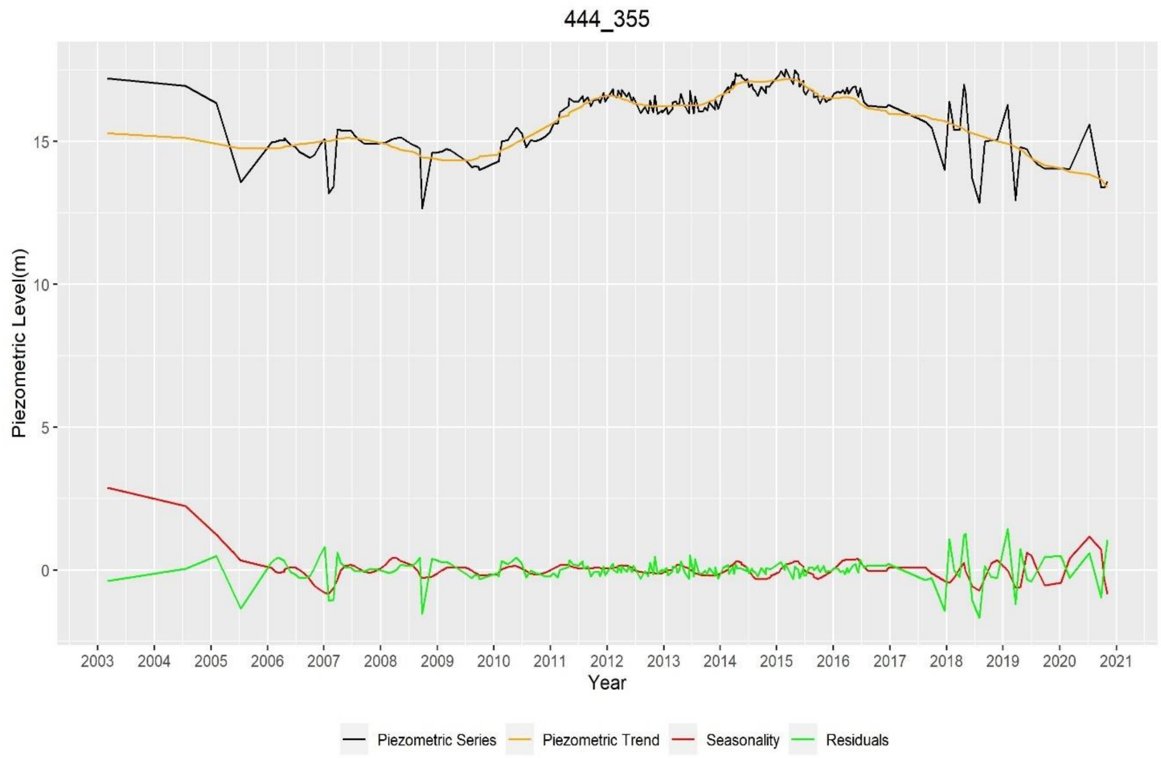


Figure 4.45: The figure showing the groundwater level trend, seasonality, and residuals of well 444/355

Generally, looking at the trend in all the wells, there observed an alternate downward and upward trend over the period under consideration. The variation of the series is controlled by climate and anthropogenic activities. Though there has been significant abstraction of water in the study area for different purposes, there seem to be a progressive recovery in many of the wells from 2017. The two significant exceptions that show drastic drop in groundwater level in 2004 are 442/94 and 443/924. Both are in areas where there has been a progressive increase in built-up areas. This drop in groundwater could be attributed to the abstraction of water for industrial purpose and the reduction of recharge due to increased impervious surface. Table 4.20 shows the descriptive statistics of the main component of the series. It can be observed that there is a very significant difference between Table 4.19 and Table 4.20. For example, there was a drastic difference in the ranges of both tables. The ranges in the latter are significantly lower than the former. This shows how SSA has removed some extreme values from the series which could be taken as noise.

