GIS and remote sensing-based integrated modelling of climate and land use change impacts on groundwater quality: Cape Flats Aquifer, South Africa

By

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DECLARATION

I, Tesfaye Tessema Gintamo, hereby declare that this dissertation is my own work and that all sources that I have used or quoted have been indicated and acknowledged as references. The thesis has not been submitted to another institution or university for the award of a degree.

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DEDICATION

I dedicate this research work to my wife and three daughters. First, my lovely wife, Edeget Alemu Tembiso, for caring for our family and standing with me during my study period. Second, my three daughters, Abigail Tesfaye, Kalkidan Tesfaye, and Biruh Tesfaye, for their love and understanding of my absence when they needed me the most as their father.

ABSTRACT

The need to ensure groundwater security is vital, particularly in urban areas. Assessing the impact of land use and climate variables on groundwater quality can help improve sustainable management. The vulnerability mapping of groundwater contamination identifies high-risk areas. Using models and technologies that forecast the distribution of contamination risk over time and place can help prioritize groundwater monitoring. Based on such needs, the Cape Flats aquifer in Cape Town, South Africa, was chosen as the case study for assessing the potential for groundwater contamination risk in urban and coastal hydrogeological settings. The Cape Flats aquifer has been highlighted as an alternate water supply source to augment current supply sources in Cape Town. However, the shallow aquifer is under pressure from agricultural and industrial activities and long-term climate variables, among other factors. The study assessed and validated the vulnerability of the South African coastal aquifer to contamination using an integrated method that included geospatial spatial modeling, a WorldWater model, a down-scaled GCM to the local scale, and a DRASTIC model based on the Geographic Information System (GIS). In this thesis, three approaches are taken: evaluating the effects of changes in key climate variables such as temperature, precipitation, and sea-level rise on groundwater quality in Cape Flats aquifer systems; using the DRASTIC index and selected water quality parameters to assess the vulnerability of the Cape Flats aquifer to groundwater contamination; using a GIS-based model to assess the risk of groundwater contamination in the Cape Flats aquifer under changing climate and land use. Groundwater vulnerability maps were created using ArcGIS software. The WaterWorld model calculates hydrological scenarios for 1950–2000 (baseline) and 2041–2060 using global data at a resolution of 1 km (impact period). Precipitation will increase until 2041 and then fall until 2060, according to the simulation. Temperatures were expected to increase by 1.9-2.3 ° C. In the future, dry climate, will increase evapotranspiration by 45 mm/year (10%) and decrease water balance by 6.8%. The A1B-AIM scenarios were used to simulate precipitation, temperature, and sea-level rise for two time periods, the 2040s and 2060s, using 20 GCMs integrated into the Greenhouse Gas-Induced Climatic Variables Model/Regional Climate Scenario Generator (MAGICC/SCHENGEN). The region's climate change projections say that there will be less precipitation in the summer and more in the winter, with temperature rises of 1.9 to 2.1 degrees Celsius. The probability that coastal areas are affected by an increase in sea level rise (17–19 cm) and increases in temperature by mid-2060 ranges from 12% to 58%. The DRASTIC model uses seven layers of hydrogeological data: depth to the water table, net recharge, aquifer media, soil media, topography, the impact of the vadose zone, and hydraulic conductivity of the aquifer. The vulnerability index ranges from 109 to 222, with 9% very high, 28% high risk, 46% moderate risk, and 17% low risk. The study area shows that increasing the DRASTIC model by LU increases the very high-risk zone by 26% while decreasing the low-risk zone by 52%. In addition to mapping groundwater vulnerability, the modified DRASTIC method can explain how urban hydrogeology affects coastal aquifers. The study uses an AHP to determine the weighting value for each hydrogeological parameter. GIS tools were used to create the GWQI map. The GIS-based model divides areas at risk of contamination into four categories: very high, high, moderate, and low. The study area has a moderate risk of groundwater contamination (42%). The southern and central suburbs of the study area are the most at risk. Based on data on the levels of water quality parameters in groundwater, the modified DRASTIC vulnerability map is consistent with land use data. In a correlation of these parameters, climate variability and land-based activities had significant effects on groundwater quality. A water quality index was calculated using selected water quality parameters for general quantification and validation. Using chemical water quality parameters, this thesis created a groundwater quality index that ranged from 56 to 142. The contamination risk index and the measured groundwater quality values showed a significant and strong positive correlation ($R^2 = 0.96$). The findings of the study are relevant to the management of water resources in the Cape Flats catchment and elsewhere in the world, particularly in Africa. DRASTIC uses GIS to assess groundwater contamination and provide data for better water resource management. As a result, computer models of contaminant transport can be used to test the DRASTIC parameters.

Keywords: Aquifer vulnerability; Cape Flats; Cape Town; Climatic variables; DRASTIC; Geoinformatics; Geographic Information Systems; Groundwater quality index; Hydrologic Modeling; Hydrogeology; Remote Sensing

The Contribution of the Study

The author (Tesfaye Tessema Gintamo) wrote the contributions (conceptualization, data analysis, and manuscript preparation) of the published articles and manuscripts under the supervision of Dr. Thokozani Kanyerere and Dr. Haile Mengistu. The following articles have been published or are in the process of being published to provide a knowledge contribution through the preparation and submission of the following manuscripts:

Paper 1: Impact of climate variability on groundwater quality: Validation and down-scaling of the impact of climate variability on groundwater quality in urban coastal aquifers in South Africa.
Gintamo, T. T., Mengistu, H., and Kanyerere, T. (2021). GIS-based modelling of climate variability impacts on groundwater quality: Cape Flats aquifer, Cape Town, South Africa. Groundwater for Sustainable Development, 15, 100663.

Paper 2: Aquifer vulnerability mapping (Risk assessment paper): Using GIS-based modified DRASTIC modelling of the Cape Flats aquifer to evaluate the vulnerability of coastal aquifers in urban hydrogeology, South Africa.

Paper 3: Development of a GIS-based integrated model to increase water security in a modern city prone to drought, Cape Town, South Africa.

Conference proceedings: (Oral and Poster presentations)

Oral presentation at the 2019 Groundwater Conference: Conservation, Demand, and Surety (GWD) 2nd Southern African Development Communities (SADC) Groundwater (https://gwd.org.za/abstracts?keys=andfield_gwd_year_presented_value=andfield_gwd_theme_target).Conference titled: Groundwater contribution to achievement of Sustainable Development Goals in the SADC Region: Johannesburg, South Africa, 4-6 September 2019.

Poster presentation at the Presented on 18 WaterNet/WARFSA/GWP-SA Symposium, Swakopmund, Namibia from 25 – 27 October 2017.
Poster presentation at the 15th Biennial Groundwater Division Conference, 14 October 2017 to 18 October 2017, Cape Town, South Africa.

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Chapter 1: General Introduction

1.1 Background of the Study

1.1.1 Study overview

The current study is an attempt to map groundwater vulnerability zones using a geographic information system (GIS) environment as a tool to assess and analyse potential contamination risks in the coastal aquifer system in urban areas under changing climate and intensive human activities. Groundwater is under pressure from agricultural and industrial activities and long-term climate variables in most developing cities. Changes in temperature and precipitation can potentially modify hydrological conditions and put cities at increased risk of contamination. In urban areas, groundwater recharge is dramatically reduced by increasing temperatures and reducing rainfall. In addition, there are increased levels of nutrient and sediment runoff from industrial and agricultural areas. Rising sea levels increase groundwater salinity through saltwater intrusion into the coastal aquifer system. In Cape Town, the potential of water supply from the Cape Flats aquifer is highlighted as an alternative means of augmenting current supply sources (Adelana and Xu, 2010). However, a large part of the Cape Flats catchment is affected by land-based activities such as agriculture, informal settlement, waste disposal, and industrial activities, all of which have the potential to pollute the aquifers. Based on this, the Cape Flats aquifer in the city of Cape Town, South Africa, was identified as the focus of a case study to determine the potential risk of groundwater contamination in the context of urban and coastal hydrogeology to provide critical information that could lead to more effective water resource management. The findings of this study are meant to help policymakers better understand how to protect, monitor, and manage water resources in a long-term way.

1.1.2 Current scholarly debate on the impact of climate and land use changes on groundwater quality

Groundwater is known to be the key to improving water security challenges in an era where demand for water supply is ever increasing, particularly in urban areas. More than 60% of the population depends on groundwater sources, and the demand for these sources is likely to increase with increasing extreme events such as drought (FAO-ONU, 2017; Kumar, 2010; Panwar and Chakrapani, 2018). In addition to extreme events, land-based activities such as agriculture and industrialisation pose additional threats to groundwater resources. Runoff within the urban area increases the loads of nutrients and sediments from industrial and agricultural areas, and rising sea levels increase the intrusion of saltwater, especially in coastal aquifers. Ensuring water quality without compromising the coastal aquifer from climatic variables and human activities is a huge challenge that requires appropriate protection and monitoring strategies for sustainable management. According to Jun et al.(2010) and Aizebeokhai (2011), more research is needed to improve understanding and modeling of land-based activities and the impacts of climate variability on groundwater quality at spatial and temporal scales relevant to decision making for better groundwater management. Geospatial hydrological modelling has gained popularity recently and can be used as one possible approach to simplify climate information and analysis of the likely influences of natural and anthropogenic events on the aquifer. For example, both Goderniaux et al. (2011) and Pouget et al. (2012) used an integrated modelling framework that can link a wide range of models, such as hydrological, water quality, and watershed models for planning and water resource management. Hagemann et al. (2013) argue that within studies considering hydrological impacts on groundwater, there is still little consideration given to the quality of the water to support decision-making for sustainable development in the future. It is highlighted that the key challenge is to thoroughly understand the potential link groundwater quality may have with land use and climatic variables on a regional scale (Shamir et al., 2015). In fact, assessing the risk of groundwater pollution is important for protecting groundwater resources because it shows which areas are vulnerable to contamination on different spatial scales.

Several studies have been conducted in the last decade to assess how they interact with climatic variables and groundwater on the issue of water quality (Aizebeokhai et al., 2017). In addition, large-scale hydrological models have shown better performance and better quantification of the impacts of human activities and climate variability on water quality. The results of scenario-based modelling depict future hydrological variations, and the result shows an increase in surface runoff, which has implications for decision makers to develop better water and land use policies. To support better water resource management, Mango et al. (2011) demonstrated the impacts of land cover and climatic variables on the hydrological processes of the upper Mara River Basin in Kenya. The modelling results indicate that small decreases in precipitation may produce large reductions in runoff due to an increase in evapotranspiration. Khatami and Khazaei (2014a) determined the benefits of GIS-based approaches in hydrological modelling that consider different layers of geographic data and create new integrated information on hydrological variables. The authors conclude that the evidence is strong for the application of GIS in hydrological modelling for the management of water resources. They (Aduah et al., 2017) developed the hydrological model to understand the impact on the water resources of a lowland rainforest basin in Ghana, West Africa, using the ACRU hydrological model to develop suitable mitigation strategies for climate and land use changes. In general, modeling platforms are a good way to solve a problem in long-term water resource management.

1.1.3 Current debate in practice on the effect of climate and land use changes on groundwater quality

The need to improve groundwater security remains critical, particularly in urban areas where the demand for groundwater as an alternative source of water supply intensifies after unprecedented growth in population and economic activity, mainly in agriculture and industrialization (IPCC, 2007). In Africa, many urban areas rely on groundwater as a fundamental part of their drinking water supply (Fitch et al., 2016a; Jakeman et al., 2016a). Despite increasing threats, more than half of the West African population lives in cities and relies on groundwater as their primary source of drinking water

(Murray-Rust and Fakhruddin, 2014). Based on current climatic variables predictions and land use practices, hydrological characteristics are likely to change in the future, often entailing uncertain consequences for aquifer systems (McGill et al., 2019a). Furthermore, South Africa is characterised by high spatial and temporal variability and is known to have scarce water resources. Cape Town, in the Western Cape province of South Africa, has been the focus of climatic variables impacts, which have adamantly secured Cape Town's placement as a city at high risk of water problems for the next century due to water scarcity. There are not many studies out there that specifically talk about how climatic variables could affect groundwater quality in urban areas when the climatic variables.

Groundwater constitutes an important source of water supply for domestic, industrial, and agricultural purposes in South Africa, with a well-documented water scarcity. According to Hansen et al. (2016), total groundwater use is estimated to be 15% of 65% of the surface area of South Africa. For example, in the Western Cape, the rapidly growing populations of Cape Town and surrounding towns, as well as economic growth, are putting an increased strain on the city's water resources. The City of Cape Town also plans to undertake a feasibility study on large-scale reuse of water. Other city investigations are underway on the potential for large-scale groundwater development and the use of the Table Mountain Group aquifer as a sustainable water resource (Ahjum et al., 2015; Srivastava et al., 2012). However, during this substantial supply-demand, freshwater resources are severely complicated by a complex climate system that is currently poorly understood within the rapidly growing City of Cape Town (Climate System Analysis Group, 2014). The main problems with understanding the regional climate system are that there are not many observations, and there are a lot of different climate models in the province.

The city of Cape Town, located in the southwest of the Western Cape Province of South Africa, is facing serious water shortages and drought problems. The increased demands for water in the city of Cape Town have led the region to opt to use groundwater as an alternative source for domestic, agricultural, and industrial purposes. Based on the demand for groundwater as an alternative water supply in Cape Town, it now needs to be managed. The Cape Flats aquifer is one of the city's critical sources of water supply. A general concern is that land use and climatic variables pose increasing groundwater potential contamination risks to the Cape Flats aquifer in the city of Cape Town. Land-based activities, such as waste disposal sites, industrial activities, and agricultural activities, have the potential to pollute aquifers. Commercial farmers in the areas surrounding the city have been suspected to use fertilizers, insecticides, and herbicides, which are likely to contribute to the degradation of groundwater quality. Continued impacts on groundwater are expected to occur due to increases in population without adequate management of urban, agricultural, and industrial activities on a regional scale. This could lead to a decrease in water quality and a decrease in socio-economic development.

This study aimed to develop a GIS-based model to highlight the impacts of climatic variables and human activities on groundwater quality in the Cape Flats aquifer in the city of Cape Town, South Africa. In this study, a combination of hydrological models (WaterWorld Policy Support System) and a modified DRASTIC model, coupled with spatial chemical analysis of water quality, was used as an appropriate tool within a GIS environment to assess groundwater pollution of the Cape Flats aquifer. The research made a great contribution to the knowledge base and established a way to protect the effects of changes in climate and land use on groundwater quality in coastal aquifers and ensure that groundwater is used sustainably in cities.

1.2 Problem Statement

1.2.1 Research Problem

The linkage between climatic variables information, hydrological simulation and human activities is the key to understanding future changes in the hydrologic cycle and subsequent deterioration of aquifer systems. Changes in the major climatic variables such as amounts and patterns of precipitation, temperature, evapotranspiration, and recharge have made groundwater resources vulnerable to contamination and other problems. This is a challenge since the hydrological cycle and its connections with underground water quality are complicated systems. Furthermore, for groundwater resources, the impacts of climate and land use changes must be fully assessed so that results-oriented monitoring can be designed and implemented as an intervention. This is necessary because groundwater resources in many parts of the world do not receive the same attention as surface water resources.

Water security and sustainability, including groundwater quality, were the focus of this study, which examines the potential impacts of change in land use and climate variability on groundwater quality in the coastal aquifer in urban areas. Groundwater is often an invisible resource, but an integrated model of the groundwater system and its connections to land use and climatic variables based on GIS is typically used to highlight areas and levels of vulnerability to potential contamination risk. Vulnerability mapping is the spatial distribution of the extent to which the natural environment of an aquifer is protected from potential contamination by human intervention (Saraswat et al., 2019). This work was specifically inspired by the growing need for such approaches that could be applied to the Cape Flats catchment in the city of Cape Town, South Africa. Intensive agricultural activities, urbanization, and industrialization threaten the quality of water in the area. Despite numerous studies that highlight concerns about groundwater quality degradation in the Cape Flats region, water quality responses to changes in climate and land use are only partially known (Adelana et al., 2010; Gxokwe and Xu, 2017; B. Mauck, 2015a). Therefore, to develop scientifically sound management in the study area, it is urgently necessary to establish strategies for vulnerability and protection against the risks of contamination of water sources. In this study, a GIS-based index method was used to evaluate vulnerability zones to human activities and hydrological variables by integrating the groundwater quality index (GWQ) and hydrogeologic parameters. The GWQ index was used to evaluate groundwater quality based on the risk of salinity, chloride, and nitrate at high concentrations. To evaluate the effects of climate variability on groundwater quality, ensembles of GCM and RCM were first used to estimate climate variables such as temperature and precipitation using the WaterWorld model. In the second phase to assess groundwater vulnerability, seven hydrogeological parameters were considered as the unit of analysis using the DRASTIC model for the Cape Flats aquifer. A groundwater contamination risk index was also used in a GIS setting to demonstrate how these tools can be used to learn more about how groundwater and climatic variables interact and how to keep groundwater safe.

1.2.2 Unit of analysis

This research has analysed the main relationships between climatic variables, land use, and groundwater quality, as well as visualising the potential contamination risk and processes of water quality pollution in the Cape Flats catchment in a GIS environment. The evaluation of the attributes of climatic variables, land use, and water quality were used to improve understanding of their interrelated relationships. Climate variables such as temperature and precipitation were used as indicators of climatic variables analysis. The units of analysis for the data obtained from remote sensing vulnerability mapping are GIS applications in ArcGIS 10.3 and other geospatial software. These were used to prepare various thematic maps and overlay analysis in a GIS platform for the identification of potential groundwater contamination zones.

1.2.3 Research Question

This study seeks to address the following research questions:

I. How are land-based activities and climate variability posing an increased risk that is likely to impact groundwater quality in the coastal aquifer in an urban catchment?

II. How has the GIS-based model explained the potential impacts regarding land use and climatic variables, which might have a negative effect on groundwater quality and inform sustainable management strategies to protect groundwater resources?

1.2.4 Research hypothesis

The present study argues that a poor understanding of potential groundwater contamination risk zones in coastal aquifer systems can lead to inadequate groundwater protection and management in urban catchments. To successfully protect and manage groundwater quality, it is necessary to understand the vulnerability zones in which contaminants are likely to occur in spatial and temporal variation using the GIS framework. A better understanding of groundwater quality would serve as the basis for determining the most effective strategies for monitoring and protecting groundwater resources.

1.3 Research Aims and Objectives

1.3.1 study aims

The goal of this study is to develop a GIS-based model that can measure and predict land use and effects of climatic variables on groundwater quality in the Cape Flats aquifer. This model can add to existing knowledge to develop deeper insight to make better decisions about how to manage water resources in specific climatic variables and land use scenarios.

1.3.2 Study Objectives

The study has three principal objectives:

Objective 1: Determine the changes in key climate variables such as temperature, precipitation, and sea level rise to understanding the possible future changes in the hydrological regimes and subsequent deterioration of aquifer systems.

Objective 2: Assess the vulnerability of the Cape Flats aquifer to groundwater using the DRASIC index method and apply the groundwater quality index method using a few selected water quality parameters.

Objective 3: Develop a GIS-based method to quantify the risk of groundwater contamination under changing climate variables and land use in the Cape Flats aquifer system.

1.4 Study rationale

1.4.1 Importance of the Study

The research will add to existing knowledge to better understand how hydrology, climate, land use, and vegetation interact to influence water quality. This knowledge becomes strategic since it contributes to better informed and more sustainable water resource management. Knowledge contribution through publication as per the following:

Paper 1: Impact of Climate Variability on Groundwater Quality

Title: Validation and down-scaling of the impact of climate variability on groundwater quality in coastal aquifers of urban areas in South Africa.

Paper 1: Impact of Climate Variability on Groundwater Quality

1.1. GIS-based modelling of climate variability impacts on groundwater quality: Cape Flats Aquifer, Cape Town, South Africa

1.2. Validation and down-scaling of the impact of climate variability on groundwater quality in coastal aquifers of urban areas in South Africa.

Paper 2: Aquifer vulnerability mapping (Risk assessment paper)

Title: Using GIS-based DRASTIC Modelling of the Cape Flat Aquifer to Improve Understanding of Potential Contaminants in an Urban Hydrogeology Setting of South African Coastal Aquifers.

Paper 3: Development of a GIS-based integrated model for feasible groundwater monitoring in coastal aquifers to improve water security in a modern, progressive city prone to drought, such as Cape Town, South Africa.

Developing practical tools such as contamination risk assessments and vulnerability mapping are important aspects that need to be considered in the development of sustainable groundwater management. In general, maps are practical tools that can help as a road map towards sustainable use and management of groundwater quality in the area. The resulting vulnerability and risk maps are simplified forms that can be easily understood. The degree of spatial distribution of water quality parameters is presented with different colour legends. This helps to better understand the parameters, as well as their implementation by the local authorities, more easily.

1.4.2 Conceptualisation of the study

The degradation of water quality is becoming one of the greatest threats to sustainability. The aquifers of agro-industrial cities are among the most vulnerable areas, especially in coastal aquifer systems. The alteration of the watershed due to urbanization, industrialization, and agricultural activities can have significant hydrological consequences. Rising temperatures and rising sea levels can increase saline intrusion into the underlying aquifers. The Cape Flats aquifer is at risk of degradation primarily due to agricultural, industrial, and other human activities. These results were essentially confirmed by (2013a) that future development of the aquifer is intended to improve groundwater resource management and protection, as there is an increasing need and scope for the city of Cape Town. However, further research should focus on protecting the aquifer and climate variability while exploiting groundwater in the region, the relationship between land use and aquifer protection, detailed mapping and delineation of groundwater vulnerability zones, and evaluation of the effects of groundwater management on the local environment, such as seawater intrusion, to prevent the aquifer from further deterioration. Recent studies by Gxokwe et al. (2020), Gxokwe and Xu (2017), and Mauck (2017) examined urban hydrogeology in the context of water-sensitive urban design (WSUD) and managed groundwater recharge (MAR) to control flooding and supplement urban water supplies. They concluded that CFA should be considered as a supplemental water source for Cape Town, particularly due to recent drought conditions. Studies have helped people make better decisions about managing water systems in Cape Town. The future development of the aquifer should improve the management and protection of groundwater resources.

The current study contributes to a detailed assessment of the risk of contamination and protection of the aquifer, with an emphasis on the use of GIS techniques to map vulnerable zones. First, modeling in a GIS climate and land use change environment provides the basis for developing water resource management strategies. Finally, the most important reason is that a GIS-based model can account for future changes in climate and land use, which in turn can help identify potential future threats to water quality. Based on available data that can be used to develop appropriate strategies to ensure sustainable use, protection and monitoring, a hydrological model based on physical evidence (WaterWorld) and a DRASTIC model were developed and eventually coupled to better understand human activities and impacts of climatic variables in the Cape Flats region. The World Health Organization (South African standard) has standardised the water quality parameters that were considered in the calculation of the water quality index for the area. A GIS-based model can account for future changes in climate and land use, which in turn can help identify potential future threats to water quality.