Table 4.20: The descriptive statistics of the main component of the series

STATISTICS OF MAJOR COMPONENT										
Wells	Observation	Mean	Median	Skewness	Range	Minimum	Maximum	Q1	Q3	IQR
433/297	142	14.60	14.57	0.28	0.82	14.20	15.01	14.42	14.78	0.36
442/36	167	-0.02	-0.07	-0.23	7.51	-3.70	3.81	18.91	24.21	5.30
442/94	628	-2.59	-2.91	0.70	3.20	-3.70	-0.50	-3.25	-1.90	1.35
443/924	600	7.20	7.25	0.01	4.16	5.12	9.28	6.23	8.12	1.89
444/85	154	29.46	29.56	-0.25	2.85	27.73	30.58	28.79	30.22	1.42
444/317	584	17.09	18.32	-0.60	8.03	12.25	20.28	14.44	19.26	4.81
444/355	202	15.83	16.23	-0.32	3.66	13.53	17.19	14.96	16.55	1.59
445/7	225	24.13	24.23	-0.30	3.31	22.39	25.70	23.64	24.59	0.95
453/18	168	11.19	11.08	0.54	1.67	10.50	12.17	10.88	11.52	0.64
454/146	158	11.62	11.60	-0.01	2.24	10.42	12.66	11.04	12.17	1.13
454/151	155	140.27	140.29	0.00	2.61	138.92	141.53	139.55	141.14	1.59

4.6 SUSTAINABILITY ANALYSIS

To assess the future state of the groundwater under the changing climate, a future water balance was created with RCP4.5 and RCP8.5 scenarios. The first is a scenario based on stabilizing future climates without thermal overshoot. The total radiative forcing of 4.5W/m2 is stabilized after 2100. RCP4.5 includes a long term, global emissions of short-lived species of greenhouse gases and land use land cover in a global economic framework (Olivares et al., 2019). The second scenario assumed high population growth, and relatively slow income growth with modest rates of technological change and energy intensity improvements, leading to long-term high energy demand and unrestricted green house gas emissions in the absence of global warming mitigation policies (Olivares et al., 2019). Table 4.21 shows the calculated climate data with respect to the climate data of SNIRH as explained in section 3.7

Table 4.21: Climate data for each RCP scenario

	RCP 4.5				RCP 8.5			
	Rain (mm)	PET (mm)	Windspeed (m/s)	Temp (^{0}C)	Rain (mm)	PET (mm)	Windspeed (m/s)	Temp (^{0}C)
2041-2070	552.44	707.96	1.3	17.71	544.35	718.25	1.3	18.22

In both scenarios, there was observed a decrease in rainfall by 6% and 7% under RCP4.5 and RCP8.5, respectively when compared to the present average values (1990 – 2020). Figure 4.46 shows the difference between these two periods. And there will be an increase in the PET by 5% and 6% under RCP4.5 and RCP8.5 respectively. Generally, the windspeed remains the same and the temperature increases by 1.33^{0}C and 1.85^{0}C under both scenarios respectively.