1.5 Scope and nature of the study

1.5.1 Scope of the study

The scope of the study was limited to the CFA in South Africa. It is a comprehensive study of a GIS -based modelling approach to contextualise urban groundwater management planning and design that focuses on integrating hydrological models in a more holistic and comprehensive manner. This allows for how climatic variables and human activities affect water quality and how integrated groundwater management works.

1.5.2 Nature of the study

The research design for the present study is an empirical study of a predictive approach using quantitative methodology. The study was carried out using the following methods: desk study, existing data analysis, satellite image processing, modelling, and mapping. Most of the data used in the study came from remote sensing data and topographic information from maps used to create different thematic layers. The appropriate weighting was applied to a spatial domain to identify potential groundwater contamination zones. Once the data are available, an application GIS is used to create and classify thematic maps that are integrated using a weighted index overlay analysis. The results obtained are classified into categories such as "poor", "low", "moderate", and "high". To validate the results, a water quality index (WQI) was calculated for the overall water quality. Selected water quality parameters (chloride, nitrate, sulfate, phosphate, and electrical conductivity) helped the study gain a better understanding of the impacts of anthropogenic activities. This study addresses contamination risk assessment and vulnerability mapping. These are important aspects to consider in the development of sustainable groundwater management.

1.6 Outline of the thesis report

This thesis is divided into six chapters. Chapter 1 is about the general introduction. It contains the background, the problem, and the objectives of the study. Continue with the significance of the study, the design of the study, and finally the outline of the thesis. Review of Chapter 2 of the literature. Provides a review of the literature on the impacts of land use and climatic variables on the hydrology of the watershed and the quality of groundwater. The focus is on the methodological approach, the methods used, the results found, and the setting in which the studies were conducted. The review was presented in a systematic way with respect to the specific objectives of the current study. Chapter 3 provides a description of the study area. Chapter 4 describes the research design and methodology. This chapter examines the various research methodologies and research methods used for this study. It describes the research design used for this study, the research methodology chosen for the study, the research methods used for data collection and analysis, the quality assurance and quality control measures taken to ensure the validity and reliability of the research findings, and the research integrity measures taken to strengthen the reliability of the research findings of a research study. Data collection and analysis methods for information systems are discussed. In addition, in this section, research methods are discussed, as are the types of research methods appropriate for information systems research. Because secondary data sources were used in this study, a section is included to explain the differences between the two and the benefits of using secondary data sources for research. Chapter 5 is a summary of the findings and a discussion of the three research objectives. It contains the results and discussion of objectives 1 through 3, as presented in Section 1.3 of this chapter, including a description of key data, data analysis, interpretation of results, comparative analysis, implications of the results, and evaluation of the study. Chapter 6 presents the conclusions and recommendations. Conclusions and recommendations are provided for the entire thesis. This chapter summarises the study and provides suggestions for future research based on the results.

Chapter 2: Review of the literature

2.1 Introduction

The first chapter contains a brief general introduction to the study, a statement of the problem, the objectives of the research, the research question, and the rationale for the study, to name a few. Previous studies were reviewed to provide a gap analysis related to integrated GIS-based modelling and to highlight its importance for groundwater protection and effective management in the context of coastal aquifers in urban settings. In a GIS setting, the principles, concepts and framework that govern groundwater quality under the coupled impacts of climatic variables and human activities are explained in detail. To place this study in the context of different scales or levels, an overview of a broad range of important issues is if address climatic variables, land use, and water security at global, national, and regional scales. The review of the studies conducted is based on key words, a search of primary works, and a review of the relevant literature. Analysis of the literature looked at investigates which methods, theories, models, or frameworks are best for the current study.

2.2 Previous research on the effects of land use change and climatic variables on groundwater quality

2.2.1 Global status of the impacts of land use and climatic variables on groundwater quality.

In the last decade, extensive research has been conducted to investigate the impacts of land use and climatic variables on groundwater resources in different countries. For example, Li and Merchant (2013) demonstrated the vulnerability of groundwater under different climatic variables and land use scenarios in North Dakota, USA. The authors integrated hydrological models and a groundwater vulnerability model in a GIS environment to map the risk of groundwater contamination in the study area. The GIS-based model was found to provide important information for decision makers in identifying potential threats to groundwater contamination and supporting measures to protect such an important resource. In another study by Fan and Shibata (2015), a watershed hydrology and nutrient model (Soil and Water Assessment Tool, SWAT) was used to assess and understand the relationships between hydrological mechanisms and water quality at the watershed scale in different climate and land use situations in Japan. Furthermore, Pervez and Henebry (2015) used an integrated hydrologic simulation model with downscaled climate and land use projections derived from global climate models (GCM) to quantify the potential impacts of future climate and land use changes in the Brahmaputra River basin in South Asia. The authors found that the hydrological systems of the basin will increase in response to climate variables in response to climate and land use change scenarios. Furthermore, Montenegro and Ragab (2012) used an integrated distributed hydrological model to simulate and better understand changes in the groundwater system in a semi-arid basin in Brazil. These modeling results show that the effects of climatic variables and land use on water resources must be considered when planning water resource management.

2.2.2 Regional status concerning the impacts of land use and climatic variables on groundwater quality

The potential impacts of climate and land use change on groundwater have long been recognised globally as a factor that negatively affects water quality and the environment. Dwarakish and Ganasri (2015) addressed the need to integrate land use change models and climatic variables models (GCM and RCM) with hydrological models to improve the efficiency of hydrological response prediction. They used a three-step process to determine how changes in land use and climatic variables might affect water resource management. First, they created a model to determine how change in land use and climatic variables might affect water resource management. Second, they created a model to find out how land use changes and climatic variables could affect water resource management, and third, they created a model to find out how land use changes and climatic variables could affect water resource management. Third, they used integrated models as an efficient technique to predict long-term hydrological variability. In the study by Osei et al. (2019), the hydroclimatic variability resulting from anthropogenic activities in the Owabi catchment in Ghana was assessed. It was also confirmed that the SWAT model has proved to be more reliable in modeling the impacts of the hydrology parameters of the catchment on water quality and pollution, and in helping to manage effective and efficient water resources. Comte et al. (2016) investigated the hydrogeological heterogeneity of the coastal environs in East Africa to identify knowledge gaps that needed further research in those areas. The results illustrate that climate, rising sea levels, and land use increase the potential threats to freshwater, and most of the deterioration of water quality is due to the intrusion of saltwater by rising sea levels.

Regardless of the specific techniques used, it has been shown that the best results are obtained with the integration of climate and hydrology models that are spatially distributed at regional and local scales. However, to better understand the complex interactions between hydrology and groundwater chemical parameters, process-based mathematical models remain one of the most powerful and versatile techniques that can be used. Groundwater hazard maps provide useful information for monitoring the changing levels of contaminants. Velazquez et al. (2013) further demonstrated the combined influence of land cover and land use activity management on water quality based on the role of temporal and spatial scales in a coastal catchment on the southern coast of South Africa in the Gouritz Water Management Area (WMA). The databases used showed that when the spatial heterogeneity of the catchment was altered by human impacts, such as agriculture, this was reflected in changes in water quality. Similarly, Zhu and Ringler (2010) analysed the impact of climatic variables on water availability in the Limpopo River basin in southern Africa using a linked modelling system consisting of a semi-distributed global hydrological model and the Water Simulation Module (WSM) model. The analysis showed that the water resources in the Limpopo River Basin are already stressed under current climate conditions. However, the study only addresses the impacts of the combination of LULC and climatic variables on hydrological processes and groundwater quality on the basin scale, which is limited.

2.2.3 National status concerning the impacts of land use and climatic variables on groundwater quality

Various modelling techniques have been used to determine the potential impacts of various land uses and climatic variables in the Cape Flats watershed. Technological change and increasing knowledge and understanding are changing perceptions of risk, and priorities for water resource management must be flexible and adaptable (Duah and Xu, 2013). However, much remains to be done regarding the coupled impacts of climate variability and human activities on groundwater quality. Previous studies by (Adelana et al., 2006a; Mauck, 2017a) developed conceptual modelling of the recharge mechanism and hydrochemical properties in the study area. The results of these analyses show that anthropogenic and agricultural activities are responsible for the degradation of groundwater quality. The authors confirmed that an integrated management tool is needed to manage water resources more effectively in the Greater Cape Town area. There is a lack of studies on the coupled effects of climate variability and change in land use on groundwater quality throughout the Cape Flats region. Therefore, there is a real need for a tool to study how changes in climate and land use might affect water resources in the Greater Cape Flats region. This tool would examine how changes in climate and land use could affect water resources. The objective of this study is to investigate the effects of land use and climate variability on groundwater quality in the Cape Flats aquifer, South Africa, using integrated modelling. The results will contribute to a better understanding of the hydrological impacts of land use and climatic variables to inform better management of water resources in the Cape Flats and identify methodological issues and gaps in the literature.

2.3 Synthesis of the literature review on how to determine how climatic variables will affect groundwater quality.

In recent decades, many scientific studies have been conducted to understand how water resources can respond to a consequence of climatic variables. Shamir et al. (2015) analyzed the variation of precipitation for the Upper Santa Cruz River, Arizona, SA using a dynamic downscaled GCM model. However, the management of water resources in the region faces challenges due to the complex natural variability of rainfall. To understand the problem, the study used a hydrological framework to assess the impact of projected climatic variables on regional water resource management. The team suggested a further study on the application of the model to assess the impact of projected climatic variables on local water resources in other regions. Following the recommendation, Arnell et al. (2015) provided strategies for a systematic assessment and protection of water management in England. However, only a few studies have examined how climatic variables could affect groundwater quality, although groundwater is important for the security of a country's water supply.

There is increasing concern about groundwater contamination by land-based activities, and climatic variables are a serious challenge for humans and the environment (Mohammadi Ghaleni and Ebrahimi, 2015). Fundamentally, sustainable water resource management and socioeconomic development are entirely based on a thorough understanding of the availability of water resources and their actual protection. Climatic variables can disrupt many aspects of economic development, given its impact on agriculture and water supplies (X. I. A. Jun et al., 2010). Under conditions of climatic variables, this response is likely to be indefensible, especially in those areas that would experience an increase in drought capacity (Jakeman et al., 2016b). As a result, there is less precipitation, which causes more water stress and more intense droughts and increases in temperature, which in turn causes more evapotranspiration, which in turn reduces recharge rates.

The issues linking climatic variables to groundwater have increasingly become a talking point among the scientific community in recent years (Fitch et al., 2016b). Groundwater contamination caused by increases in sea level and changes in precipitation and temperature has been extensively reported to be most likely caused by climatic variables (Pasini et al., 2012). Although climatic variables legitimately influence the main hydrological factors, for example, air temperature, precipitation, and evapotranspiration (Kløve et al., 2014; Kumar, 2010; Panwar and Chakrapani, 2013), the connection between climatic variables and groundwater quality is more complex and poorly understood. The IPCC demonstrated that more research is needed to improve the understanding and modeling of climatic variables related to the hydrological cycle at scales relevant to enable decision-making at all levels. The connection between climate-change variables and groundwater quality is more complex and poorly understood. The IPCC demonstrated that more research is needed to improve the understanding and modeling of climatic variables related to the hydrological cycle at scales relevant to enable decision-making at all levels. Information on the effects of climatic variables on water is lacking, especially when it comes to groundwater quality (Aizebeokhai, 2011a).

In recent decades, many scientific studies have been conducted to understand how water resources may respond to the consequences of climate variables. Shamir et al. (2015) analysed precipitation variation for the Upper Santa Cruz River, Arizona, USA, by using a dynamic downscaled GCM model. However, the management of water resources in the region faces challenges due to the complex natural variability of rainfall in that area. To understand the problem, the study used a hydrological framework to assess the impact of projected climatic variables on regional water resource management. The team suggested a further study on the application of the model to assess the impact of projected climatic variables on local water resources in other regions. Following the recommendation, Arnell et al. (2015) provided strategies for a systematic assessment and protection of water resources and their management in the water environment in England. However, few studies have looked at how climatic variables could affect groundwater quality, although groundwater is important to any country that relies on it for its water needs.

2.4 Synthesis of the Review of the Literature on Groundwater Vulnerability Assessment in a Coast Aquifer

Changes in land use and land cover (LULC) affect hydrological processes by altering evapotranspiration (ET) and surface runoff. Runoff patterns are the result of indicated human activity that affects evapotranspiration based on the water balance in the hydrological cycle. These findings indicate that changes in land use induced by human activity in the water cycle should not be ignored. Furthermore, Peter et al. (2018) demonstrated the combined influence of land cover and land use activity management on water quality based on the role of temporal and spatial scales in a coastal catchment on the south coast of South Africa. Human impacts such as agriculture, do indeed affect water quality, which was spatially heterogeneous in the catchment. In recent years, the change in land use has emerged as the most important variable among environmental threats and changes that ultimately affect groundwater quality. Changes in land use affect a wide range of environmental characteristics, including water quality and the climate system they influence. Consequently, changes in land use for agriculture and urban growth are sometimes accompanied by changes in groundwater recharge and associated groundwater quality. In South Africa, several drivers of increased pollution risk have been identified, including urbanisation, deforestation, reduction of wetlands, industry, mining, and agricultural activities. To achieve this objective, moderate-resolution satellite data (30-m Landsat series imagery) acquired in 1995 and 2016 were used. Overall, the results have discussed the impacts of the change in land cover in relation to basin hydrology and water resource management. In particular, the Cape Flats watershed has been under significant pressure over the past decade. The area has seen strong population and economic growth, as well as new urban development and agricultural land expansions, and changes in the hydrology of the area.

2.5 Synthesis of the literature review on mapping groundwater contamination risks using GIS-based integrated modelling

In recent years, sustainable management of groundwater quality has increasingly relied on geospatial models. Hydrologic modeling is considered a reliable alternative to other widely used tools for studying the factors that control the impacts of climatic variables and land use on water resources. Various tools have been used to describe groundwater quality, allowing informed decision making for management (Machdar et al., 2018a). According to Li and Merchant (2013), GIS-based groundwater modelling for contamination risks is critical for protecting groundwater resources. It is used to identify future potential threats to water quality. In addition, GIS -based models that account for future changes in climate and land use form the basis for developing strategies to protect and sustainably manage water resources. By mapping vulnerable areas, it is possible to determine which areas are more susceptible to contamination and work to prevent the risk of contamination. This study focused on the use of modelling techniques to assess groundwater quality and vulnerability to aquifers. Groundwater quality assessments are relatively complex. However, they can be accurately modelled using extensive applications of GIS -integrated advanced statistical methods.

2.6 Theoretical and conceptual frameworks

2.6.1 Theoretical framework

In recent years, many models based on geographic information systems (GIS) have been developed to assess the risk of potential groundwater contamination. GIS-based modelling is discussed in this research in relation to land-based activities, climate variability, and groundwater quality. Some studies address how the climatic variables associated with land-based activities (e.g., irrigation expansion, industrialization, and urbanisation) poses a threat to groundwater, particularly in urban areas of coastal aquifer systems. Integral GIS-based integrated modelling has recently gained popularity as a potential approach to better understand the interactions between climate variables, anthropogenic pressures, and the water quality problem. Integrated modelling is also one way to achieve accurate and reliable hydrological predictions through the use of a single scenario (Dwarakish and Ganasri, 2015).

Technological advances in recent years have enabled resource management in the coastal watershed at the urban scale. Advances in integrated modelling approaches should soon provide the ability to assess the potential impacts of climatic variables on groundwater resources on a regional scale. These methods have shown a marked improvement in the quality of results related to land use, and climatic variables scenarios tend to be coarser in resolution, adding no new meteorological insights beyond GCM-based changes and thus simplifying the spatial variation of hydrological parameters. Additionally, GIS-based models have historically excelled in providing an opportunity for spatially explicit analyses of model results and their representation on maps. Saatsaz et al. (2011) examined the hierarchy and evolution of climate models using downscaling techniques, general circulation models (GCMs), and hydrological model development to improve the effectiveness of modeling approaches used in assessing the impacts of climatic variables on hydrological conditions. The results indicate that coarse resolution for regional-scale features is important for assessing the impacts of climatic variables on hydrological regimes, which limits the applicability of hydrological models. A GIS-based numerical tool facilitates water quality studies by bringing together key data and analytical components in a GIS to perform overlay and index operations and provides the use of analytical tools and visualisation capabilities in groundwater modelling. However, the level of protection and the methods by which these efforts are carried out vary widely across a region. Another example can be seen in a study by Khan et al.(2011), which applied a GIS-based tool to study the impacts of land use changes on groundwater quality in a rapidly urbanising area in South India. In general, effective water resource management relies on comprehensive modeling tools to facilitate an informed decision-making process. However, none of these interventions has had a significant impact on the integration of urban groundwater systems with their surroundings (Cheng et al., 2017; Malik and Shukla, 2019b; Zhou et al., 2018).

2.6.2 Conceptual Framework

This research was developed primarily within the framework of a GIS-based integrated model designed to help improve the understanding of the impacts of groundwater quality in an urban environment. The GIS-based model allows users to effectively run a variety of proven water quality models within a single GIS format that integrates multiple models. The models generate GIS models, data analysis, decision making and results analysis. This study is also based on the WaterWorld Policy Support Tool, which assesses hydrological and water baseline conditions and water risk factors associated with scenarios for land-based activities (Mulligan, 2015; Van Soesbergen and Mulligan, 2014). The model is linked to a geographic information system (GIS) to enable appropriate generation and management of model input and output data and advanced visualisation of model results for effective water resource management under future climatic variables and land use scenarios. **Error! Reference source not found.** shows the conceptual framework for this study. It shows how groundwater quality and climatic variables are linked, as well as the role groundwater storage can play in adapting to climatic variables, if it can be found.

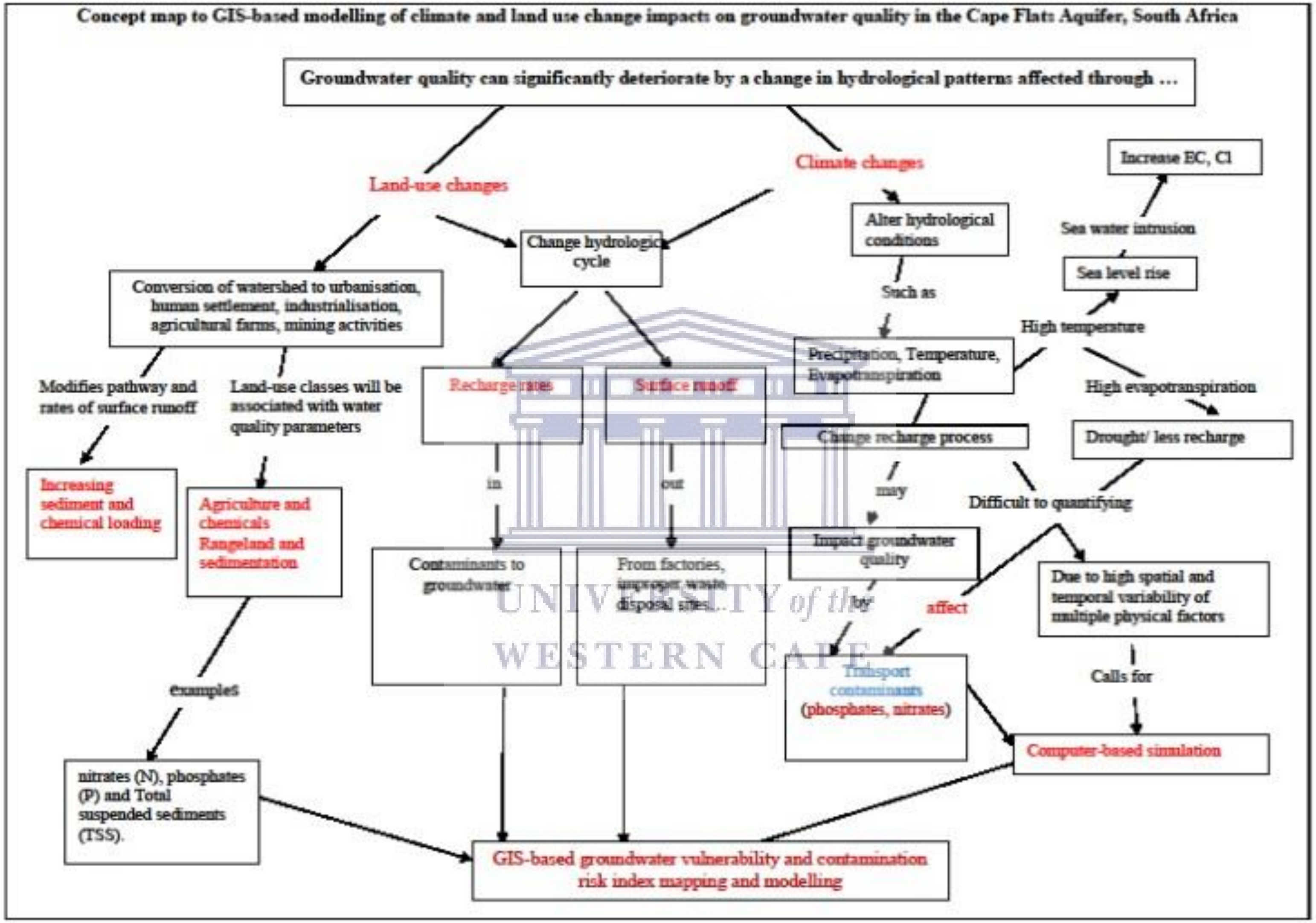


Fig. 2.1. Framework for testing the research hypotheses

2.7 Research and Interpretation Frameworks

The review was presented as follows: First, assess the impacts of climate variability on groundwater quality using a hydrological model in a GIS environment. Second, the DRASTIC model calculates the vulnerability of the aquifer using geospatial software and hydrogeological data in a geographic information system (GIS). Furthermore, the evaluation of typical groundwater hazards and processes that occur in coastal aquifers was discussed based on integrated GIS techniques. In addition, peer-reviewed academic sources were mentioned that do not focus on the effects of climate and land use on groundwater quality. Furthermore, the review focused on the use of an integrated distributed hydrological model and a modified DRASTIC model coupled with a spatial chemical analysis of water quality in a GIS setting under changing land use and climate conditions. Finally, this review has shown that we still do not know much about how pollution affects groundwater quality in an urban setting. This study should help fill this gap.

First, it is important to find out how changes in land use and climatic variables could affect water resources. Second, it is also important to find out how different characteristics of land use and climatic conditions affect the hydrological response. Finally, integrating different hydrological models can be a good way to manage water resources more effectively.

2.8 Overview of Gap Analysis

In this chapter, a review of the literature of previous researchers was presented to highlight the existing knowledge gap in the assessment of groundwater quality risk under changing climatic conditions and land-based activities. However, most of these studies have been limited to the spatial variability of factors that control hydrological processes in the basin and their effects on groundwater quality. More research is needed to better understand and model the effects of climatic variables on hydrological variables and systems at the spatial and temporal scales that are important for people to make decisions about what to do.

Climatic variables and land-based activities continue to put more pressure on groundwater pollution in cities. Unfortunately, research on the problems caused by hydrological variability is limited. A conceptual framework is needed to improve understanding and modeling of climatic variables at spatial and temporal scales relevant to decision making. Information on the impacts of groundwater resources, climatic variables, and changes in land use affects the provision of more effective watershed management. However, an aquifer complex presents several challenges in evaluating an aquifer's susceptibility to pollution. Despite significant progress in the development of vulnerability assessment methodologies, there are still significant research gaps. Much must be learned about the difficulties in assessing groundwater vulnerability and risk.

The Cape Flats aquifer is in a low-lying coastal area, which means it is at a continuing (high) risk of contamination. The future impacts of climatic variables and land-based activities on water resources are still uncertain and need to be determined and quantified. There is a knowledge gap in the literature on the coupling of climatic variables and land use change with impacts on Cape Flats Aquifer water resources. The study aims to build a GIS-based integrated model that will help us better understand the impacts on groundwater quality in an urban setting. Unlike previous research, this study reveals spatially distributed hydrological parameters at the basin scale, providing a better understanding of the critical factors that affect groundwater quality. The method based on GIS provides the flexibility to address very complex groundwater resource management problems under the conditions of climatic variables and human activities. The DRASTIC model is a proven tool to study groundwater vulnerability. Vulnerability maps are made to show which areas have the highest risk of groundwater contamination. Benefits include mapping vulnerability and developing and managing groundwater monitoring plans.

In the following chapters, the case study area is presented, and the methodology is discussed based on its application to the Cape Flats watershed. Furthermore, key findings from vulnerability and contamination risk maps that were made for the land use and climatic variables scenarios chosen are looked at to see which areas are at risk from human activities and climatic variables.

Chapter 3: Description of the study area

3.1 Location and climate

The case study area is in the metropolitan area of Cape Town, South Africa, which is in the western Cape province. It is in a low-lying coastal area southeast of the city of Cape Town that lies between latitudes -33.8125_N to -34.125_S and longitudes 18.375_W to 18.8125_E (Fig. 3.1) The Cape Flats area straddles Table Bay and False Bay and predominantly connects them. The research area is defined by a large, steep sandy area that connects the Cape Peninsula's hard rock with the low-lying coast (Conrad et al., 2004). In particular, a strip of sand extends along the west coast from Cape Town, Bellville, and up to the Atlantis areas.

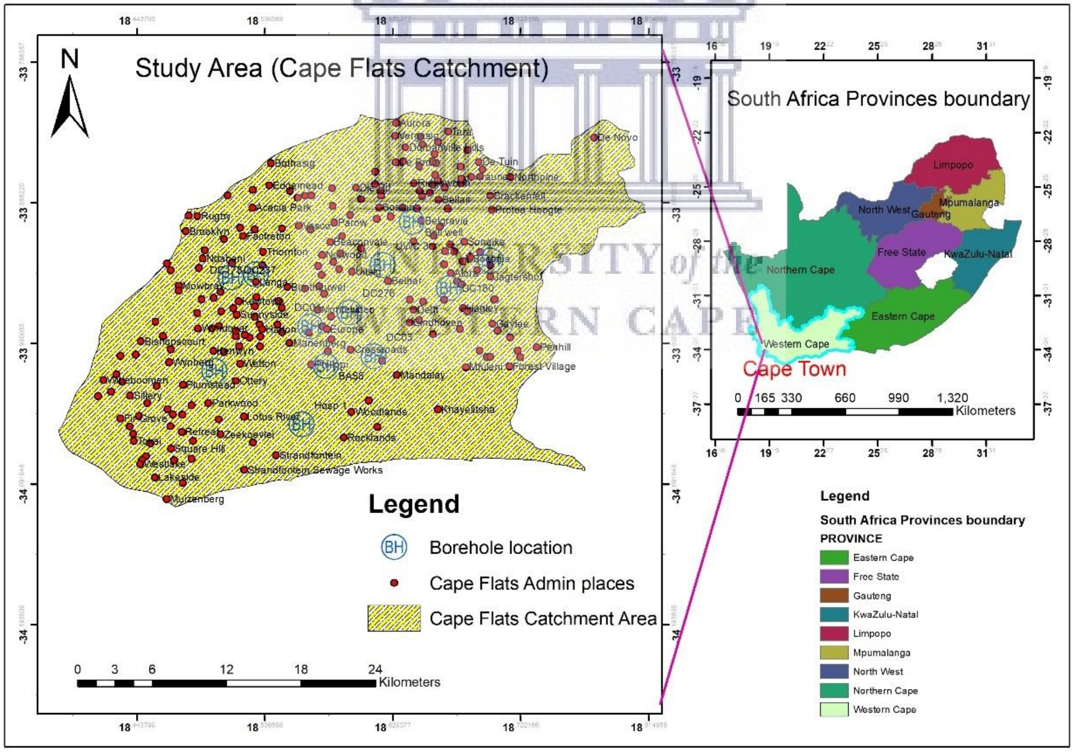


Fig. 3.1. Cape Flats map showing study areas

The Cape Flats area has a generally similar Mediterranean climate with hot, dry summers and cold, wet winters. It has a semi-arid climate like the Mediterranean, with low rainfall and high temperatures. Fig. 3.2 shows climate data from meteorological stations at Cape Town International

Airport, evaluated over a 39-year period (1979-2018), with large rainfall variations ranging from 284 mm to 707 mm. The average annual rainfall is about 511 mm, measured at the Cape Town International Airport meteorological station for the period 1979-2018. The highest rainfall in Cape Town was 707 mm in 1976 and the lowest amount was 284 mm in 2017.

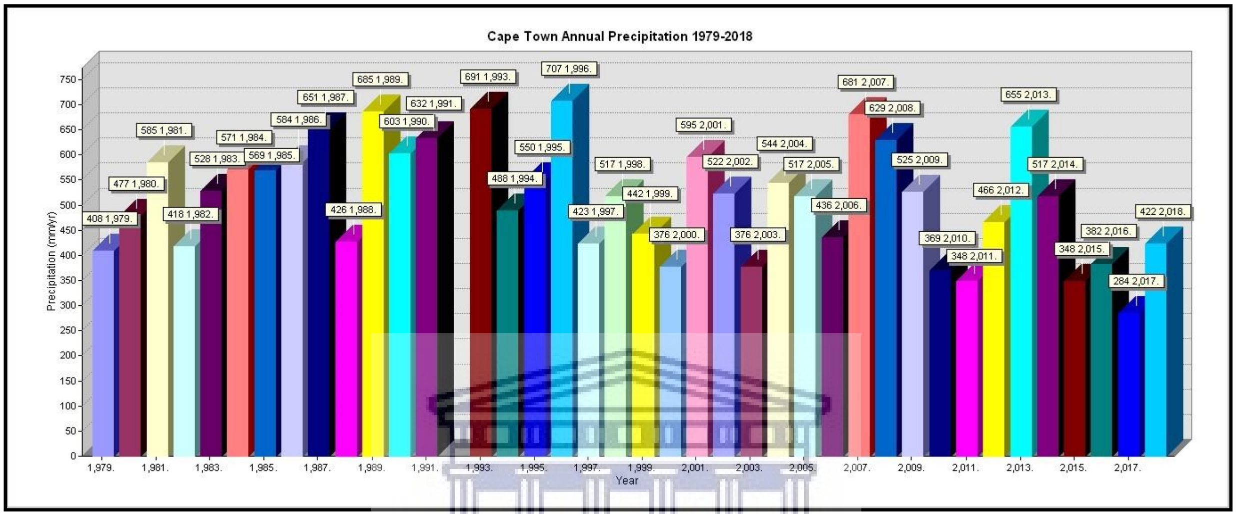


Fig. 3.2. Mean annual rainfall derived from the year 1979 to 2018

The average annual values on the basin scale (1979-2018) for temperature: maximum, minimum, and mean are 29.7°C, 15.7°C, and 22.4°C, respectively (.). The upper middle row indicates the mean temperature for the periods, and the bottom line shows the minimum temperature change (°C). The highest temperatures occur in January (29.5°C), while the lowest is in July (15.7°C). The changes in the mean monthly temperature from 1950–2000 (left side bars) to 2041–2060 (right side) show significant increasing trends in temperature, except in the month of May, in both periods, the annual temperature increased by more than 2.17 ° C in the entire CFA catchment, as indicated in. In this figure, it can see how the WaterWorld model compares with the temperature data from Cape Town International Airport over a period (1979–2018).

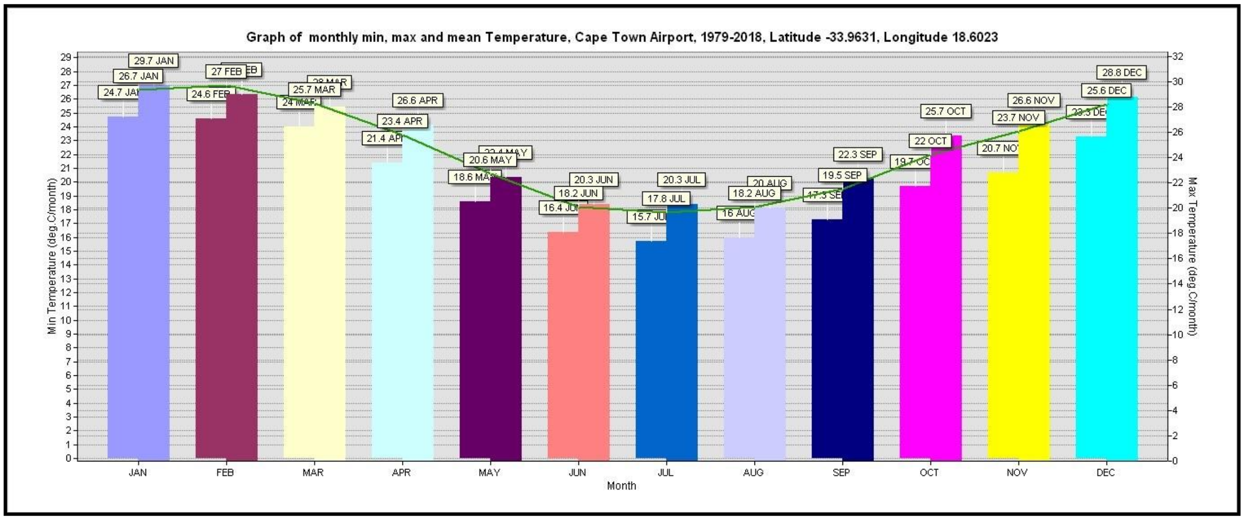


Fig. 3.3. Monthly minimum, maximum, and mean temperature (Cape Town International Airport, recorded from 1979–2018), compared to the WaterWorld model

3.2 Geology and hydrogeology of the Cape Flats Aquifer

The geological formation of the Cape Flats is depicted in Figure 3.2. The area is made up of Cenozoic sands that lie on top of the Malmesbury shale (Tredoux et al., 1980). Various sand formations cover the entire area, resulting in various sand formations. The Langebaan formation is distinguished by very fine to medium calcareous sands with cross-bedding along the coast (Hartnady and Rogers, 1990). According to Tredoux et al., the Springfontein formation consists of angular fine to clayey sands. The Velddrif Formation is a patchy deposit of partially consolidated lime-rich shell and sand beds with shelly layers (Theron, 1984). The Neogene deposits of the Western Cape include the Pliocene Varswater Formation. This formation is underlain by the Saldanha and Elandsfontein Formations from the late and middle Miocene. There are several other Cenozoic deposits that do not have formal names.

The Cape Flats are part of the "late-tertiary and recent sands" unit of Dingle (1973) geological map. They are essentially Quaternary sediments that cover the Neogene deposits, about which little is known except through boreholes and quarries (Theron et al., 1992). The Sandveld Group's quaternary deposits are mostly aeolian sand, with minor fluvial to marine deposits thrown in for good measure (Rogers, 1982). The presence of abundant small shells and shell fragments distinguishes the Witzand Formation, which consists of very fine to very coarse calcareous sands. The Langebaan Formation is a limestone member of the Bredasdorp Group that has been incorporated into quaternary sediments of the Sandveld Group. The sand body of the Cape Flats is horizontally stratified, with several lithostratigraphic units identified. The sedimentation process began in a shallow marine environment, progressed to intermediate beach and wind-blown deposits, and finally to aeolian and marshy conditions. The bedrock topography shows a palaeovalley that is more than 40 m below mean sea level in the northeastern part of the area (Meyer, 1981).

The geological unit of the area includes alluvial sediments of peat, clay, and silt, as well as unconsolidated deposits in low-lying coastal areas. Geologically, the Cape Flats catchment comprises sedimentary deposits of the Sandveld Group. It is classified as the Cenozoic age. It overlies an extensive impervious layer of Malmesbury shale. The underlying bedrock consists of the Cape Granite Suites west (Fig. 3.4). The geological unit generally includes fluvial, marine, and aeolian tertiary and quaternary deposits (Adelana, 2010; Umvoto Africa and Ninham Shand Consulting Services, 2008). Littological deposits include interbedded sands, clay, clayey sand, limestone, sandstone, coarse gravel, and peat (Gnandji et al., 2013). The stratigraphic summary ranges from the oldest to the youngest as follows: First, unconsolidated to semi-consolidated sediments (sand, calcrete, calcarenite, aeolianite, conglomerate, clay, silcrete, and limestone). There are two main sources of the sand: quartzite and sandstone from the Malmesbury Formation and the Table Mountain Series. Second, eolian sand is deposited as dunes on top of the marine sands. Third, arenite is predominantly composed of arenaceous rocks (sandstone and feldspathic sandstone). The geology of the area was described in detail by THERON (1984) and is summarized in Fig. 3.4.

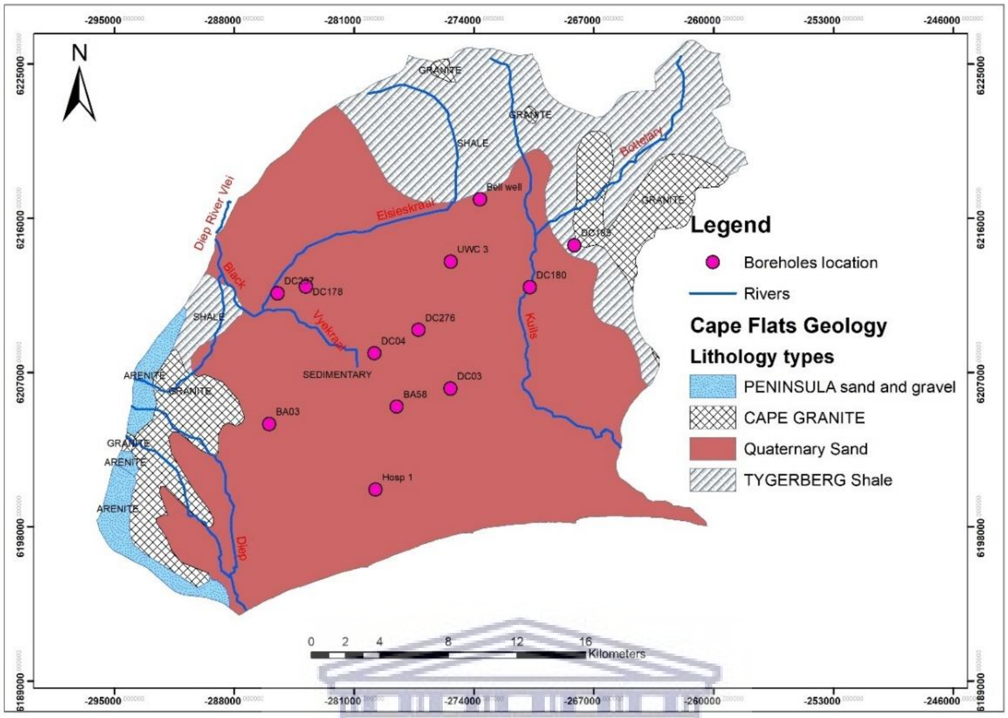


Fig. 3.4. Geological map of the study area with boreholes and rivers

The hydrogeology of the Cape Flats aquifer consists of porous sedimentary deposits, and it is bounded to the west by the bay called False Bay. It is a vital source of water for the people of Cape Town, its metropolitan area, and its local industries. The groundwater basin of the Cape Flats is made up of highly permeable sand and gravel layers. The low-lying Cape Flats aquifer in Cape Flats is shallow and unconfined, with the thickness of the quaternary deposits varying from 20 to 30 m. The Quaternary Alluvium aquifer is the most important aquifer in the catchment and is also the most sensitive to groundwater contamination. Quaternary alluvium is made up of elements such as clay, silt, sand, and gravel that cover all the other lithological units. The primary aquifer consists of clean coarse-grained sand and is generally highly productive. The aquifer is made up of clean and coarse sand and is typically high-yielding. Arenaceous sandstone is the first significant lithologic unit in the area and exhibits fractures and degrees of weathering. Arenaceous rocks consist of feldspathic sandstone that occurs as sills and dykes mainly in the limestone-shale-marl intercalation (Reid, 1991). It is surrounded by the A layer of Malmesbury Shales and Cape Granite. In many parts of the aquifer, the groundwater level is close to the ground surface and the water intake wells are located along the coastline, where the groundwater level can often fall below the sea level. The groundwater table varies between 2 and 10 m below the ground surface in the inland area (Adelana et al., 2006). The flow of groundwater is from high-altitude areas to lower-altitude areas toward the coast. Several wetlands, dams, and streams flow through the Cape Flats area. Recharge to the aquifer occurs primarily through precipitation falling on its surface (Segun et al., 2006). The most recent work on recharge estimation was done by Hay et al. (2015) and Mauck (2017). The main groundwater recharge zones are in the higher elevation mountain areas, which are in the eastern part of the region. Additionally, the groundwater level fluctuation pattern in the Cape Flats shows clear seasonal variations due to high evapotranspiration and low precipitation, as shown in Fig. 3.5. It is an important source of water for the residents of Cape Town and its metropolitan area and its local industries. However, according to (2010a), based on analysis of hydrogeologic data and aquifer parameters, the Cape Flats aquifer can store enough water to support its development as a water source, although it is very vulnerable to surface contamination because it is mostly unconfined.

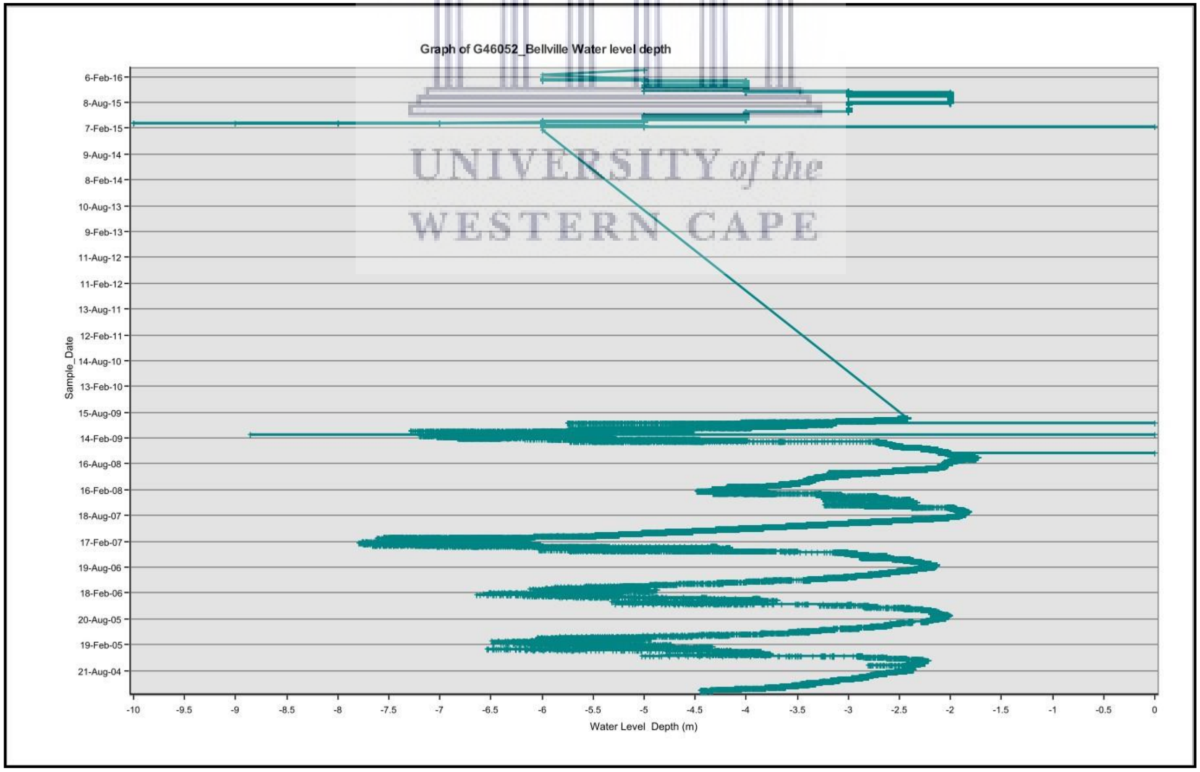


Fig. 3.5. Seasonal changes in water level fluctuation

3.3 Topography and drainage system

Topographic factors play an important role in the regulation of groundwater in the urban coastal catchment area. Most of the time, topography influences groundwater quality by increasing the rate at which particulate matter enters a groundwater body and changing the water chemistry. Due to slow runoff, flat topographic areas get a lot of contaminants. This gives the contaminant more time to enter the groundwater. However, areas with steep slopes make it easier for runoff to carry pollutants that come from the ground (Victorine Neh et al., 2015). Nonpoint sources have been found to be the source of metals, nutrients, and salts in groundwater on Cape Cod, Massachusetts (Dawes et al., 2012; Report, 2019). The topography of the study area varies between 0 and 1057 m above sea level along the northern ridge, while in the south and southeast, the elevation gradually decreases to 5 to 7 m above sea level (Fig. 3.6). In the middle, much of the land has a topography that ranges from 0 to 66 meters, especially along the False Bay coastline. This means that the area has a wide range of topography, from lowland plains to very rough and mountainous areas at higher altitudes. Toward the central part, a considerable area of the Cape Flats has topographic elevations in the range of 0 m (along the False Bay coastline) to 66 m, mainly below 36 m to the south of an arcuate line connecting False Bay and the northern and western shorelines. The lowland areas of the Cape Flats usually receive less rain and have higher evapotranspiration rates than the mountain areas.