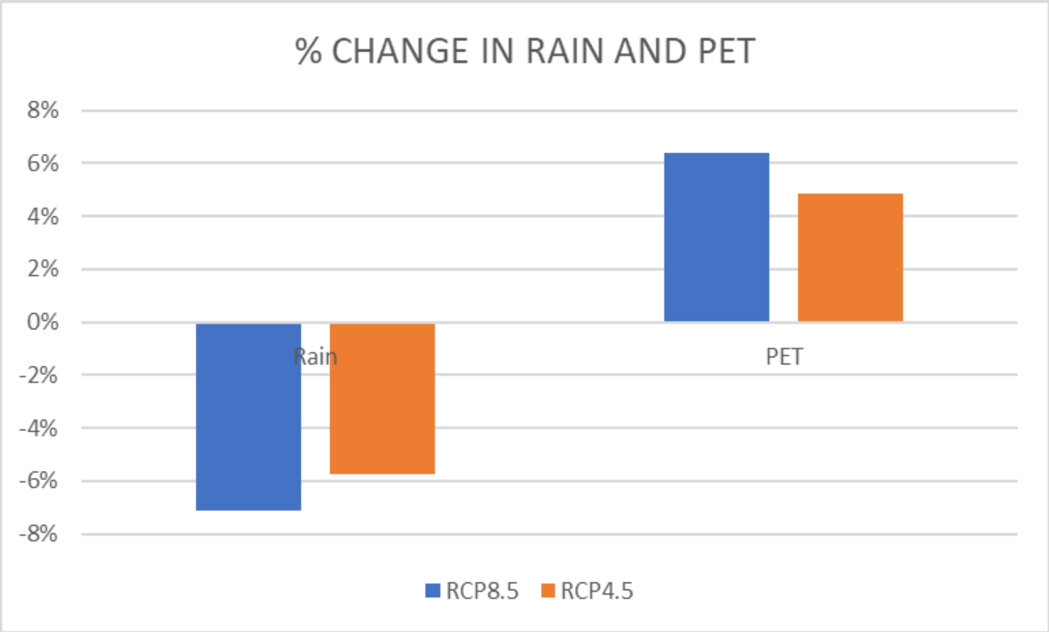


Figure 4.46: percentage change in rainfall and PET between the present (1990-2020) and the future (2041-2070) under both RCP scenarios

To compare the climate under both scenarios, Figure 4.47 shows the difference between the data from both scenarios. RCP4.5 tends to be more favourable for groundwater recharge with higher precipitation and a lower PET. The windspeed remain the same in both scenarios and as expected, the temperature of RCP8.5 is 0.51^{0}C higher than RCP4.5. This also explains the higher PET under this scenario.

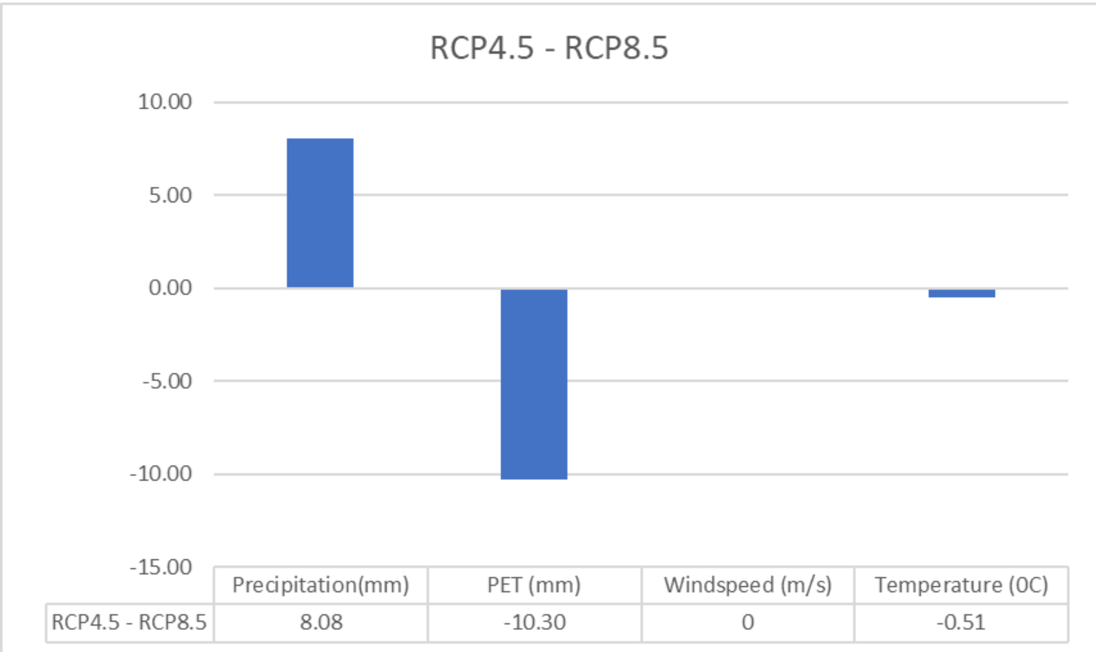


Figure 4.47: Difference between RCP4.5 and RCP8.5 climate scenarios

The groundwater level was assumed to be constant (10m) for the three scenarios as explained in section 3.7.

Table 4.22 shows the water balance under the two scenarios. Both have similar results because both have climate data in similar range. The recharge under RCP4.5 is slightly higher than that of RCP8.5. Generally, the difference between the water balance components in both scenarios is between 1 and 5mm.