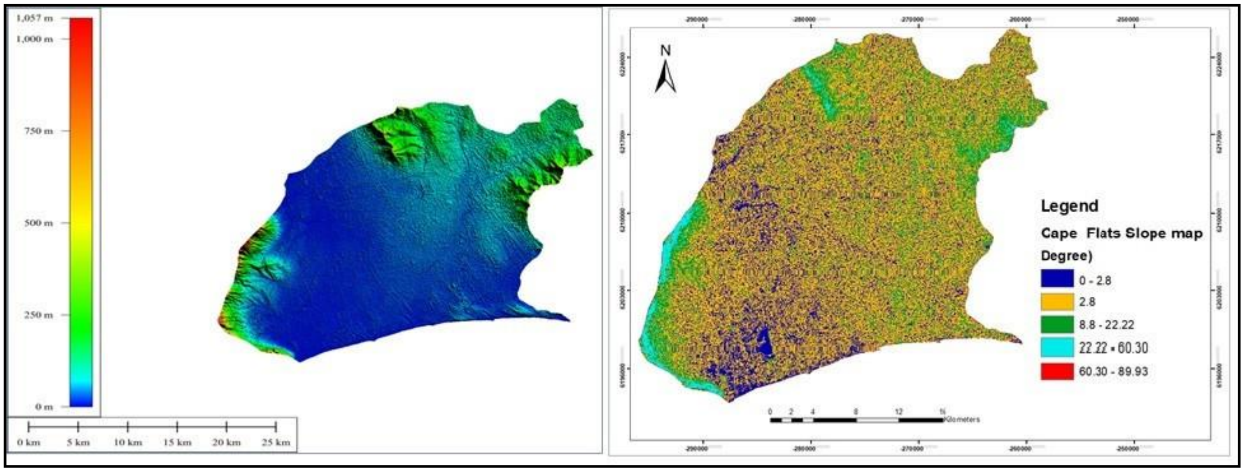


Fig. 3.6. Digital Elevation Model (DEM) and Topographic Map

The slopes are steep to the north and west, mountainous to the south, and gentle to flat in the center. The valley floor appears to be depositional soil of sand dunes and is generally flat. Much of the valley has faults or steep slopes on both sides. Erosion, deposition, and land use practices all contribute to the structure. In addition, the research region is part of the western ridge valley, which has hills, deep and vast valleys with rivers, and narrow, gently sloping plains between them. The morphology of the research area is complex due to the steep terrain. Mountains in the east that are higher than the rest of the study area are places where groundwater can be refilled.

The DEM setup, fill, flow accumulation, flow direction, stream order, and computation of subbasin characteristics were all done using the DEM. The resulting sub-watersheds were then divided into HRUs using remote sensing and GIS (HRUs). The subwatersheds were then separated into HRUs (HRUs). Most of the data in this study came from DEM and elevation maps of the area. To set up and fill in the DEM. Sub-basin characteristics and flow accumulation were also calculated. Remote sensing and GIS were utilized to categorize the sub-watersheds (HRUs).

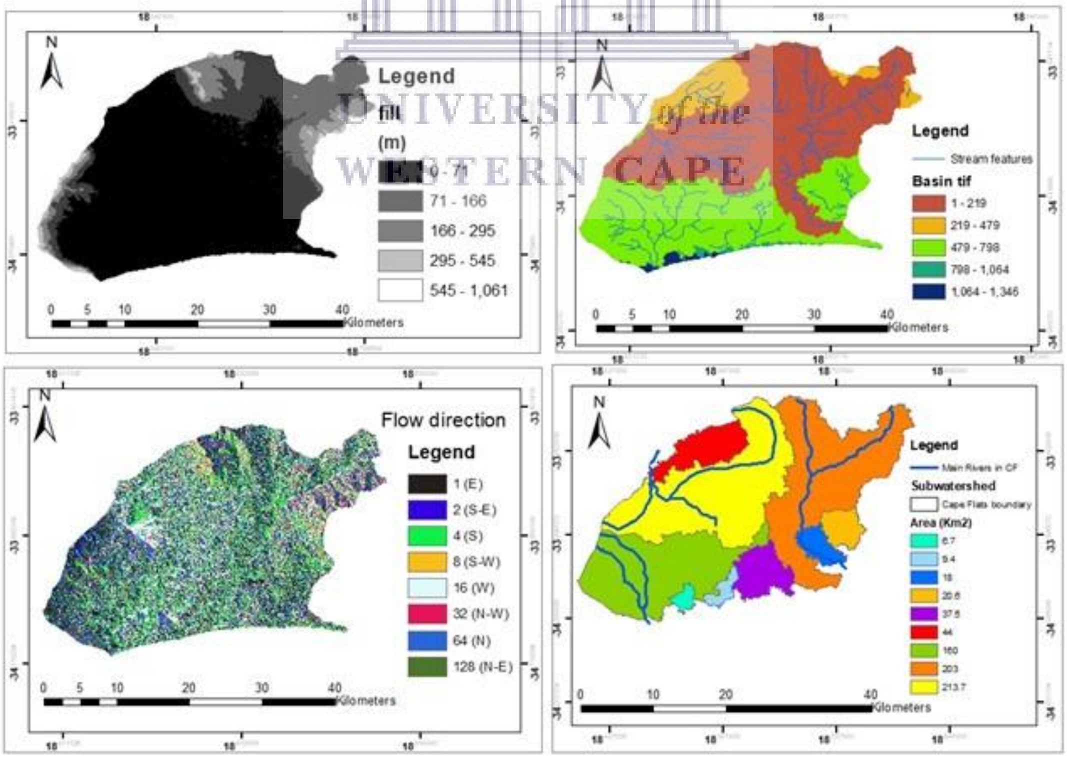


Fig. 3.7. Delineation of the basin on a topographic map

A risk assessment of groundwater quality can be used to determine the most effective management actions to improve water quality. The Cape Flats catchment is distinguished by steep slopes to the north and west, undulating topography in the south, and gentle to flat terrain in the center. The Cape Flats in South Africa are distinguished by undulating topography, mountainous regions, and valleys of small and large streams. The general direction of groundwater flow is variable, flowing in different directions (Fig. 3.7). There are two major rivers in the area: the Elsieskraal River, which flows from the north-eastern side to the south-western side, and the Vygekrasal River, which flows from the south to the west.

3.4 Land Use Changes

Based on the land use/cover classifications of 2001 and 2015, the change in land use and cover was analyzed in the last 14 years, as was the contribution of farmland, forest, grassland and other major land use types to runoff. The Cape Flats cover various types of land use, mostly consisting of industrial areas built up, agricultural, formal, and informal townships, thicker bushland areas, shrublands, and wetlands.

For land use/ land cover control, runoff and evapotranspiration, identification, and interpretation of land use patterns of the area were prepared based on satellite images. The Cape Flats catchment typically covers various land use/ land cover classes described as the following: cultivated land, bare land, grassland, plantation, shrubland, riparian plantation, woodland, exposed surface, marshy land, and water bodies (Fig. 3.8).

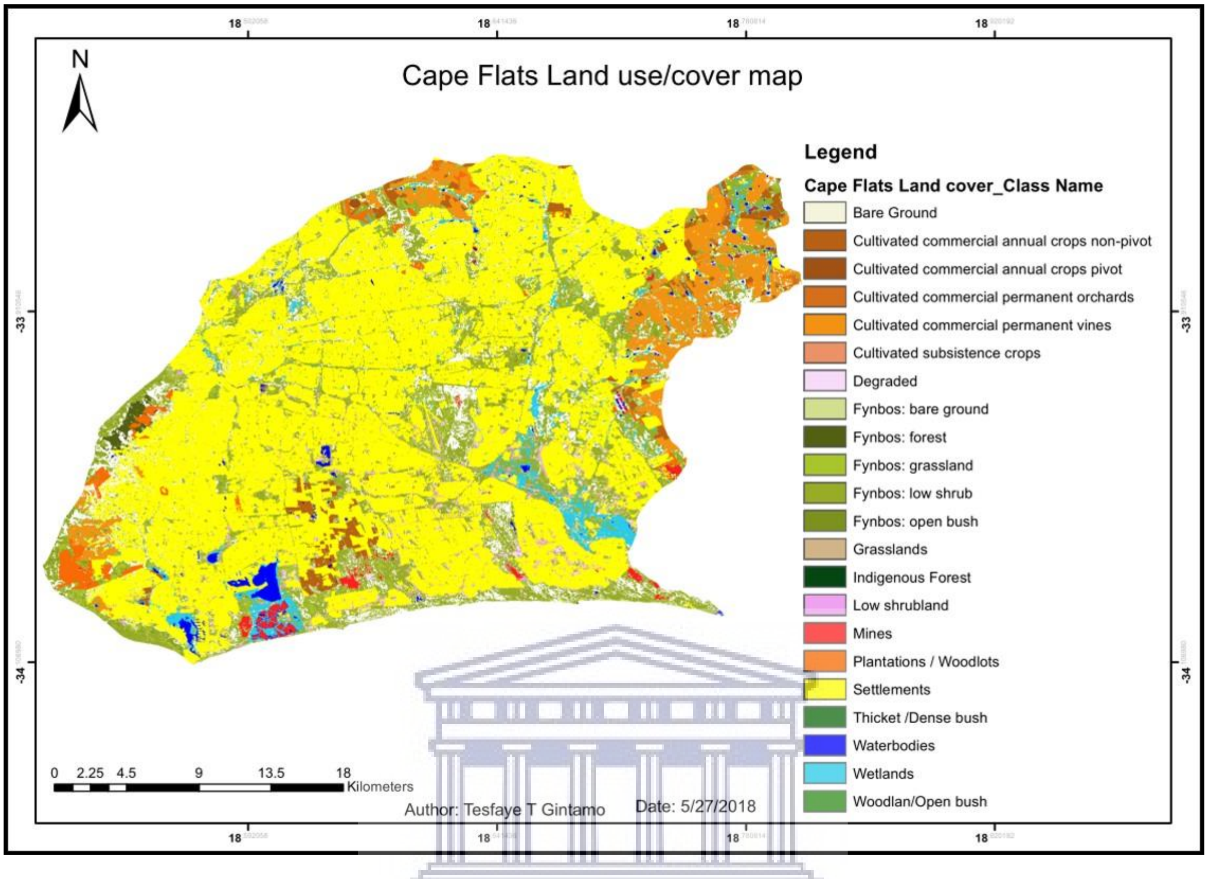
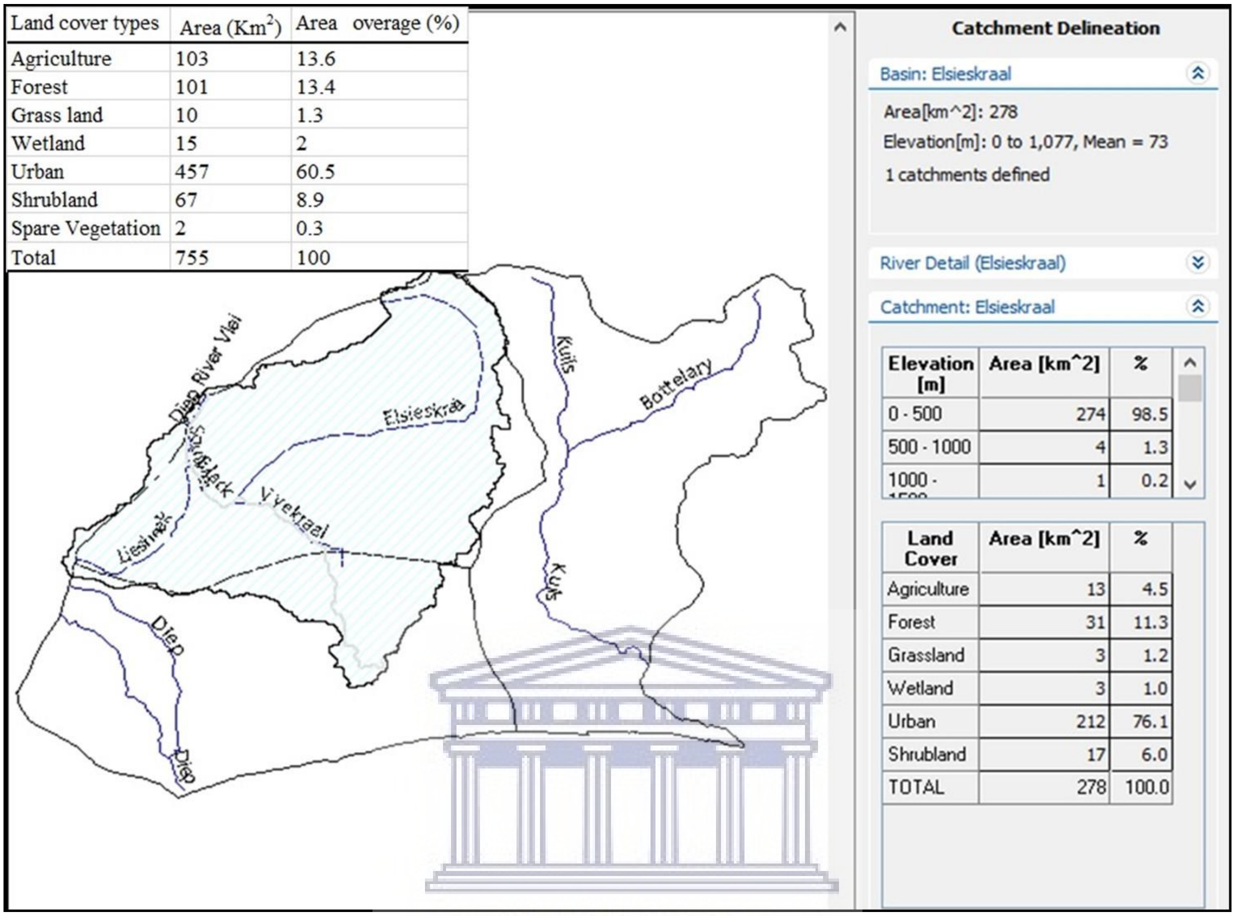


Fig. 3.8 Land use/ land cover types and area coverage of the study area

In the Cape Flats region, residential and commercial developments could affect the quality of the water that recharges the Cape Flats aquifer. This may contribute to the increase in salt concentration in this shallow groundwater. For example, in the modern world, the Philippi area is at risk from urban farming, as well as socioeconomic development and industry (McGibbon et al., 2017). The Cape Flats catchment area typically covers various types of land use, consisting mostly of built-up industrial areas, agricultural, formal and informal townships, areas of thicker bushland and shrubland, as well as wetlands (Fig. 3.9).



Land cover types	Area (Km^2)	Area overage (%)
Agriculture	103	13.6
Forest	101	13.4
Grass land	10	1.3
Wetland	15	2
Urban	457	60.5
Shrubland	67	8.9
Spare Vegetation	2	0.3
Total	755	100

Catchment Delineation

Basin: Elsieskraal

Area[km^2]: 278

Elevation[m]: 0 to 1,077, Mean = 73

1 catchments defined

River Detail (Elsieskraal)

Catchment: Elsieskraal

Elevation [m]	Area [km^2]	%
0 - 500	274	98.5
500 - 1000	4	1.3
1000 -	1	0.2

Land Cover	Area [km^2]	%
Agriculture	13	4.5
Forest	31	11.3
Grassland	3	1.2
Wetland	3	1.0
Urban	212	76.1
Shrubland	17	6.0
TOTAL	278	100.0

Fig. 3.9 Land use/cover map of the Elsieskraal and rivers and coverage in the study area (Based on WEAP watersheds declination)

Chapter 4: Research design and methodology

4.1 Introduction

Chapter 3 introduced the concepts, goals, and guidelines of data model design and the data model framework for representing the core classes of the data model. Chapter 4 presents details of the modelling design and methodology. The first section describes the general components of the data model and is followed by a detailed description of each component and the different classes in it. This thesis involved the study of the integration of multiple methods, which can be divided into four types: 1) climatic variables on groundwater quality modeling with the WaterWorld model; 2) groundwater vulnerability with the modified DRASTIC model; 3) model within a GIS framework; and 4) groundwater quality index. This study looked at the effects of climatic variables and rising sea levels on hydrologic regimes and groundwater quality in the Cape Flats catchment (the case study area). It looked at the effects of climatic variables and rising sea levels on hydrologic regimes and groundwater quality in the Cape Flats catchment (the case study area).

4.2 Research Design

4.2.1 Research Design

This study adopted an experimental design that was used to develop a quantitative model of concurrent climate and land use processes in the Cape Flats aquifer and to assess impacts on groundwater quality based on the GIS framework. The study was carried out as follows: desk study, existing data analysis, satellite image processing, modelling and mapping. Primary data are obtained from satellite data acquisition and image processing. ArcGIS 10.3 is used to produce maps and the analysis of various collected data sets. For the validation of the results, the water quality index is calculated for the overall quantification of the water quality. Vulnerability and risk maps with hotspots are shown. They can help groundwater managers and planners make better decisions about how to use groundwater and how to protect it.

4.2.2 Methods for Sampled Design

The study was carried out as follows: desk study, existing data analysis, satellite image processing, modeling, and mapping. The data used for processing is collected from different government agencies, authorised government websites, and previous research projects. Primary data are obtained from satellite data acquisition and image processing databases.

4.2.3 Data Types and Their Sources

Satellite data was used to determine the topography of the area where the study took place. The ArcGIS 10.3 software used USGS satellite data with a spatial resolution of 30 meters to obtain elevation and slope data. The digital elevation model (ASTER-DEM) was used to obtain the data. (http://earthexplorer.usgs.gov/). This application is useful to understand surface runoff and could be used in flood management and control systems in the future. The South African Meteorological Service (http://www.weathersa.co.za/) provided meteorological data. For the period from 1979 to 2018, rainfall and temperature data at Cape Town Airport were examined. The data were also used to validate the WaterWorld model and verify the input data of the model. Furthermore, improper landfills pollute runoff and contaminate near-surface groundwater. Landfill information is available on Cape Town's online maps (https://citymaps.capetown.gov.za/EGISViewer/).

Secondary data is obtained from various sources, namely the Council of Scientific and Industrial Research (CSIR), the Department of Water and Sanitation (DWS), as well as the City of Cape Town municipality (CoCT). The data collected included the type, geometry, hydraulic parameters, and inputs that vary in time, as well as the boundary conditions (Table 4.1).

Table 4.1 Data types and their sources

Data Type	Detail of the data	Format	Output layer
Bohole data (water table level)	National Groundwater Database (NGDB) of the Department of Water Affairs	Lithology log	Depth to the water table (D)
Average annual rainfall	DWA, Climate data from the Cape Town International Airport Hydrological Station	Table	Net recharge (R)
Hydrogeological map	Hydrogeological map, DWA	Map	Aquifer medium (A)

Soil Map	Soil, Climate, and Water Institute of the Agricultural Research Council	Map	Soil type (S)
Remote sensing imagery	ASTER DEM satellite data	Satellite image	Topography (T)
Hydrogeology	Hydrogeology map	Map	Impact of the vadose zone (I)
Hydraulic Conductivity	Hydrogeology map	Pumping test data	Hydraulic Conductivity (C)
Land Use	Land use and cover maps	Map	Land use (Lu)

4.3 Methodological Approach

The methodology used is a GIS -integrated approach based on a linear combination of multiparametric data to assess the risk of groundwater contamination in the Cape Flats catchment. The index technique is commonly used as a water quality assessment technique based on hazards that provide the composite influence of individual parameters on overall water quality for various purposes (Machiwal et al., 2018a). Based on the methodological flow chart (Fig. 4.1), the point data-based maps had to be previously converted into area data sets for each parameter. Various thematic layers of the GWQ index, hydraulic conductivity, and aquifer thickness were prepared using the geostatistical method.

First, the effects of land use activities, land cover change, and climate variability on water quality resources were examined using the WaterWorld model in a GIS environment. The WaterWorld model requires numerous inputs that include a digital elevation model (DEM), land use, soil, precipitation, temperature, and water quality to facilitate modelling of climate and land use change and quality. Based on the WaterWorld model, changes in precipitation, temperature, and land use changes are simulated to assess impacts on groundwater recharge, water balance, and evapotranspiration (ET). In addition, changes in precipitation, temperature, and the effects of sea level rise have been simulated using MAGICC and SCENGEN in the TerrSet Geospatial Monitoring and Modelling System.

In the second stage of this study, the overlay and index methods (DRASTIC) model was used to determine the extent of the vulnerability of aquifers in a GIS environment. The GIS-based DRASTIC model is a popular model for assessing groundwater vulnerability because it is relatively inexpensive, simple, uses data that are commonly available or estimated, and produces a result that is easily interpreted and incorporated into the decision-making process. The DRASTIC model uses a scoring system based on seven hydrogeological characteristics of a region. Depth to the water table (D), net recharge (R), aquifer media (A), soil media (S), topography or slope (T), and hydraulic conductivity (C). The DRASTIC approach consists of three steps: data set selection, rating, and parameter weighting. Each parameter in a hydrogeological setting is assigned a numerical rating ranging from 0 to 10, with 0 indicating low vulnerability and 10 indicating high vulnerability, which is then multiplied by a weighting factor ranging from 1 to 5.

In the third step, an integrated model based on GIS was used to develop risk indicators for groundwater contamination. GIS based modelling of groundwater sources to verify contamination potential is critical to protecting groundwater resources because predicting groundwater contamination risk is fundamental to identifying potential future threats to water quality. In addition, GIS -based models that account for future changes in climate and land use provide the basis for developing strategies to protect and sustainably manage water resources. By mapping vulnerable areas, it is possible to determine which areas are more susceptible to contamination, and thus work to avoid contamination risks. The evaluation of the risk assessment index (RI) provides a probability of groundwater contamination based on potential surface sources. This was evaluated by integrating information on the groundwater risk index. Low values of the risk index indicate a much lower probability of groundwater contamination. On the contrary, a higher value of the vulnerability index indicates a greater likelihood that the aquifer will be affected by the risk of contamination.

An empirical predictive approach was used to develop an integrated model of the effects of climate and land use change on water resource quality in the Cape Flats aquifer. GIS-based models integrated hydrological models, a DRASTIC model, and surface and groundwater water quality index analyses. The results of an analysis of scenarios of land use/land cover and climatic variables were used as part of a Global Information System (GIS) study for the CFA. The results were compared with the groundwater vulnerability index and key groundwater quality parameters to assess the impact of climate change on water quality (Fig. 4.1).