Table 4.22: Water balance of RCP4.5 and RCP8.5

	RCP4.5				RCP8.5			
Year	AET	Runoff	Recharge	%Recharge	AET	Runoff	Recharge	%Recharge
2041-2070	323.98	127.5	102.17	18	318.68	125.74	101.10	19

The result of the analysis shows that the future recharge is lower than the present value. This was not far expected considering the values of the rainfall and PET due to climate change. The future water balance was calculated with WetSPASS-M and compared to that of 2018 as simulated in section 4.3.2. Figure 4.48 shows the change in water balance between the periods under the two climate scenarios.

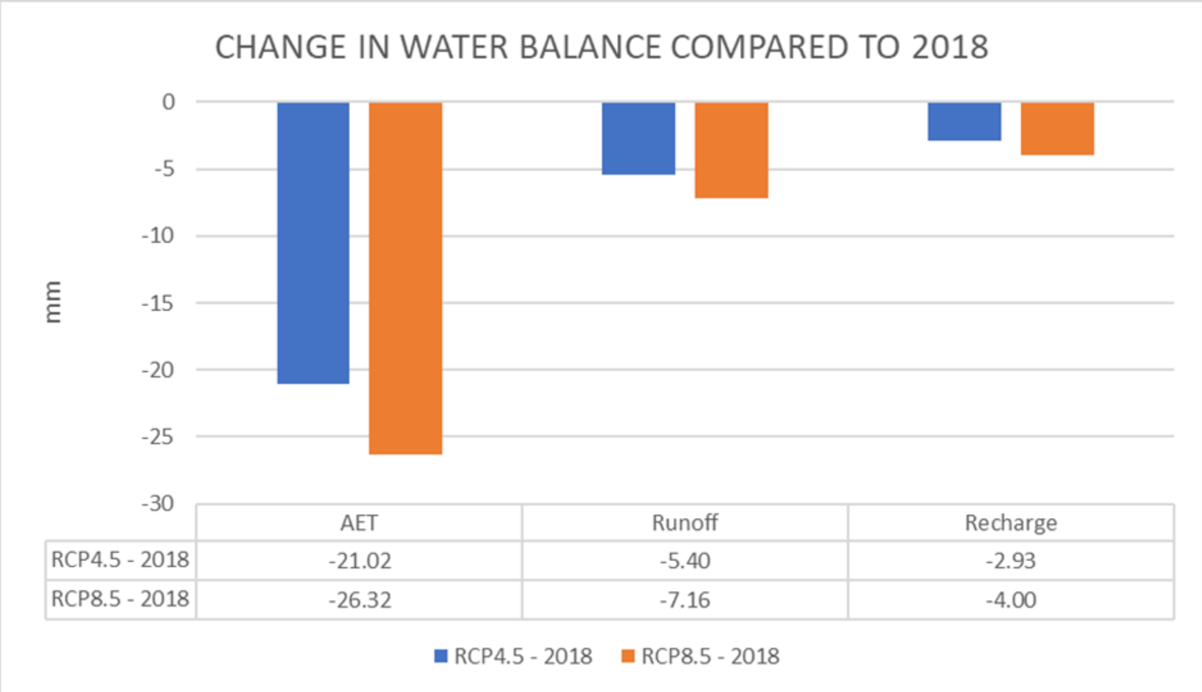


Figure 4.48: The difference in the components of the water balance between 2018 and the future scenarios.

The only uncertainty in this assessment is the intensity of rainfall, its duration, and the monthly distribution. Climate change may lead to the narrowing of precipitation periods over the year, leading to higher intensity rates, increased runoff, the possibility of flash floods, and less recharge. Since the monthly distribution of the rainfall and the future rain intensity could not be determined, this analysis is subjected to uncertainty.

To assess the recharge zones in the future, recharge maps were created for both RCP scenarios. The recharge zones are similar in both. The zone of maximum recharge is where agriculture is being practiced making the groundwater vulnerable to pollution. Figure 4.49 shows the recharge maps.

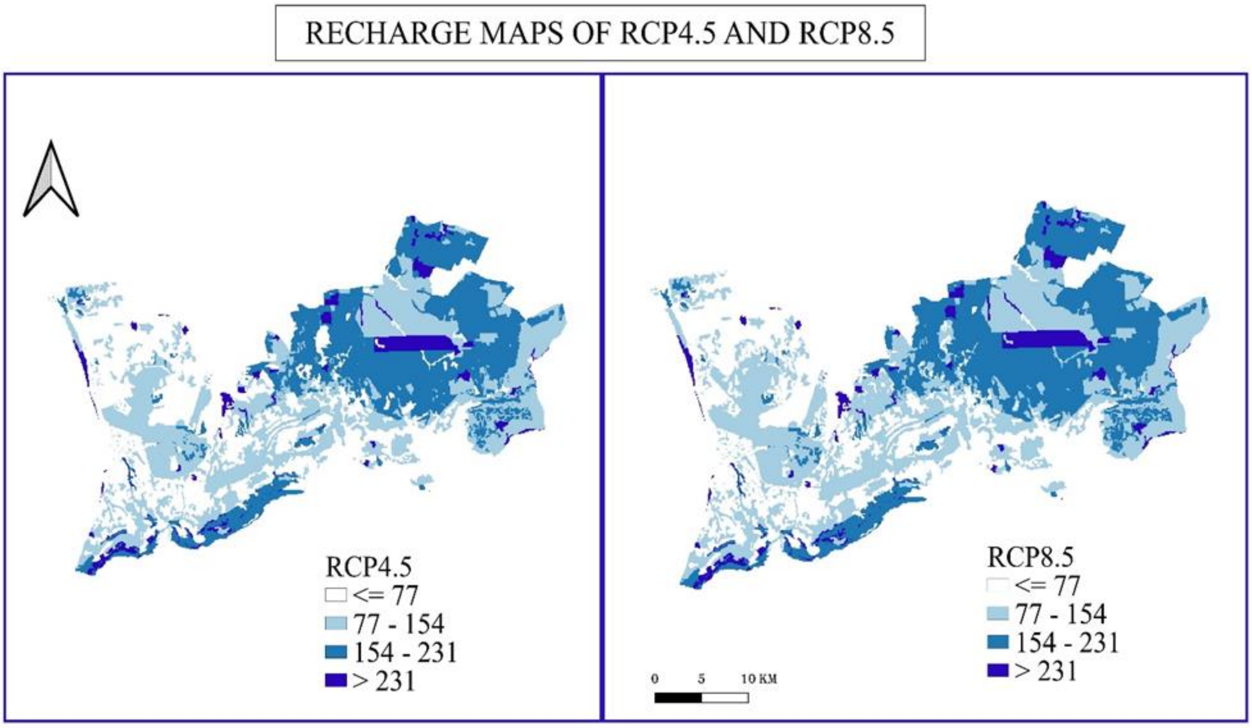


Figure 4.49:Spatial distribution of recharge under the climate change scenarios.

5 CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

This work was done to holistically assess the impacts of climate, land use and demographic growth on the groundwater resource. The study area has experienced a significant change in population from 1990 to 2018 with an increase of about 27%. The groundwater abstraction was also studied by the number of wells constructed in the area. There has been an increase in the number of wells especially in Palmela where the main land use is agriculture. This shows there has also been a significant groundwater abstraction in the area.

The dominant land use is built-up, agriculture, pine, natural vegetation, and permanent pastures. Others are water bodies, wetlands, open built-up and orchards whose changes were not too significant. The built-up area has expanded from 12.5% in 1990 to 19.22% in 2018. There has been a corresponding reduction in pine and agriculture from 1990 to 2018. The natural vegetation and permanent pastures have undergone a progressive increase in area from 1990 to 2018. The increase of the built-up area shows that urbanisation has occurred, and many green areas have been replaced by artificialized areas. This has an implication on the groundwater system especially recharge. The change in all these land use types has a corresponding alteration of the components of the hydrological systems. For example, increase in built-up areas lead to increased impervious surfaces thereby reducing the groundwater recharge, and increasing surface runoff. The change in land use types can also be said to be driven by the change in population and change in economic activities to accommodate the changing population. The change in each type is particular to some municipalities. For example, Almada has most of its land artificialized while Palmela has agriculture more agricultural lands. These land use types (anthropogenic activities) have a very strong influence on both overexploitation of groundwater and the vulnerability of shallow aquifers to pollution especially from industrial and agricultural sources.