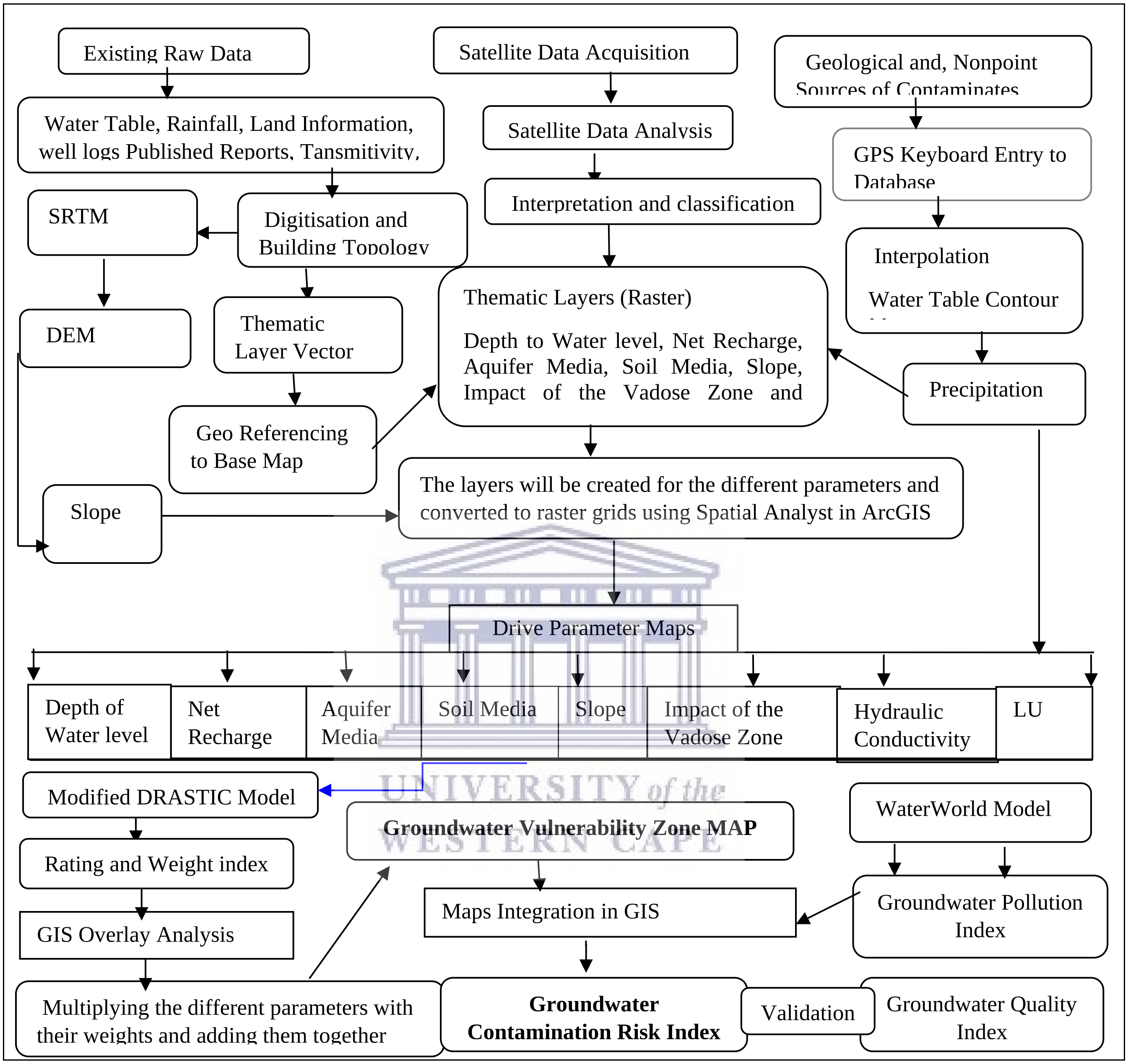


Fig. 4.1. Flow chart of the groundwater contamination risk mapping methodology applied to the Cape Flats aquifer

4.4 Research Methods

4.4.1 Data collection and analysis methods for the evaluation of the impacts of climate variables on groundwater quality (WaterWorld model).

Geospatial hydrological modelling can be used to analyse the likely impacts of climatic variables on groundwater systems (Dwarakish and Ganasri, 2015). Climate model resolutions are too coarse for groundwater resource applications and must be downscaled. Downscaling projections of future climate by global climate models is critical for impact studies (Aizebeokhai, 2011b). Downscaling allows GCM experiments to be used for regional-scale impact studies. The WaterWorld model was used to predict the effects of climatic variables on the hydrological system of the Cape Flats watershed. First, the effects of changes in land-based activities on water quality are modelled under current conditions. Then, the same analysis is performed under future climate scenarios. The annual and monthly variability of precipitation is compared under scenarios of current and future climatic variables.

There are several tools and information sources for examining GCM estimates of regional change, among which is the Climatic Variables Adaptation Modeler (CCAM) to model the future climate and assess its impacts on sea level rise. The gaps between the ability of GCMs and their utility in hydrological modelling are minimised by downscaling. It has been demonstrated that results with improved precision are achieved by downscaling GCMs to local-level scales from regional-level scales to assess the effects of climatic variables on the hydrological cycle (Zhang et al., 2016). The regional climate models (RCMs) used in this type of downscaling have a very complicated physics-based structure.

In TerrSet, geospatial modelling and climate generating scenarios (SCENGEN) were used to estimate changes in global mean temperature and sea level rise. In addition, MAGICC/SCENGEN allows a user to compare the average change in temperature or precipitation simulated by the GCMs with their relative inter-model variability. Trend analysis was carried out for the seawater-level data results with a prediction of a probability of about 0.03 to 0.58 that the coastal areas would be affected by sea-level rise at the end of 2060, where areas certain to be underwater are given values of 1 because of increasing temperature.

4.4.2 Data collection and analysis methods for groundwater vulnerability assessment (GIS-Based Modified DRASTIC Model)

A groundwater vulnerability map is one of the management and protection tools that will facilitate the planning of human activities to help reduce adverse impacts on groundwater quality. A DRASTIC method assesses the contamination potential dependent on the seven hydrogeological parameters, including the depth of the depth of the depth of the water table. Data from wells and hydrological data were used to develop the GIS database. GIS software is a powerful tool to generate different thematic maps, GIS databases, format conversion, overlay maps, and integrate maps. The DRASTIC parameters were rated and weighted based on the relative probability of contamination risk on the ground. Each parameter is assigned a weight depending on its relative importance in influencing the contamination potential. The typical weighting and rating ranges are considered from 1 to 10 and from 1 to 5, respectively. A rating of 1 relates to the least contamination potential, and a rating of 5 relates to the highest contamination potential (Aller et al., 1987). According to Shirazi et al. (2012), maps can be overlayed to produce vulnerability maps within a GIS framework. The final index value indicated the comparative amount of groundwater vulnerability of a specific area. The higher the degree of vulnerability, the greater the risk of groundwater contamination. The value was calculated for each rating of the parameters and then multiplied by the weight that was given to each below.

$$DI = Dr * Dw * Rr * Rw + Ar * Aw + Sr * Sw + Tr * Tw + Ir * Iw + Cr * Cw + LUr * LUw.$$

Where: DI = DRASTIC index, r = rating value for each parameter, w = weighting associated with each parameter

Based on the above equation, the analysis of all parametric and vulnerability maps was performed using ArcGIS 10.3 software. The data used for the processing have been collected from different government agencies, authorised government websites, and previous research projects. These variables, or parameters, were used to define the hydrogeological setting of a specific area. Each range or zone has a rating that shows how important each individual factor is in putting the aquifer at risk.

4.4.3 Data collection and analysis methods for mapping and modelling groundwater contamination risk (overlay analysis in GIS).

GIS-based modelling using downscaling techniques was employed to link climate models and catchment-scale hydrological models. Furthermore, the water quality data from existing wells in the study area was used to validate the resulting groundwater contamination risk map. The results of this study will provide important information about the effects of land use and climatic variables on hydrological regimes and groundwater quality under certain scenarios of climatic variables and land use. This knowledge is important because it will help us better understand and manage water resources in a more sustainable way.

4.4.4 GIS-based techniques for mapping the groundwater quality index (GWQI).

Recently, geographic information system (GIS) technology has been successfully integrated with advanced statistical and geostatistical methods, providing improved interpretation capabilities for the assessment of water quality on different spatial scales. (Machiwal et al., 2018b) suggest that GWQI based on GIS is a useful criterion to assess the impact of changes in climate and land use on groundwater quality in a rapidly urbanizing region.

Water quality evaluation is critically important for the protection and sustainable management of groundwater resources, which remain variably vulnerable to ever increasing human-induced physical and chemical pressures (eg, aquifer pollution) and to climatic variables/variability. Previous studies have applied a variety of tools and techniques, ranging from conventional to modern, for characterisation of groundwater quality worldwide. Recently, geographic information system (GIS) technology has been successfully integrated with advanced statistical and geostatistical methods, providing improved interpretation capabilities for the assessment of water quality on different spatial scales (Machiwal et al., 2018).

4.5 Quality assurance and quality control

4.5.1 Evidence on the adequacy of the collected data

Empirical studies of the predictive approach using a survey of available data are used to simulate the effects of land use and climatic variables on the quality of water resources in the CFA based on a GIS platform. The integrated model based on GIS is a process-based hydrology and water quality model, designed to estimate the impacts of anthropogenic activities and climatic variables on water quality in complex catchments. The data used for processing was collected from various government agencies, authorised websites, and previous remote sensing research. Data sources included electronic and paper-based (reports) data in various formats. The depth of the water table in the Cape Flats was determined from the average water level of each well in the National Groundwater Archive (NGA) of South Africa. Elevation and slope data were extracted from the digital elevation model (ASTER-DEM) with a spatial resolution of 30 m from USGS satellite data (downloaded from The United States Geological Survey (USGS) Earth Explorer (https://earthexplorer.usgs.gov/). Data from the water balance model included in the WaterWorld model (http://www.policysupport.org/waterworld) are based on globally available data that support a spatially explicit, physically based global model. Land use and land cover (LULC) data for the Cape Flats watershed were obtained in 2015 from the satellite imagery from Landsat 8 thematic mapper. The water quality data from laboratory analyzes of existing wells and the literature in the study area were mapped to validate the resulting groundwater contamination risk map.

4.5.2 Evidence on the reliability of the collected data

Remotely detected data combined with GIS yields credible results that can be used for numerous studies and decision-making purposes. To ensure reliability and validity of the results, the secondary data was obtained from accredited sources, where one could see if the data being used was correctly collected and if it was the type of data that was needed. Lastly, the thematic maps were converted into the same geographical coordinate system before being integrated to ensure that they cover the same region in the study area.

4.5.3 *Evidence on the Validity of the Collected Data*

The data used in this study include recent laboratory analytical results and the literature. Three variables were selected to serve as indicators of the general state of water quality. The variables selected are nitrate (NO3), electrical conductivity (EC), and chloride (Cl^-). Electrical conductivity (EC) (mS/m) as an indicator of salinity and chloride (Cl) (mg/l) to show the effects of agriculture, wastewater discharges, and industrial wastes. Electrical conductivity (EC) was evaluated to show temporal changes in water quality. Data from previous water quality studies were used to compare the results and validate the model against observational data. The chemical analysis of groundwater in the study area revealed high levels of nitrates and chlorides. These results are consistent with the studies by Gnandji et al. (2013b). There is a strong correlation between some characteristics of water quality and the contamination risk index in the study area. The parameters that show positive correlation are electrical conductivity, chloride, and nitrate. The Pearson correlation between the contamination risk index and electrical conductivity in the Cape Flats aquifer shows a strong positive relationship ($R^2 = 0.83$). A groundwater quality index (GWQI) was developed using a geographic information system (GIS). In this study, it was determined that a GIS technique can be used to map groundwater quality parameters, which is consistent with the available laboratory data on point source water quality.

4.5.4 *Theoretical requirements on research integrity*

A written request was made to the South African Weather Service (SAWS) to obtain the meteorological data. This comprised an explanation of the use of the data for the intended study objectives and, for completeness, the principle of justice, so that all parties involved would remain well informed. Furthermore, the confidentiality of all data was ensured by not sharing them with third parties and guaranteeing that they would not be used for other purposes other than this research study. The study was based on previous studies in this field (Lamchin et al., 2018; Tan and Ab, 2013a; Khan et al., 2010), who applied a GIS-based impact assessment of changes in land use on groundwater quality due to a rapidly urbanized region. The models represent influences on hydrological processes that contribute to water resource contamination in the study area.

Permission to access data from the United States Geological Survey (USGS) website was granted prior to generation. Additionally, the study used more commonly accepted professional, scientific guidelines, codes, and norms for the management of water resources security. Furthermore, research to support new technologies and effective implementation of existing research guidelines adhered to the University of the Western Cape and international policies alike. On this subject, there was honesty when acquiring data and objectivity when guided to present the results. Furthermore, data from this research will provide a scientific basis for the more efficient implementation of sustainable groundwater resources in the study area. Furthermore, the knowledge and the resulting model gained will be applied to future studies to study other groundwater resources.

4.5.5 Operationalising responsibilities for the ethical conduct of research

Permission to access the Department of Water and Sanitation boreholes and secondary data was obtained through an agreement between the University of the Western Cape and the Department of Water and Sanitation. To obtain the climate data, a request was made for permission to use the South African Weather Service (SAWS) data, which was obtained through an agreement between the researcher and the institution. This included an explanation of the use of the data and study objectives to fulfil the principle of justice, so that all parties involved would remain well-informed. Rainfall and temperature data required confidentiality; therefore, they were kept safe and not shared or used for any other purpose other than for the purpose of this research. To obtain the chemistry data, a request was made to the previous CSIR support research laboratory for results in the study area. This included an explanation of the use of the data and study objectives to fulfil the principle of justice, so that all parties involved would remain well-informed. Furthermore, all data would not be shared with third parties, nor used for any other purpose other than for the purposes of this study of research, to avoid and ensure that no harm was/would be done to humans, animals, or the environment during this study.

4.6 Study Limitations

Most of the data used in this study were secondary data. Therefore, it was of great importance to download the data that represented and covered the study area in question. The main limitations of this research project were obtaining reliable data on groundwater levels in well fields and ensuring data quality.

It is also worth mentioning that most of the input parameters in the present GIS based DRASTIC models are derived from the literature values and the data used in previous studies in the study area. However, the results of the modified model DRASTIC can be compared with those of other (independent) methods under similar hydrogeological conditions. A major limitation of the DRASTIC model is the way rating and weight parameters. The Analytical Hierarchy Process (AHP) was used to determine how important each parameter is. This reduces subjectivity in the evaluation process.

Finally, the main problem with this study is that there are not enough hydrogeological parameters to use as input for the DRASTIC model because there are not enough people who have them. Missing data values were statistically replaced by daily averages for the previous years for which data values already existed by interpolation.

The study examined the potential for groundwater contamination from climatic variables and land use in urban areas. The first four chapters highlight the way this study was conducted. The present chapter presents the results obtained following the methods mentioned in Chapter 4. In addition to this, two sets of publication papers are presented in Chapter 5. The focus of Paper 1 was to assess the impact of climate variability on groundwater quality in the Cape Flats aquifer (CFA) in South Africa by using geospatial modelling. Paper 2 highlights the role of the modified GIS-based DRASTIC model in the evaluation of groundwater vulnerability (section 5.3) as an assessment tool. Additionally, a combination of GIS-based models highlighted the importance of better groundwater vulnerability assessment (section 5.4). Finally, the results of the individual chapters are summarised in a broader perspective.

Chapter 5: Impact of Climate Variability on Groundwater Quality

5.1 GIS-based modelling of climate variability impacts on groundwater quality: Cape Flats aquifer, Cape Town, South Africa

Abstract.

The need to improve groundwater security remains critical, particularly in urban areas. Groundwater resources in urban areas are still under threat from climatic variables. Assessing the impact of climatic variables on groundwater quality is a difficult technical challenge. A Geographical Information System (GIS) is an important tool for the protection and management of groundwater resources. The primary goal of using GIS was to simplify climate information for decision makers to use for practical tasks related to climatic variables. The Cape Flats aquifer in the South African city of Cape Town was chosen as a case study. The WaterWorld model was used to simulate hydrological scenarios related to climatic variables and groundwater quality parameters. Geospatial data were combined using ArcGIS 10.3 to create a vulnerability map of groundwater. The WaterWorld hydrological model simulated the years 2041–2060. Simulated precipitation will rise until 2041 and then fall until 2060. Under the future dry climate, water balance simulations showed a decrease of about 8.6% per year. Temperatures were expected to increase by 1.9 ° C to 2.3 ° C. Groundwater vulnerability index and electrical conductivity concentrations showed a strong positive correlation. Using the WaterWorld model in a GIS environment to simulate hydrological scenarios on climatic variables and groundwater quality parameters can provide practical and feasible insights for actions to improve groundwater management.

Keywords: Cape Flats; Cape Town; Climatic variables; Geospatial modelling; Groundwater quality; WaterWorld model.

This chapter is based on paper 1:
Gintamo, T. T., Mengistu, H., and Kanyerere, T. (2021). GIS-based modelling of climate variability impacts on groundwater quality: Cape Flats aquifer, Cape Town, South Africa. Groundwater for Sustainable Development, 15, 100663.

5.1.1 Introduction

Groundwater is critical to addressing water security challenges. However, climate factors, including precipitation and temperature, affect the hydrological cycle, which in turn has an effect on groundwater quality (Abbas et al., 2016). Urban areas are particularly vulnerable to groundwater contamination. Changes in climate variables can increase urban stormwater runoff and transport nutrients and sediment loads from industrial and agricultural areas (McGill et al., 2019b; Miller and Hutchins, 2017; Olivier and Xu, 2019). Assessing the impact of climatic variables on groundwater quality is a difficult technical challenge (Kumar, 2012a; Ugwu, 2019). The main problem is the lack of understanding of how groundwater and hydrological processes interact at different spatial and temporal scales (Salvadore et al., 2015). Because it identifies vulnerable zones at different spatial scales, GIS is an essential tool for the protection and management of groundwater resources (Khatami and Khazaei, 2014b; Rawal et al., 2016; Tsihrintzis et al., 1996). This study attempted to fill some of these knowledge gaps by using GIS-based hydrological modelling.

Hydrodynamic effects on groundwater have piqued the interest of those attempting to better understand and interpret climate data for decision makers (Climate System Analysis Group, 2014; Kumar, 2012b; Rudd et al., 2018). Demlie (2015), Jakeman et al. (2016) and Khatami and Khazaei (2014) investigated salinity concentrations in near-surface aquifers in central Ethiopia and northern Tunisia, respectively, to determine how climatic conditions affect the hydrological cycle. Farjad et al. (2016) offered geographically distributed modeling tools to highlight the complexities of analyzing the impacts of meteorological change on water resource management. Soesbergen and Mulligan (2014a) and Nashwan and Shahid (2020) used general circulation models (GCM) to look at the effects of climatic variables on groundwater-related basins. In general, the studies show how to use GIS-based modeling tools to investigate the effects of climate variability on groundwater-related basins and how to spatially depict climatic variables using remote sensing data.

Groundwater security is becoming a growing concern in South Africa as domestic, agricultural, and industrial water demands increase. The drought in Cape Town has raised concerns about water scarcity and pollution. Cape Town is subject to highly variable and uncertain hydrological conditions, which endanger unconfined aquifers. Changes in climate variables can increase urban stormwater runoff and transport nutrients and sediment loads from industrial and agricultural areas. The Cape Flats aquifer (CFA) is a critical groundwater resource in the metropolitan region of Cape Town. Climatic variables can affect groundwater quality by increasing the loading of nutrients and sediments in the underlying aquifers. Studies on groundwater risk associated with climate variability conducted in the Cape Flats catchment are limited.

This study assessed the impact of climate variability on groundwater quality in the Cape Flats (South Africa) using a hydrological model (the WaterWorld model) and a geographic information system (GIS). The study focuses on determining temperature and precipitation, as well as the consequences of changes in hydrologogical conditions and subsequent groundwater quality.

5.1.2 Descriptive and inferential statistical analysis on the impacts of change on groundwater quality

Climatic variables are likely to alter the parameters of the hydrologic cycle. Under a wetter future climate scenario, there would be much more runoff, leading to more flooding. Higher air temperatures are likely to result in more evapotranspiration, which could lead to less groundwater recharge. Climatic variables are likely to alter the parameters of the hydrologic cycle. The recharge of water will be less as the temperature increases and the rainfall decreases. Climatic variables can also increase pollutant loads from industrial and agricultural land (Hosseini et al., 2017). Higher levels of nitrogen and phosphorus would indicate more rainfall, especially in fully agricultural areas (Velazquez et al., 2013). However, an estimation of the total water balance is a substantial issue for watershed modelling to simulate the major components of the hydrological cycle. Global atmospheric general circulation models (GCM) have been developed to simulate the current climate and are used to predict future climate variables to see how groundwater will respond to spatially varying recharge and subsequent impacts on groundwater quality (Db et al., 2017; Hagemann et al., 2013). In this context, the distributed, physically- based WaterWorld Policy Support system was used to simulate the individual hydrological components of the total water balance for the Cape Flats catchment area in Cape Town by using geospatial modelling as an assessment tool. Furthermore, increasing sea levels in the future would cause some parts of the aquifer to be submerged under sea water, with the associated risk of compromising groundwater quality.

5.1.3 Scenario of climatic variables during (1950 to 2000) and (2041 to 2060)

Modelling the hydrological consequences of climatic variables has received increasing attention for scientific studies. In this study, climatic variables simulations were run based on the WaterWorld model and applied to a multimodal spatial ensemble scenario of the Intergovernmental Panel on Climatic Variables (IPCC) fifth assessment and Representative Concentration Pathways (RCP8.5s) emissions for the 2060s. The climatic variables of the 19

GCMS data were analysed for the scenario created in and are used to assess the potential impacts of climatic variables in the Cape Flats region at a spatial resolution of 1 km.

Table 5.1. Climatic variables scenarios used in this study for the Cape Flats region

Stack 0 | Variable	Value
IPCC Assessment Report	cmip5
Emissions scenario	rcp85
Downscaled by	WorldClim
GCM name	CCSM4 National Center for Atmospheric Research
Projection year	2041-2060
Show scenario	Show baseline and scenario

5.1.3.1 Temperature

Increased temperatures degrade water quality by increasing evapotranspiration. Increased evapotranspiration is likely to reduce groundwater recharge, which can lead to higher salt concentrations. The Cape Flats coastal plain will experience an increase in temperature.

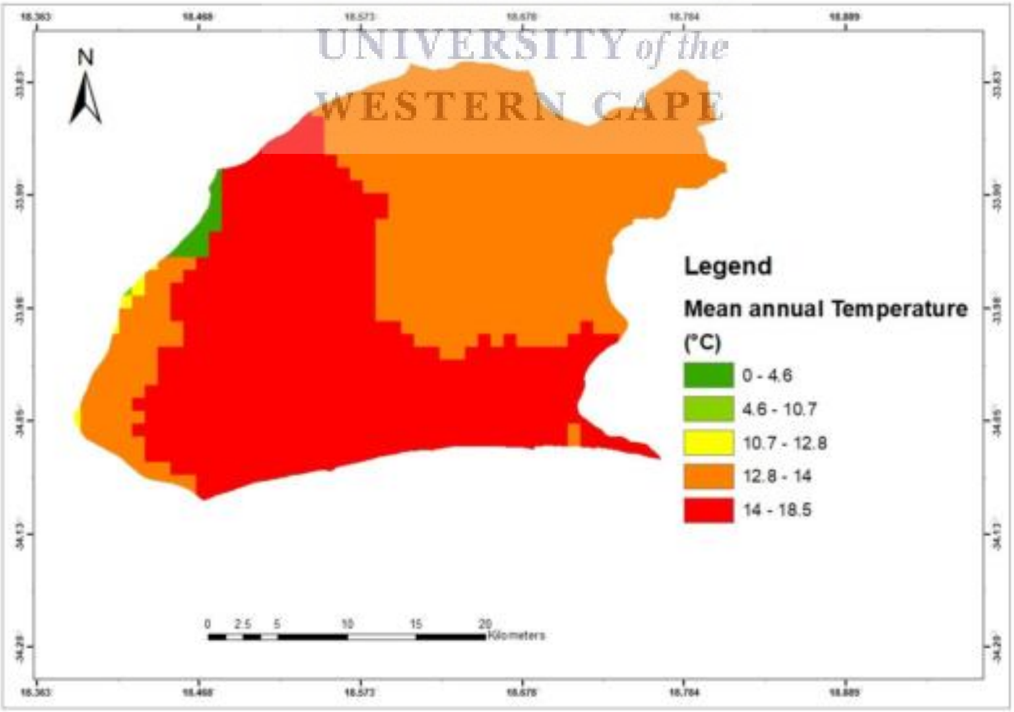


Fig. 5.1 Annual temperature in the Cape Flats (1950-2000).