The assessment of water balance and recharge using WetSpass-M was made under two scenarios. The first was the impacts of land use and climate which showed that the spatial variation of the hydrological components was driven my climate and land use. For example, there was a direct relationship between actual evapotranspiration and windspeed. There was an increase in runoff in the built-up areas. There was a lower recharge in 2018 than the previous years. Apart from the change in land use, this was also driven by the change in climate as precipitation in 2018 was less than 50% of that of 1990. This change in recharge with an increase in population can lead to overexploitation of groundwater since the region depends on groundwater for all consumptions.

The second is the impacts of land use change only. This showed that land use has an impact on water balance and recharge. Increased built-up areas led to an increase in impervious surface and ultimately, an increase in runoff. The reduction of the area of pine and agriculture also led to a reduction in actual evapotranspiration. The recharge also reduced because of the land use. The recharge zones were delineated to see the region with the maximum recharge. The zones with the maximum groundwater recharge in 2018 are in the western part for the study area. This area is particularly used for agricultural purpose. The other recharge zone is the southern part along the coast which has the land use of Natural Vegetation

From the specific vulnerability assessment using the susceptibility index, some parts of the areas are susceptible to groundwater contamination. These are areas with a high recharge and anthropogenic activities like agriculture and industries. Since the western part is the major recharge zone and with agriculture practices, the region is highly susceptible to groundwater contamination.

The piezometric (groundwater level) analysis using the SSA showed that there has been an alternating upward and downward trend in the series. This trend is controlled by the seasonal variation of rainfall, abstraction, and the irrigation from agricultural lands. The series from some piezometers have a very small variation due to deep groundwater depth. There was a sharp drop in groundwater level (about 4m) in some monitoring stations in 2004, and this remained stable till 2013 after which there was a little upward trend. This was particularly noticed in piezometers in built-up areas. This could be attributed to groundwater abstraction and a corresponding reduction of recharge in those areas due to an increase of imperviousness. Generally, the analysis showed that only one source (surface recharge by rainfall or irrigation) contributed to the fluctuations of the series and there was no downward trend for more than five years without an upward trend. The evaluation showed that even though there has been an increasing population and well construction over the years, there has not been a depletion of the groundwater resource in most of the monitoring stations. From the piezometric trends, it was not possible to establish a direct relationship between recharge and piezometric level. The major threat to groundwater is contamination from agricultural sources.

The sustainability assessment under the climate scenario of RCP4.5 and RCP8.5 also showed that climate change will play a major role in the variation of the hydrological components in the future. From the water balance analysis done for the mid-century, the recharge reduced compared to the present value, but the reduction was not dramatic. Also, RCP4.5 has a more positive result than RCP8.5 in terms of groundwater recharge. The only uncertainty is the rain intensity and duration. If the rain intensity is high in the future, the recharge will be lower than the one presented in this work and runoff will be very high. The higher rain intensity could also have a lower effect on the recharge since the geology of the area is majorly limestone and sandstone and could support the macropore (preferential) flow of water.

5.2 RECOMMENDATIONS

The following solutions can be applied to solve some of the problems discussed in this research.

1. Demographic analysis should be done to control the number of people migrating to the municipalities for population control.
2. A sensor that can measure the exact abstraction rates from each well should be installed to get the actual abstraction data.
3. A strict policy should be made and enforced against the construction of illegal wells.
4. Urbanization should be prevented from extending into the recharge zones.
5. Low impacts development (LID) should be adopted in many areas to enhance groundwater recharge. For example, the use of green roofs, permeable pavements, and infiltration trenches.
6. The use of fertilizers and other chemicals for agriculture should be regulated within the acceptable concentration to prevent groundwater contamination.
7. A very effective campaign should be organized to inform the public about the importance of (ground)water management and protection.

6 LIMITATIONS OF THE REASEARCH

There are few uncertainties and limitations in this research work.

1. The data used for all the analyses are from secondary sources and the reliability of the work will depend on the reliability of the data.
2. The climate data (for the analysis under section 4.3.1) was really limited and some were filled with the long-term average monthly values. Also, the spatial variation in potential evapotranspiration could not be made since the value was only calculated for one station and assumed to be the same in the study area.
3. The future analysis is subjected to uncertainty. The intensity and monthly distribution of rainfall of the present were used for the future scenarios. This may not represent the real-life scenario if climate change causes the rainfall regime to be short and with high intensity, leading to more runoff or flash floods, and less groundwater recharge.