5.1.3.2 Precipitation

Changes in precipitation affect groundwater quality, as urban runoff increases nutrient loading and can enter aquifers. The climate of Cape Town is influenced by the complex and diverse topography of the region. Annual precipitation in the central basin ranges from 0 mm to 578 mm. The upper catchment receives much more precipitation than the lower catchment (Fig. *5.2* a). The precipitation distribution in mountainous regions is markedly uneven due to elevation differences and topographic exposure to wind-driven rain. Precipitation in the upper, middle and lower zones ranges from 728 mm to 1182 mm, 654 mm to 728 mm and 0.012 mm to 654 mm, respectively. The precipitation projections show a wide range in the catchment, with annual precipitation ranging from 0 to 1042 mm/year (Fig. 5.2b). Annual precipitation in the central basin ranges from 0 mm to 578 mm.

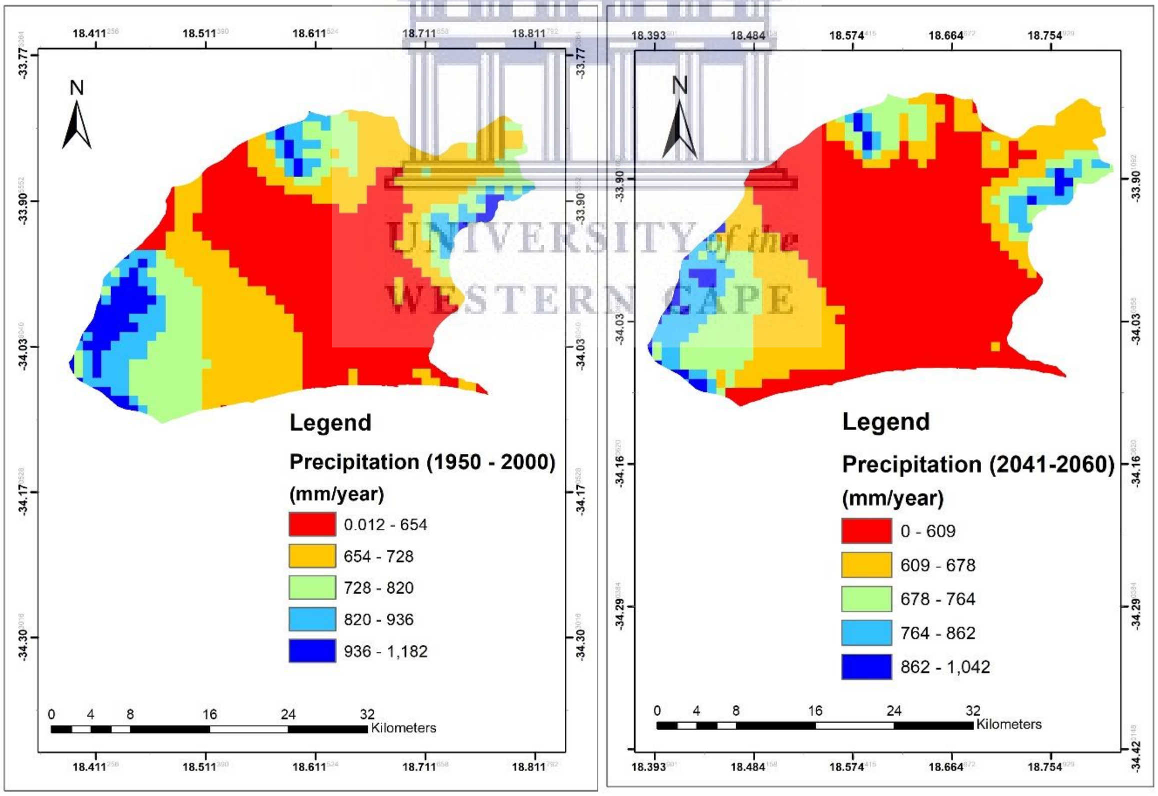


Fig. 5.2 Annual rainfall change baseline projected (1950-2000) (left) and (241-2060) (right).

5.1.3.3 Actual Evapotranspiration

Annual actual evapotranspiration (ActEvap) is lower in the mountain zone (92 to 444 mm/year) and higher in the plain. According to the results of this study, ActEvap increases by 45 mm (10 %) between 2041 and 2060 compared to the period 1950 to 2000.The average annual actual evapotranspiration in the Cape Town region is 540 mm per year, which is 29 mm/year more than the average annual precipitation. There are large differences in the ActEva response across the basin, with large differences between elevation zones. Actual annual evapotranspiration (ActEvap) is lower in the mountainous zone (ranging from 203 to 380 mm/year) and higher in the flat area, ranging from 48 mm/year to 907 mm/year throughout the catchment (Fig. 5.3).

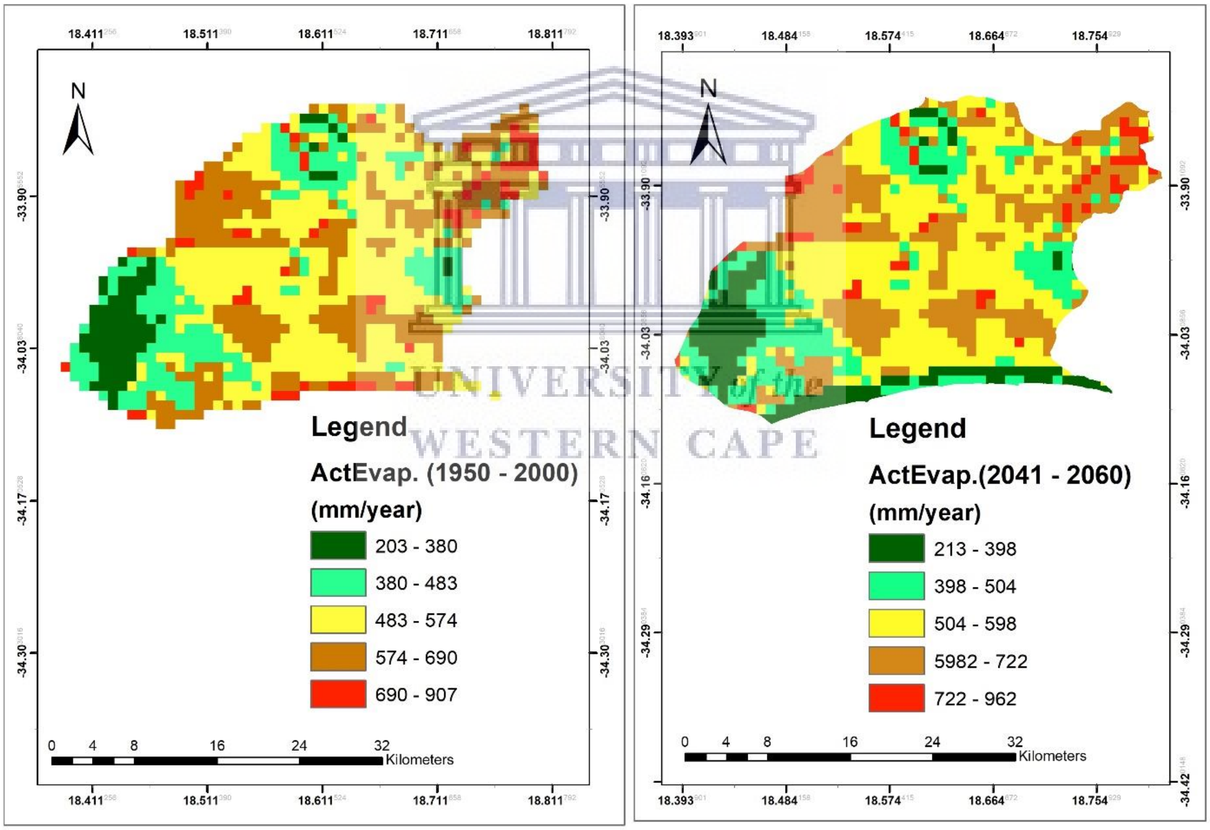


Fig. 5.3. Actual evapotranspiration for the baseline (1950-2000) and for the period 2041-2060.

5.1.3.4 Runoff

Stormwater runoff is a natural component of the hydrological cycle. Water that seeps into the ground eventually replenishes groundwater aquifers. Stormwater runoff is the surface flow of precipitation that accumulates in and flows through natural or man-made conveyance systems. It eventually finds its way to groundwater flow. Storms of rivers cause runoff, and storms cause much more water to flow into rivers (as runoff) as shown in Fig. 5.4. Since some of the runoff is absorbed into the ground, less water flows into a river during a storm. This makes flooding less severe. In the event of flooding, for example, wastewater from wastewater treatment plants and landfills poses a risk of contamination of drinking water.

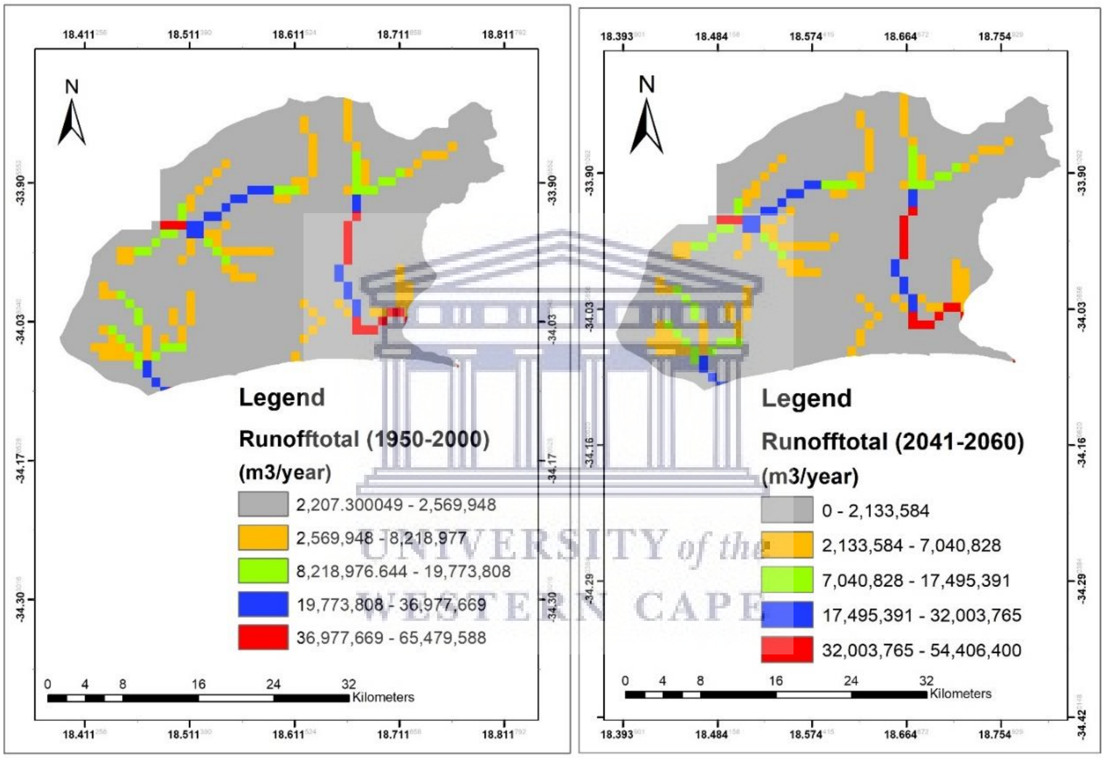


Fig. 5.4 Annual runoff in the study area (1950 – 2000) and (241 – 2060).

5.1.3.5 Water balance

Groundwater recharge is calculated using the water balance method as precipitation from grid cells minus actual evapotranspiration. Fig. 5.5a (left) shows the WaterWorld water balance for the simulation period (1950-2000) and the projected water balance for the average of 19 GCMs through 2060. Fig. 5.5b (right) shows the projected water balance in the basin for an average of 19 GCM. Most of the central basin receives between -184 and 204 mm of recharge per year. Accretion rates at the base of the mountains are expected to be between 204 and 370 mm/year. Different zones can be derived from the model results as a result of different levels of rainfall and land area.

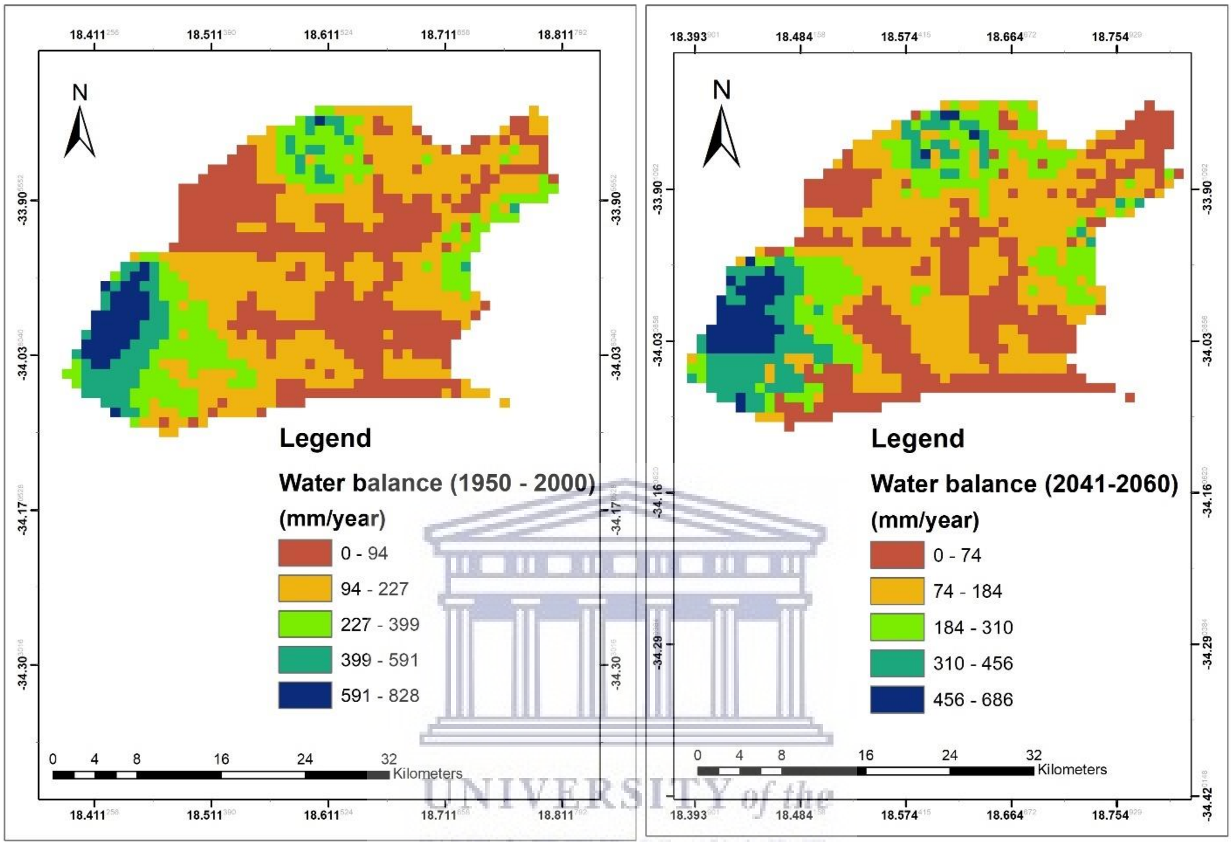


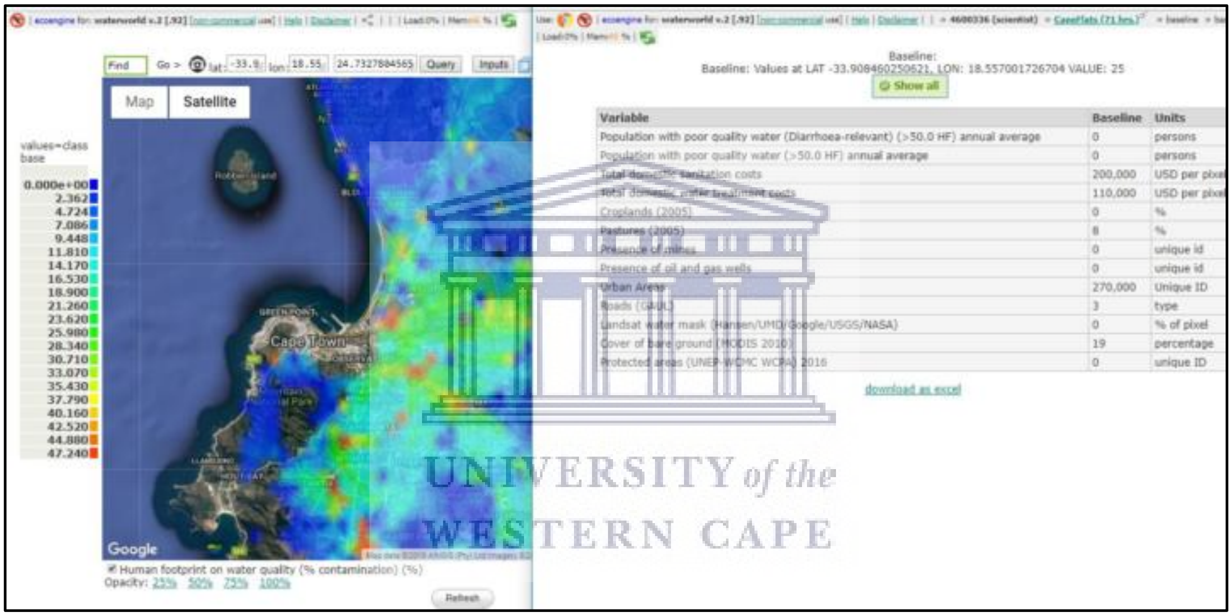
Fig. 5.5. Water Balance Map (1950-2000) and Projected Water Balance Map (2041-2060)

Fig. 5.5b illustrates the projected water balance in the catchment for the mean of 19 GCM by 2060. The WaterWorld model was applied here to understand the local-level variability in water balance, and results show significant differences in the catchment. Most of the central watershed receives about 0 to 184 mm/year recharge. The recharge at the foot of the mountains is expected to receive rainfalls between 310 and 686 mm/year.

5.1.4 Effects of Climatic Variables on Groundwater Quality

Climate change is likely to affect areas already stressed by salt and storm water. Meanwhile, human footprint pollution (HF) increases in some areas, while decreasing in others due to higher climate variables.

Fig. 5.6 depicts the changes in the pollution index of the human footprint when the WaterWorld climate scenarios are used.



Baseline:
Baseline: Values at LAT -33.908460250621, LON: 18.557001726704 VALUE: 25

Variable	Baseline	Units
Population with poor quality water (Diarrhoea-relevant) (>50.0 HF) annual average	0	persons
Population with poor quality water (>50.0 HF) annual average	0	persons
Total domestic sanitation costs	200,000	USD per pixel
Total domestic water treatment costs	110,000	USD per pixel
Croplands (2005)	0	%
Pastures (2005)	8	%
Presence of mines	0	unique id
Presence of oil and gas wells	0	unique id
Urban Areas	270,000	Unique ID
Roads (GAUL)	3	type
Landsat water mask (Hansen/UMD/Google/USGS/NASA)	0	% of pixel
Cover of bare ground (MODIS 2010)	19	percentage
Protected areas (UNEP-WCMC WCPA) 2016	0	unique ID

Fig. 5.6. Human footprint on contamination index (%) map

Climate change and natural climate variability can be difficult to predict or measure. The GIS technique enables direct identification of areas at risk of groundwater contamination. Fig. 5.7indicates the changes in the human footprint pollution index with the WaterWorld climate scenarios implemented. In the mean situation, human footprint pollution increases in some locations but decreases in most, in line with higher volumes of climatic variables. Areas already plagued by salinity and storm water are more likely to be affected by climatic variables.

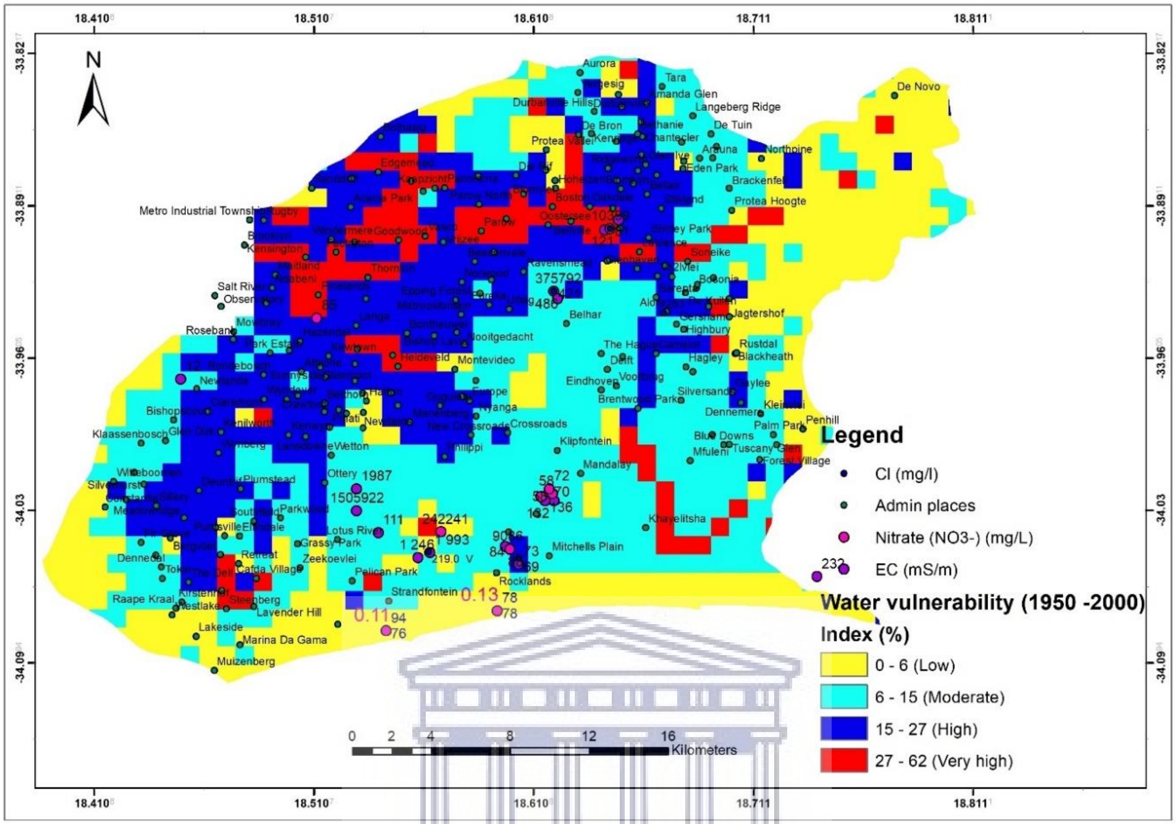
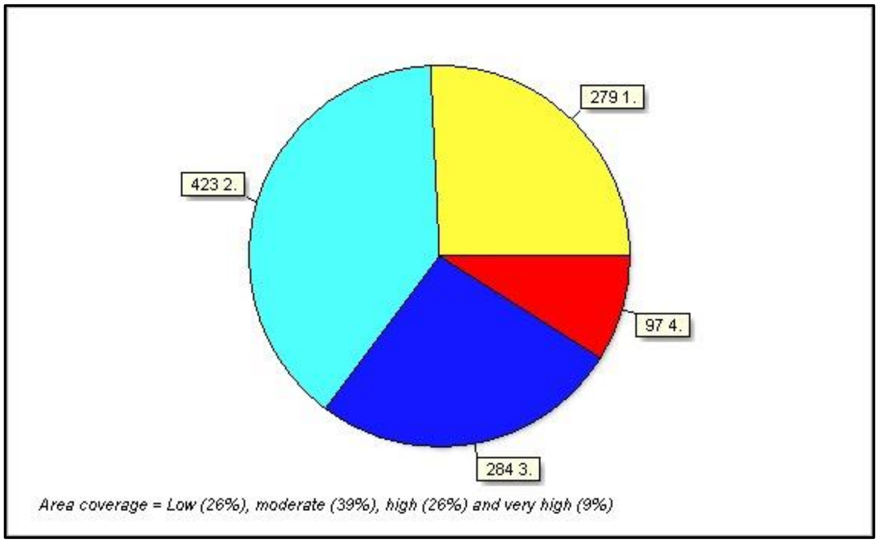


Fig. 5.7. Groundwater vulnerability (Human footprint on the water quality Index)

Sites with vulnerability ratings of 'very high' and 'high' occupied 35% of the total area, while sites with a hazard rating of ‘moderate' covered 39% of the total area. The "low" vulnerability classifications accounted for 26% of the total region (Fig. 5.8).



Area coverage = Low (26%), moderate (39%), high (26%) and very high (9%)

Fig. 5.8. Coverage of the vulnerability index area in the Cape Flats aquifer

5.1.5 Interpretation of the Results

This part concerns the results of our study on the impact of climatic variables on groundwater quality. Groundwater vulnerabilities are strongly related to climate variability, primarily due to extreme weather events. Physically based climate models provide the most accurate data for forecasting variables such as precipitation and temperature. The study specifically identified areas that are vulnerable to climate variability. Precipitation, temperature, actual evapotranspiration, runoff, and recharge are significant factors that determine the factors that cause groundwater deterioration. Areas that were highly vulnerable to climate variability were characterized by low or high rainfall, increased surface runoff, and low recharge. The southern and central suburbs of the study area were more vulnerable to groundwater pollution with low recharge and high surface runoff.

5.1.6 Comparative assessment of the results

The comparison with previous recharge estimates is shown in Table 5.2.

Table 5.2 Comparison of recharge values in the model with other sources

Local studies (Gerber, 1980)	BRBS method (DWAF 2002)	GRAII method (DAWF,2006)	GRDM method (DWAF,2006)	Chloride Mass Balance (CMB) method (Segun et al., 2010)	WaterWorld model (current study results)
115 – 267 mm	90.35 mm	67.84 mm	70.45 mm	29 mm (UWC)	0 – 94 mm
138 – 327 mm	112.13mm	104.79 mm	110.41 mm	52mm (Mitchells Plain)	74 – 184 mm
105 –243 mm	55.05 mm	48.63 mm	61.91 mm		94 – 277 mm

Source (Umvoto Africa, 2009; Michael et al., 2010).

5.1.7 Implications of the results

The study demonstrated the ability to apply hydrogeological concepts and hydrologic parameters to groundwater research, particularly in relation to water quality. These findings provided useful information on the initiatives required to improve groundwater security to mitigate the effects of climatic variables.

5.2 Validation and downscaling of the impact of climate variability on groundwater quality in coastal aquifers of urban areas in South Africa.

Abstract

Impact of climate variables on coastal aquifers. Changes in precipitation, temperatures, and sea level affect hydrological processes. There may also be other consequences, such as seawater intrusion and deterioration of water quality. Changes in precipitation, temperatures, and sea level affect hydrological processes. This can lead to seawater intrusion and deterioration of water quality. Accurate predictions of key climate variables are necessary to assess the effects of climate variables on groundwater resources. The impact of climate on the Cape Flats catchment in Cape Town, South Africa was evaluated using downscaled global climate models and TerrSet Geospatial Monitoring and Modeling Software. TerrSet is a remote sensing and integrated geographic information system developed by Clark Labs at Clark University. It includes tools for climate scenario generation using the National Center for Atmospheric Research's (NRC's) MAGICC and SCENGEN models. This study used a large ensemble of regional climate models for the Cape Flats catchment, South Africa. Precipitation, temperature, and sea level rise are simulated for two time periods, the 2040s and the 2060s for the Cape Flats catchment, South Africa, using 20 GCMs integrated into the Model for the Assessment of Greenhouse Gas Induced Climatic Variables under the A1B-AIM scenarios. Results indicated that temperature and evapotranspiration will increase in all months of future years. Climate change projections for the Cape Town region predict a decrease in precipitation of 3.3% in summer and 23% in winter, accompanied by increases in temperature of 1.9 to 2.1 ° C. There is a probability of 0.12 to 0.58 of coastal areas being affected by sea level rise (17–19 cm) at the end of 2060 and increases in temperatures by mid-2060. Overall, the model results support existing efforts by Cape Town water resource managers to protect the Cape Flats aquifer. Water managers in South Africa should work on improving land management practices that help groundwater recharge as part of a plan to deal with climate change.

Keywords: Cape Flats; Cape Town; Climatic variables; Geospatial modelling; groundwater quality.

5.2.1 Introduction

Coastal aquifers at risk of degradation due to climatic variables and rise in sea level. An increase in temperature and fluctuating precipitation can have significant hydrological consequences. Increased sea surface temperature due to climatic variables often leads to sea level rise, resulting in salt intrusion into nearshore aquifers. Water quality is a major concern for water users, particularly in urban and industrial areas. The Cape Flats aquifer is at risk of being degraded primarily by agricultural, industrial, and other human activities. Changes in hydrology will have an indirect impact on the physicochemical quality of water. The intrusion of sea water into low-lying coastal areas may lead to a deterioration in groundwater quality. Several unsolved hydrology problems highlight the complexities of extreme hydroclimates. The impact of hydroclimatic extremes on water resources is still not fully understood, despite the discovery of an increasing trend in such extremes over the last few decades. There is a need to develop strategies for potential risk management and adaptation in the face of a changing climate. Downscaling global climate model (GCM) projections of future climate is critical for water resource impact studies. In Washington, coastal areas south of Point Grenville are the most likely to experience future problems from sea level rise.

Coastal aquifers in southeast Cape Town could be affected by the rise in sea level caused by global climatic variables. Some parts of the coastal aquifer would be below sea level, compromising groundwater quality. The CF area is working on these issues to keep water quality within drinking water standards. Hydrogeochemistry should be used to confirm seawater intrusion in coastal aquifers with low-altitude topography. Precipitation in the CF area is expected to increase, as is the level of the Atlantic and Indian Sea. An increase in rainfall is predicted to increase groundwater recharge and increase groundwater levels, potentially contributing to groundwater quality deterioration or flooding in the low-lying aquifer area. contamination of the point source can occur due to both formal and informal settlements in and around the area. The metropolitan region of Cape Town is experiencing rapid urbanization. The Cape Flats coastal aquifers are important sources of fresh groundwater for both humans and the natural environment. Future climatic variables could lead to an increase in sea level rise and seawater intrusion. Pollution of groundwater is of particular concern for human and non-human use. Rising sea levels would submerge some parts of the aquifer beneath the sea, compromising groundwater quality. The rise of sea level will cause a saline intrusion into coastal aquifers. Groundwater flooding has become more likely in parts of South Africa's Cape Flats catchment due to climatic variables and sea level rises. The study has provided an understanding of the complex groundwater flow systems, which will aid in future assessment and management of aquifer vulnerability. Integration of PCA and HCA with conventional groundwater type classification as well as hydrogeochemical data helped to provide a more complete picture of the region's groundwater system.

However, global climate models (GCM) are too coarse to provide meaningful information. The Climatic Variables Adaptation Modeler aims to address the challenge of adapting to a rapidly changing climate. There are 39 different climate models within CMIP5 that provide estimates of precipitation change in future time periods. Most members of the ensemble predict increased winter rainfall along the east coast. Most members of the ensemble also predict minor to significant increases in winter rainfall over the southern Cape. GIS-based hydrological modeling could help scientists better understand the effects of climatic variables on aquifer salinization in the Cape Flats catchment. Future studies will need to better delineate the upcoming sea level rise at the local scale.

5.2.2 Description of the main data and model

Climate models have become an important tool for predicting climate variables and assessing their hydrological impacts. The Intergovernmental Panel on Climatic Variables (IPCC) has examined several models that project scenarios for global greenhouse gas emissions. General atmospheric circulation models have been used to predict climate variables. WorldClim is a variable spatial resolution database that provides historical global climate data. Global climate models (GCMs) are too coarse to provide meaningful information in time and space. Downscaling methods for GCM results have been proposed to provide more accurate information. TerrSet's Climatic Variable Adaptation Modeler uses models from the National Center for Atmospheric Research to simulate a rapidly changing climate. NCAR's MAGICC and SCENGEN models are used to create climate scenarios. SCENGEN is a climate scenario modeling tool included in TerrSet's Climatic Variable Adaptation Modeler. It allows users to select emission scenarios, climate sensitivity, time scale, and other factors. The SCENGEN component uses MAGICC's global mean temperature results to scale the results of 17 GCMs using the A1B- AIM scenario in the Cape Town Cape Flats aquifer, which is becoming increasingly important.

5.2.3 Descriptive and Inferential Statistical Analysis

It is important that the effects of climate variables and sea level rise on coastal aquifers are accurate and that they can be downscaled. Global Climate Models (GCMs) are too coarse to provide this information, and therefore downscaling methods are needed to provide the climatic variables information at the scale needed to make decisions. In this study, Generate Climatic Variable Scenarios, constructed according to precipitation projections with reference to seasons for the 1990 and 2060 timeframes, based on IPCC A1B-AIM emission scenarios, were used. Furthermore, based on these scenarios, seasonal and annual precipitation, temperature, and sea level rises are simulated with the ClimGen model. There are 39 different climate models within CMIP5 that provide estimates of precipitation change in future time periods. This study used a large ensemble of regional climate models (RCMs) from Regional Climate Downscaling to explore future precipitation characteristics over the CFA. Annual precipitation c is shown on the maps in average seasonal rainfall (mm) in the Cape Flats catchment for DJF, MAM, SON, and JJA for the periods 2040-2060 (Fig. 5.9, Fig. *5.10*, Fig. *5.11* and Fig. *5.12*). The change in annual average precipitation in the Cape Flats catchment is projected to decrease within a range of a 3.3% decrease and a 23% increase in both summer and winter seasons, respectively, by 2060 for the A1B-AIM scenarios. Most ensemble predict increased winter rainfall along the east coast. Most ensemble predict minor to significant increases in winter rainfall in the south-west Cape, although drying is also possible. In the far future, the projected rainfall signal appears to be becoming somewhat more established, with most ensemble members indicate rainfall increases during summer over the summer rainfall region. An ensemble of downscaling of ten CGCM projections for rainfall over the next few decades has produced a more consistent signal for each season and time. In the far future, the signal appears to be becoming somewhat more established, with most ensemble members indicating increases during summer over the summer rainfall region.

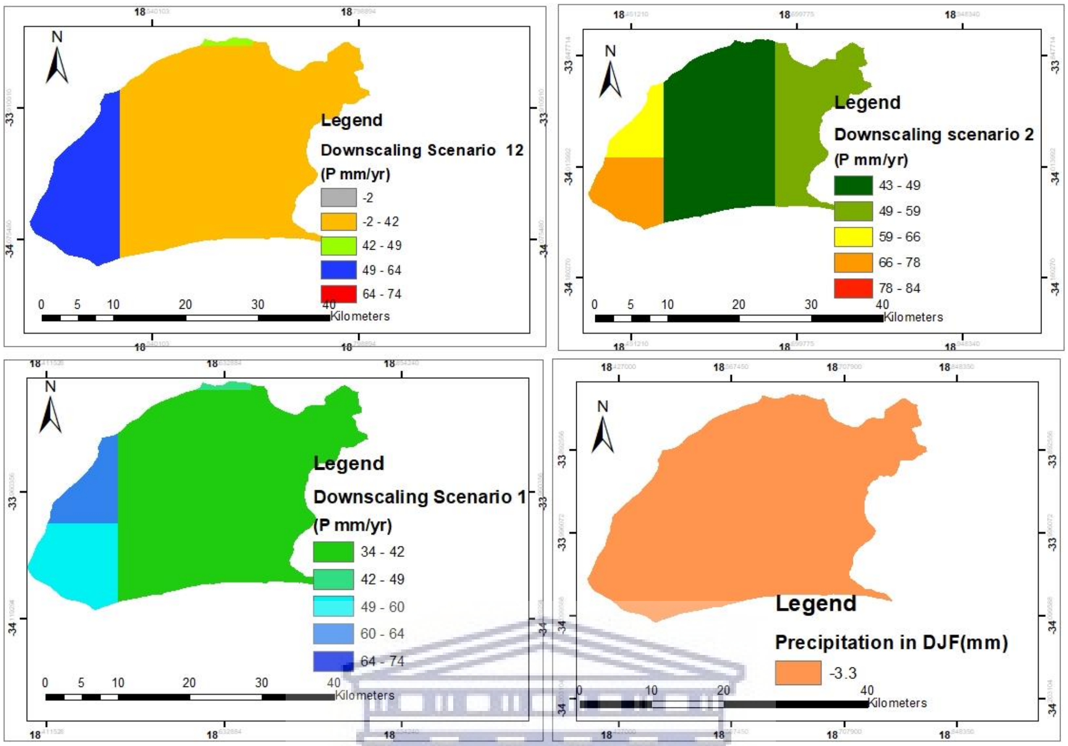


Fig. 5.9 Precipitation in the summer season

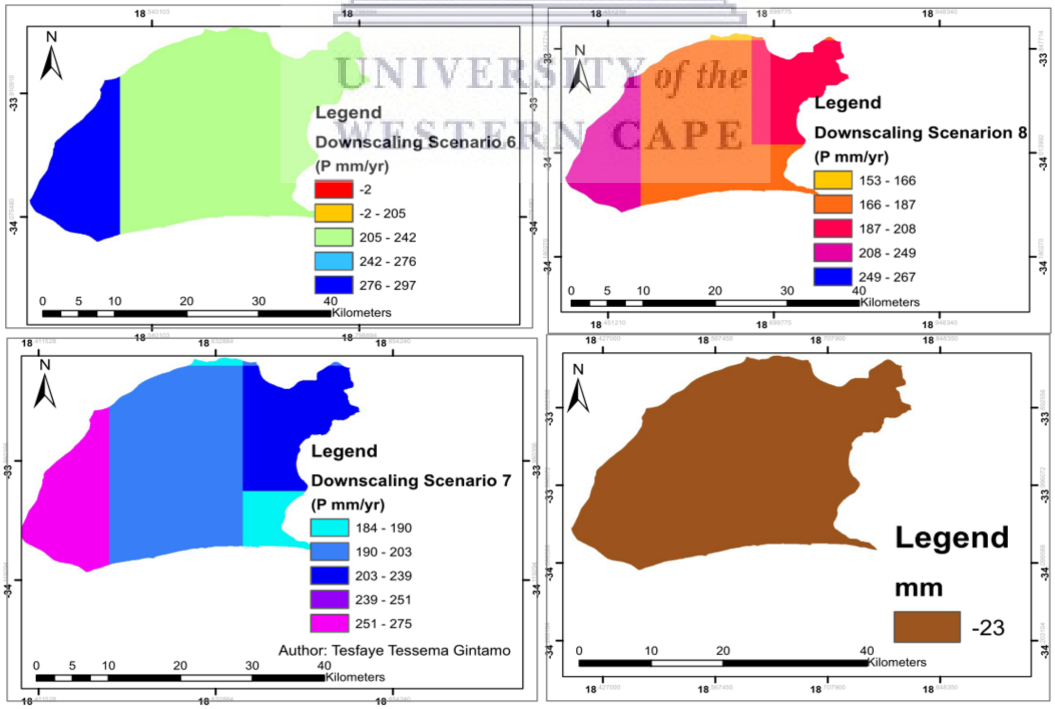


Fig. 5.10 Precipitation in Winter season

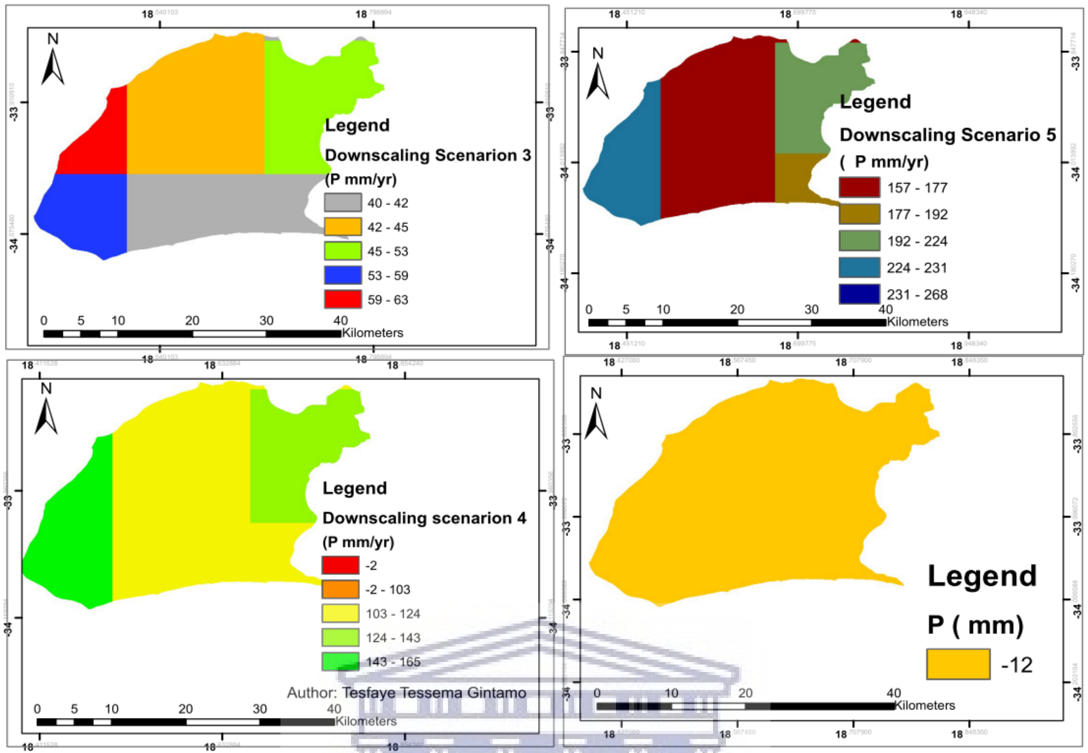


Fig. 5.11 Precipitation in the autumn season

Multimodal means all changes in precipitation percentages from 1990 to 2060. In the Cape Flats catchment, a robust decrease in precipitation intensity is projected in both DJF and JJA throughout the year range. In the CFA catchment, precipitation is projected to decrease significantly (up to 14 mm/day in SON on more than 30% of the land). The climate of Cape Town is controlled, and the relatively complex topography of the region is considered. The models agree that the Mediterranean region and southern Africa will have fewer precipitation in the future.

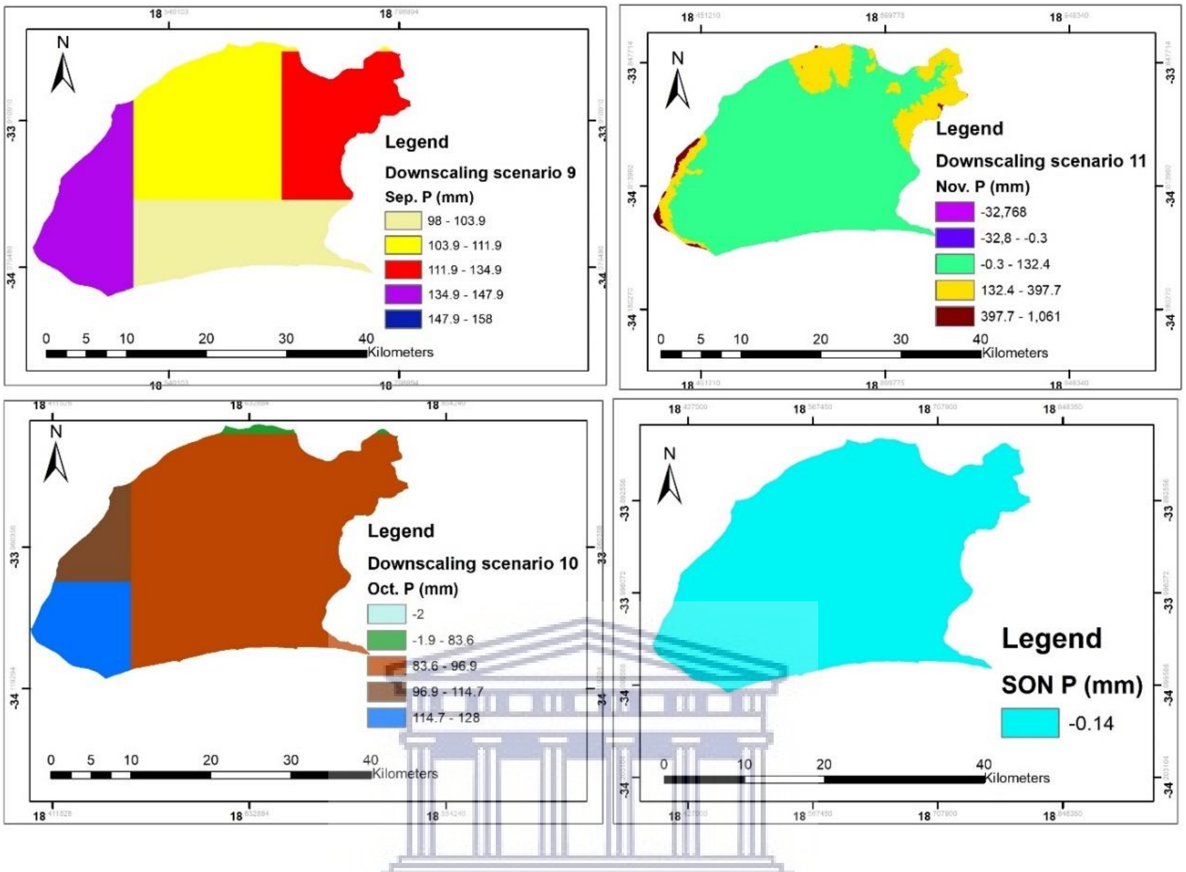


Fig. 5.12. Precipitation in Spring season

The Cape Flats could see a temperature increase of 1.9 ° C to 2.3 ° C for the period 2041–2060. Similarly, Cape Town could see a temperature increase in the range of 1.25 to 2.0 ° C between 2046 and 2060 for Cape Town, according to Jack et al. (2016).