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APPENDIX

Table 1: Table showing the calibrated values of land use parameters for WetSpass-M

Code	LUSE_TYPE	RUNOFF_VEG	VEG_AREA	BARE_AREA	IMP_AREA	OPENW_AREA	ROOT_DEPTH	LAI	MIN_STOM	VEG_HEIGHT	nManing	LandFactor	AerodynResistance
2	build up	grass	0.1	0.4	0.5	0	0.3	1	100	0.1	0.02	0.5405	225.16
10	open build up	grass	0.5	0.5	0	0	0.3	1	100	0.5	0.0945	0.38544	124.22
21	agriculture	crop	0.9	0.1	0	0	1	8	30	5	0.9865	0.3541	39.97
23	Permanent Pastures	grass	0.8	0.2	0	0	0.3	4	30	2	0.947	0.2286	66.33
29	orchard	forest	0.8	0.2	0	0	1	4	120	4	0.955	0.244	47.84
31	pine	forest	1	0	0	0	2	10	150	16	0.945	0.355	27.62
44	Wetlands	open water	0.3	0.3	0	0.4	0.5	2	50	0.5	0.7135	0.271	124.22
54	Water Bodies	open water	0	0	0	1	0.05	0	100	0	0.02	0.1	0.00
307	Natural Vegetation	grass	0.9	0.1	0	0	0.5	3	30	3	0.844	0.1471	54.70

Table 2: Table showing the definitions and units of land use parameters for WetSpass-M

Parameter	Full name	Unit
Veg_area	Vegetation area fraction	-
Bare_area	Bare area fraction	-
Imp_area	Impervious area fraction	-
Openw_area	Open water area fraction	-
Root depth	Rooting depth	m
Lai	Leaf Area Index	- area fraction
Min_stom	Minimal stomatal resistance	s/m
nManing	Manning's roughness coefficient	-
Veg_height	Vegetation height	m
AerodynResistance	**Aerodynamic resistance**	**s/m**

Table 3: *Table showing the calibrated values of soil parameters for WetSpass-M*

Code	SOIL	FIELDCAPAC	WILTINGPNT	PAW	RESIDUALWC	A1	EVAPODEPTH	TENSIONHHT	P_FRAC_SUM	P_FRAC_WIN	Teta
1	Sand	0.1359	0.02	0.17	0.032	0.62	0.2	0.0514	0.08	0.01	0.09
2	loamy sand	0.1563	0.01	0.2	0.035	0.56	0.2	0.0419	0.08	0.01	0.1
4	silty loam	0.24074	0.025	0.19	0.015	0.53	0.3	0.0432	0.0913	0.03	0.128
5	loam	0.2609	0.02915	0.2	0.027	0.52	0.4	0.0441	0.0902	0.05	0.103
11	silty clay	0.36195	0.12	0.27	0.046	0.5	0.3	0.17	0.12	0.25	0.124

Table 4: Table showing the definitions and units of soil parameters for WetSpass-M

Parameter	Full name	Unit
Wilting point	Wilting point	**- (volume fraction)**
Field capacity	Field capacity	**- (volume fraction)**
Residual wc	Residual water content	**- (volume fraction)**
a_1	a1 soil empirical parameter for ET calculation	**-**
PAW	Plant Available Water	**- (volume fraction)**
Tensionhht	Tension saturated height	**M**
Evapodepth	Soil evaporation depth	**M**
P_frac_winter	Precipitation fraction in winter which has an intensity higher than the soil infiltration rate	**- (volume fraction)**
P_frac_summer	**Precipitation fraction in summer which has an intensity higher than the soil infiltration rate**	**- (volume fraction)**

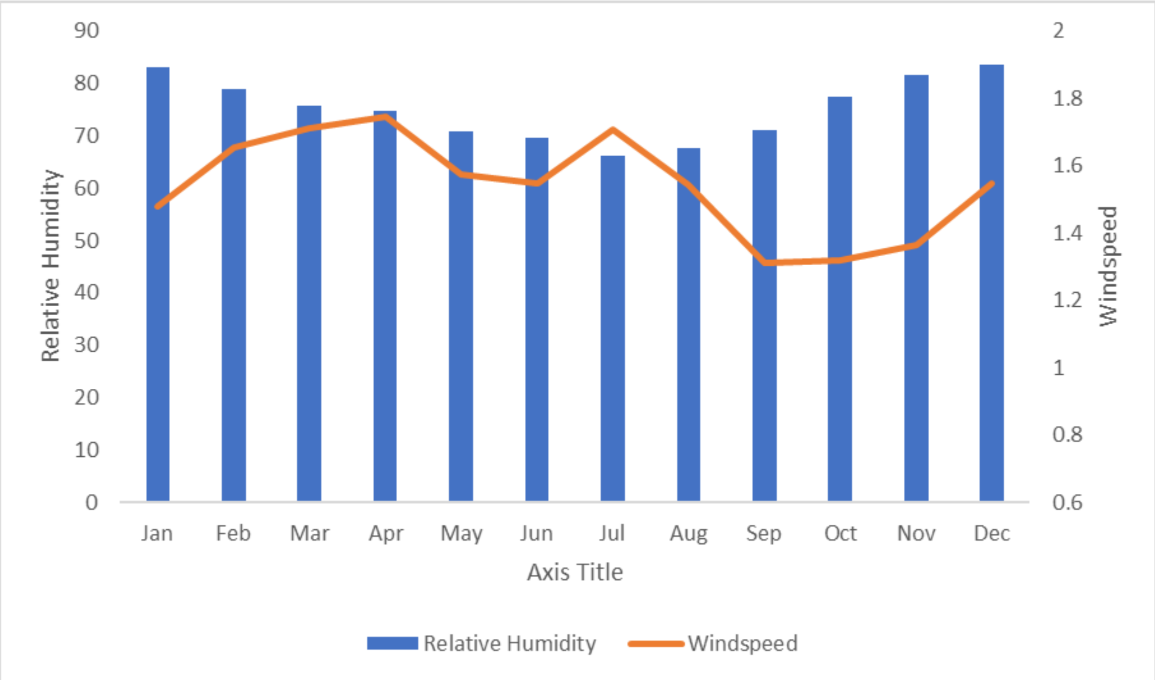

Fig1: Monthly average relative humidity (%) and windspeed(m/s)

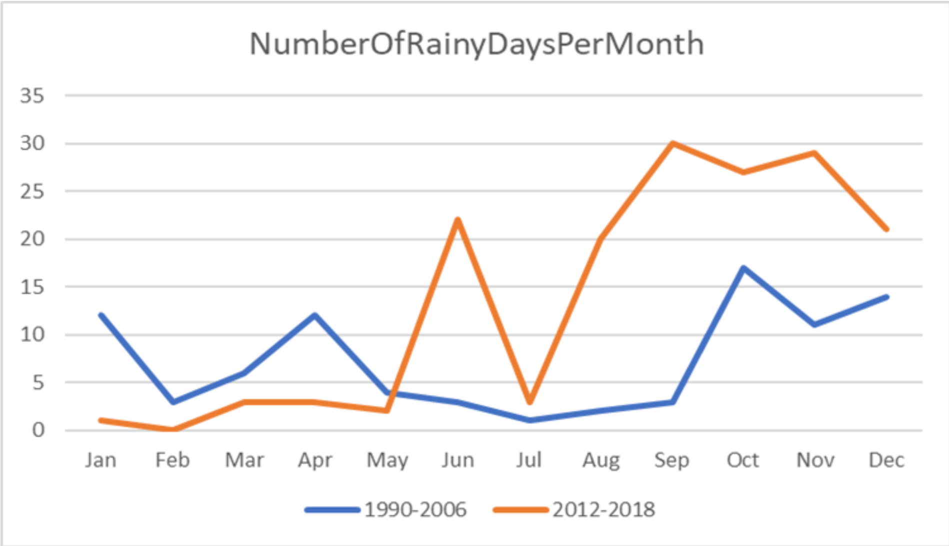

Fig2: Number of rainy days per month.