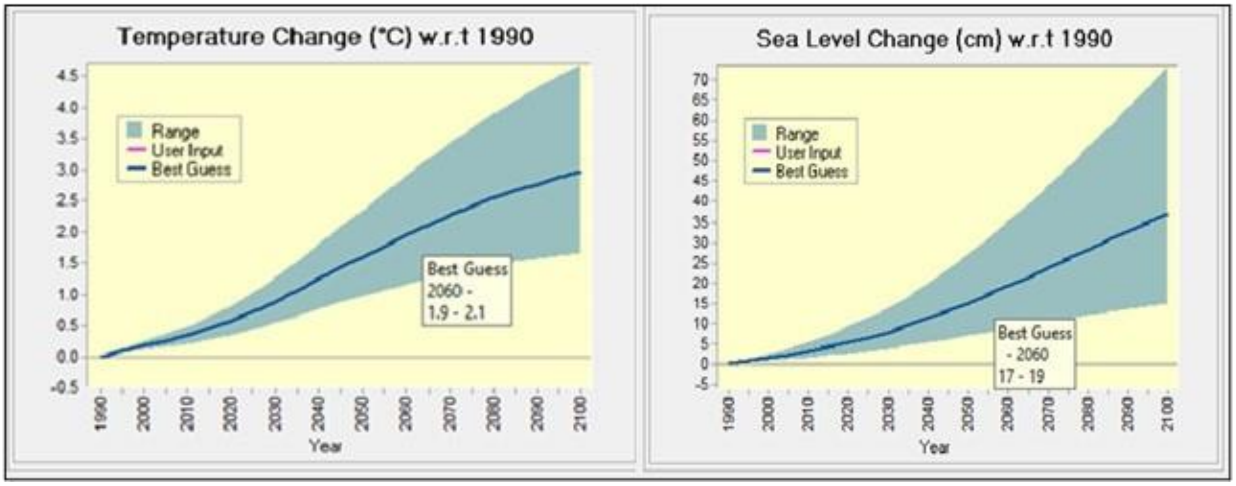


Fig. 5.13 Projected relative sea level rise for the Cape Flats area (relative to the year 1990)

The sea level rise impact model within the Climatic Variable Adaptation Modeler is an effective tool for estimating the extent and specific land areas likely to be affected by rising oceans. The model produces a probability image where areas certain to be underwater are given values of 1, and areas certain to remain unaffected are given a value of 0. Values between 0 and 1 represent the probability that any specific pixel will be impacted by an increase in sea level. At the end of 2040, about 12 to 56 % of coastal areas are predicted to be affected by increases in sea level. Fig. 5.14 clearly shows the consequences of an increase in sea level for the Cape Flats region and its surrounding area. The blue area shows the range of relative sea level rise and the black line shows the projection that incorporates the global and regional effects of warming oceans, melting land ice, and vertical land movements.

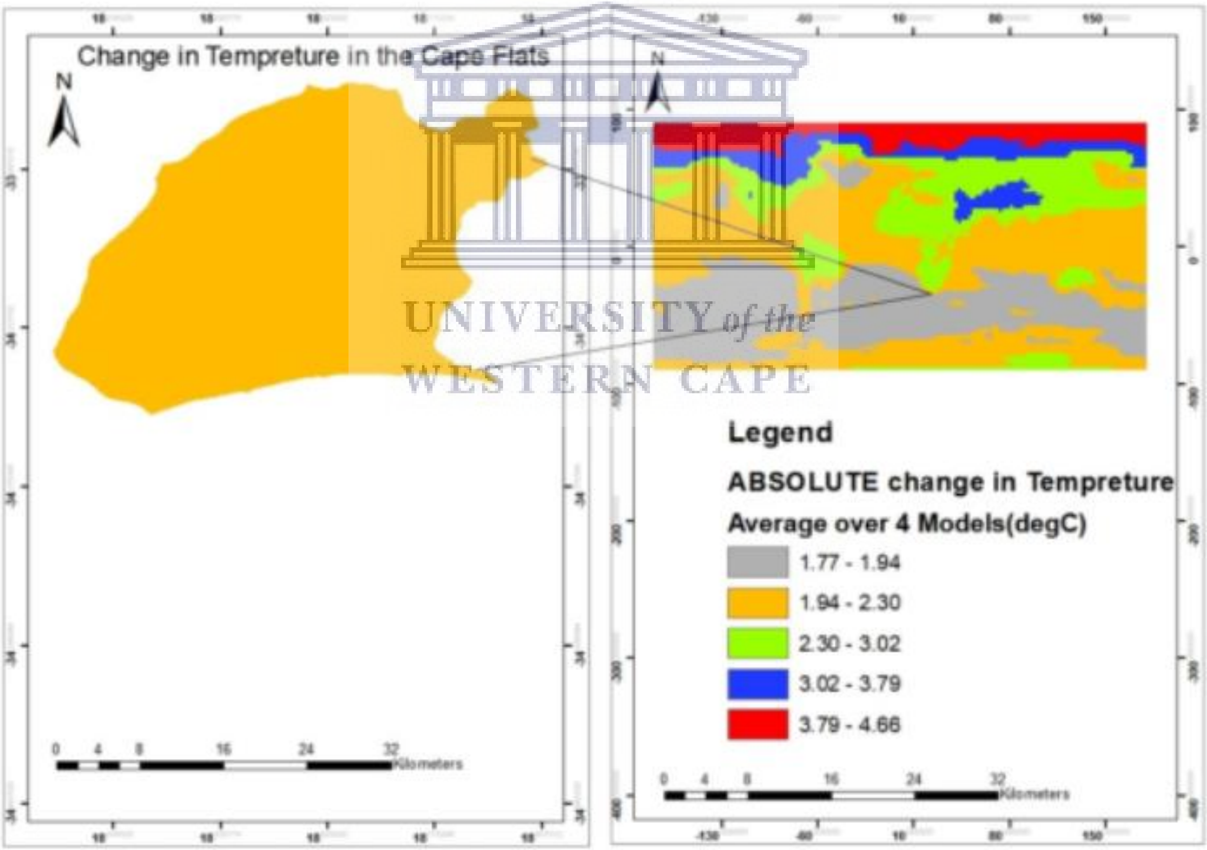


Fig. 5.14. Projected change in temperature downscaled for the period (2041- 2060).

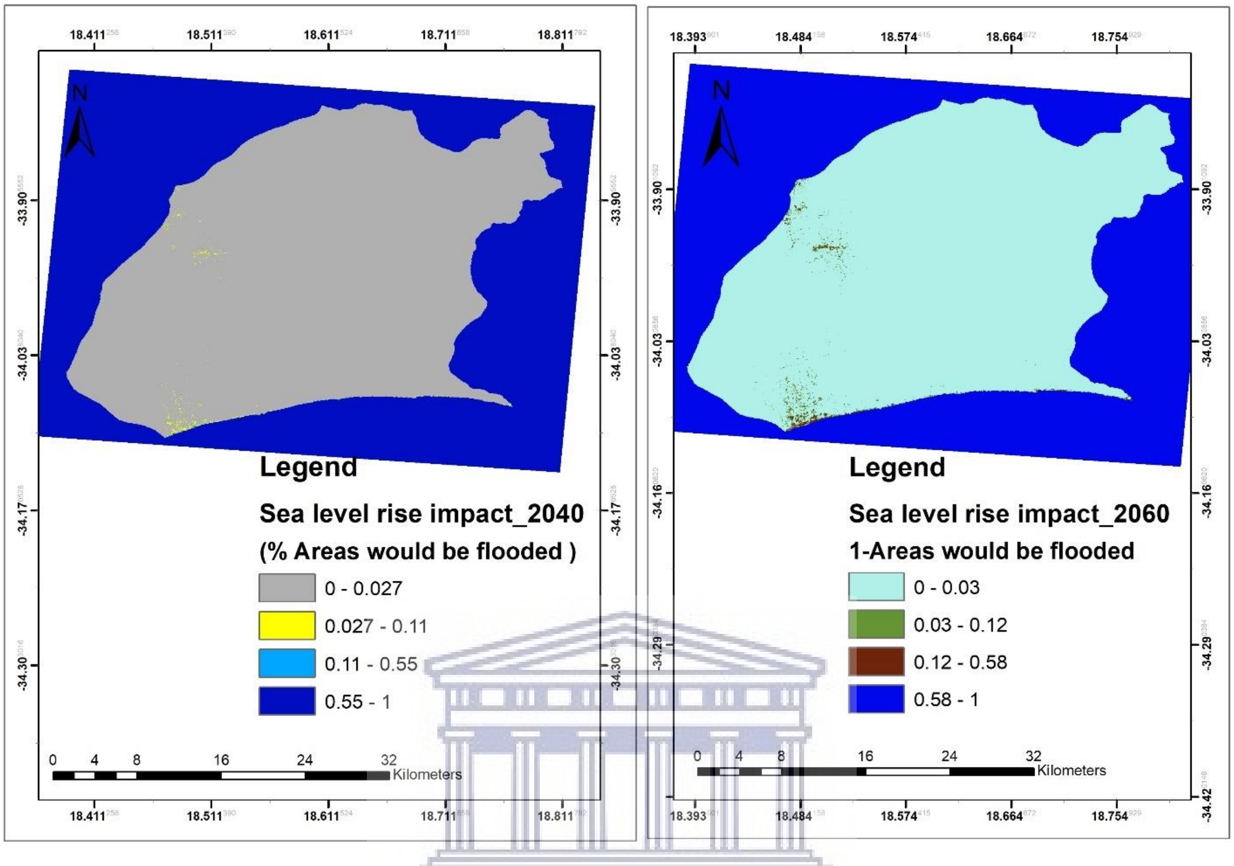


Fig. 5.14. The projected relative sea level rise for the Cape Flats catchment (relative to the year 2000) is based on emission scenarios (ranging from A1B to AIM)

FiguresFlood simulation CFA.mp4

In this study, an increase in the resolution of monthly precipitation images for the Cape Flats region for the years 2041 and 2060 has been indicated for scenarios A1B and B1 (high and medium regionalised) for the period 2041-2060, with the baseline 1990. The TerrSet Geospatial Modelling System shows the local impacts of Intergovernmental Panel on Climatic variables scenarios of 0.19-meter sea level rise, resulting in predictions of a probability of about 0.12 to 0.58 of the coastal areas being affected by sea levels at the end of 2060, where areas certain to be underwater are given values of 1 because of increasing temperature. The results show that the hydrological cycle will become more active in the future in a way that is significant on a yearly basis.

5.2.4 Interpretation of the Results

Downscaling global climate model (GCM) projections of future climate is critical for water resource impact studies. Precipitation, temperature, and sea level rise are simulated for two time periods, the 2040s and 2060s. An increase in temperature and fluctuating precipitation can have significant hydrological consequences. Coastal aquifers in southeast Cape Town could be affected by the rise in sea level. In the Cape Flats catchment, a robust decrease in precipitation intensity is projected in both DJF and JJA. The Mediterranean region and southern Africa will have less precipitation in the future. The general mountainous nature of the Cape Fold Belt results in sharp climatic variables for the entire area. Coastal aquifers are at risk of degradation due to climatic variables and a rise in sea level. Rising sea levels would put some parts of the aquifer under water, which would affect groundwater quality.

5.2.5 Validation of the Results

Hydrogeochemistry should be used to confirm the intrusion of seawater into coastal aquifers with low-altitude topography. Four variables are selected to be used as indicators of the general state of water quality. The selected variables are nitrate (NO3-), electrical conductivity (EC), and chloride (Cl^-). Electrical conductivity (EC) (mS/m) as an indicator of salinization, and chloride (Cl) (mg/l) for representing agricultural impact, sewage effluent discharge, and industrial waste. Electrical conductivity (EC) was assessed to highlight temporal changes in water quality. The available observation water quality data from previous studies were used to compare the results to validate the model results against the observed data (Adelana et al., 2014; 2010; Davis et al., 2011; Gnandji et al., 2013). The chemical analysis of the groundwater in the study area revealed high levels of nitrates and chlorides. The mapping of groundwater quality parameters using the GIS technique was found to be in close agreement with the available point source water quality laboratory data (Fig. 5.15).

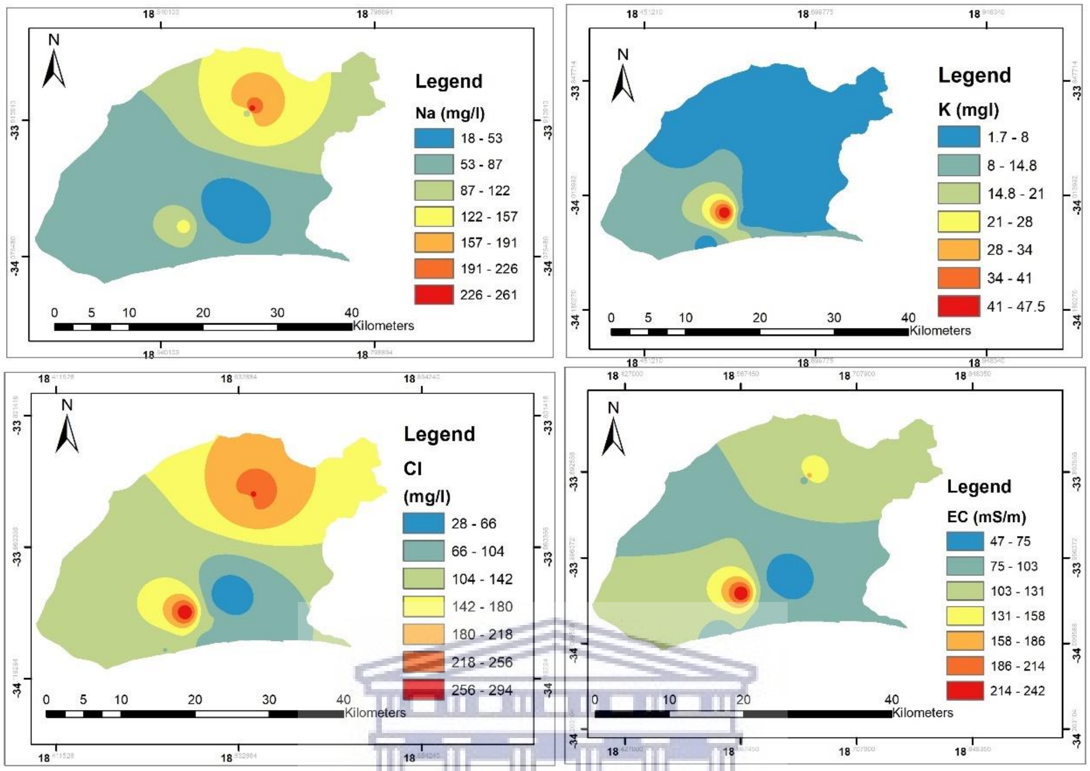


Fig. 5.15 Spatial distribution of the mean concentration of nitrate, chloride, and electrical conductivity in groundwater.

5.2.6 Implication of the Results

In general, the results presented suggest that climate variability likely has a potential impact on shallow aquifers. Variability in groundwater quality is more strongly correlated with temperature than with precipitation, but precipitation is more important in increasing surface runoff in shallow aquifers. The water quality parameters shown in Fig. 5.16 provide evidence that shallow aquifers are becoming increasingly contaminated, necessitating the design of feasible measures to protect aquifers, even though not all factors explaining the threat of groundwater contamination were captured in the analysis. Furthermore, spatiotemporal trends in climate variability and groundwater quality require long-term monitoring efforts to determine impacts. Hydrologic modeling and coupling with spatial analysis of chemical water quality in a GIS environment under changing climate conditions provide important information for more effective water resource management. The findings could be useful in the development of effective water resource management strategies. A rise in sea level is likely to cause seawater to enter groundwater resources near the coast, causing salt water to accumulate. At the end of 2040, about 2.7 to 11% of coastal areas are predicted to be affected by sea level rises. More accurately assess the impact of rising sea level on groundwater resources.

5.2.7 Conclusions and recommendations

Validations of the impact of climatic variables on the seasonality of climate variables in the Cape Flats catchment in Cape Town, South Africa, were evaluated using down-scaled global climate models coupled with TerrSet Geospatial Monitoring and Modeling Software in a GIS environment. TerrSet is a remote sensing and integrated geographic information system developed by Clark Labs at Clark University for the analysis and display of digital geospatial data. The Climatic variables Adaptation Modeler is a suite of tools to model the future climate and assess its impacts on sea level rise. It includes tools for climate scenario generation using the National Center for Atmospheric Research's MAGICC and SCENGEN models. Under the A1B and A2 emission scenarios, precipitation during and after the monsoon is expected to decrease in the Cape Flats catchment in all seasons. The results indicated that temperature and evapotranspiration will increase in all months of future years. The area could warm to 2.3 ° C in the 2060s, with an increase in annual evapotranspiration of up to 10% in the same period. We found a decrease in the seasonality of precipitation (both a decrease in the wet season and in the dry season). The greatest seasonal decrease of up to 23% are expected in the 2060s. As a result, decreases in dry season recharge are expected, with a span of 6.8 % for the highest monthly changes in the 2060s. This is expected to exacerbate the problem of seasonally uneven distribution of water resources: a pattern that indicates the possibility of more frequent floods in the wet season and droughts in the dry season. The rise in temperatures has an impact on the hydrological cycle, as it increases the evaporation of available water resources. The general mountainous nature of the Cape Fold Belt results in sharp climatic variables for the entire area. At the end of 2040, about 2.7 to 11% of coastal areas are predicted to be affected by increases in sea level. There is a probability of about 0.58 coastal areas being affected by the rise of sea level rise (17–19 cm) at the end of 2060, where areas certain to be underwater are given a value of 1. These findings add substantially to our understanding of linking groundwater vulnerability with climatic variables on the regional scale for an accurate assessment of the impacts of climatic variables on seawater intrusion in coastal groundwater systems. Future studies will need to better delineate the upcoming sea level rise at the local scale.

Chapter 6: Aquifer vulnerability mapping using a GIS-based overlay and index and the groundwater quality index methods in the Cape Flats aquifer, South Africa.

Manuscript title: **Using GIS-based modified DRASTIC modelling of the Cape Flats aquifer to improve understanding of groundwater vulnerability in the urban hydrogeology setting of coastal aquifers, South Africa.**

Abstract

The assessment of the vulnerability of aquifers to contamination has received new attention due to population growth and socioeconomic activities such as agriculture and industrialization, among others. This study aims to assess the vulnerability of groundwater using the modified model DRASTIC based on the Geographic Information System (GIS). The Cape Flats Aquifer in a low-lying coastal region southeast of Cape Town served as the case study. The DRASTIC GIS model considers important hydrogeological parameters such as depth of the water table (D), net recharge (R), aquifer medium (A), soil (S), topography (T), influence of the vadose zone (I) and hydraulic conductivity (C). Inverse distance weighting (IDW) spatial interpolation and the analytical hierarchy process (AHP) were used for spatial interpolation of point observation data. A weighted overlay analysis was used to calculate the index DRASTIC, which ranges from 109 to 222. The study area is divided into four different groundwater vulnerability zones, very high, high, moderate, and low, representing 9%, 28%, 46% and 17% of the study area, respectively. The moderate potential for groundwater contamination is more prevalent in the study area (46%). The areas with high and very high susceptibility to contamination are mainly concentrated in areas with lower slopes and the water table. The results for the study area show that after modifying the model DRASTIC with a factor of LU, the very high-risk zone increases by 26%, while the area under the low-risk zone decreases by 52%. The results highlight the importance of the DRASTIC model in the vicinity of GIS to analyze groundwater vulnerability and provide more effective water resource management.

Keywords: Aquifer vulnerability; Cape Flats; climatic variables; Cape Town; DRASTIC model; GIS; Water quality index.

6.1 Introduction

The groundwater resources in coastal areas are under severe pressure due to human activities and natural processes such as climate change. The complexity of the hydrogeologic conditions makes it difficult to better understand them. Groundwater vulnerability must be thoroughly mapped. Many studies have shown that the modified model DRASTIC for assessing vulnerability of aquifers is more accurate than the traditional overlay and index model models (Mogaji, 2018; Ramaraju and K. Krishna, 2017; Saatsaz et al., 2011b). These models can be used to manage and protect groundwater sources in cities across the world, such as Cape Town. Spatial decision support systems should be developed using state-of-the-art tools and techniques. The main innovation for vulnerability mapping and visualization is the modified model DRASTIC combined with the GIS-based method. A study has looked at the vulnerability of groundwater to various potential threats in shallow coastal aquifers in the Cape Flats catchment in South Africa using the DRASTIC model and GIS. The results demonstrate the importance of effectively managing groundwater, including planning, monitoring, and protection for sustainable use.

6.1.1 Results of the groundwater vulnerability assessment using the modified GIS-based DRASTIC model

6.1.2 Preparation of thematic maps

Thematic layers were created for each of the DRASTIC parameters using ArcGIS 10.3 software in raster format. First, thematic layers were converted into grid cells with weights of related elements. Furthermore, these were integrated and analysed using weighted linear combination techniques. The integrated layer grids were grouped into different zones of potential groundwater contamination risk to assess groundwater vulnerability to pollution. Data were collected from existing databases and maps, as well as remote sensing. All these data were managed using GIS databases. Each data layer listed in (Figs. 5.18 to 5.25) will be briefly described.

6.1.2.1 Depth to the water table (D)

The "depth to the water table" (D) is the level from the ground surface to the saturated zone. Indicates the thickness of the unsaturated zone through which a contaminant travels before

reaching the aquifer. The higher the depth of the water table, the lower the chances of groundwater pollution (Alaween et al., 2013). Although shallow water table levels imply higher contamination chances. Data for 69 wells located within the Cape Flats catchment were provided by DWS Groundwater Achieve (GWA) and existing literature was used to form thematic maps. Because the depth to water level varies between 1 and 36.9 m, the rates vary between 2 and 9 (
Fig. 6.1).

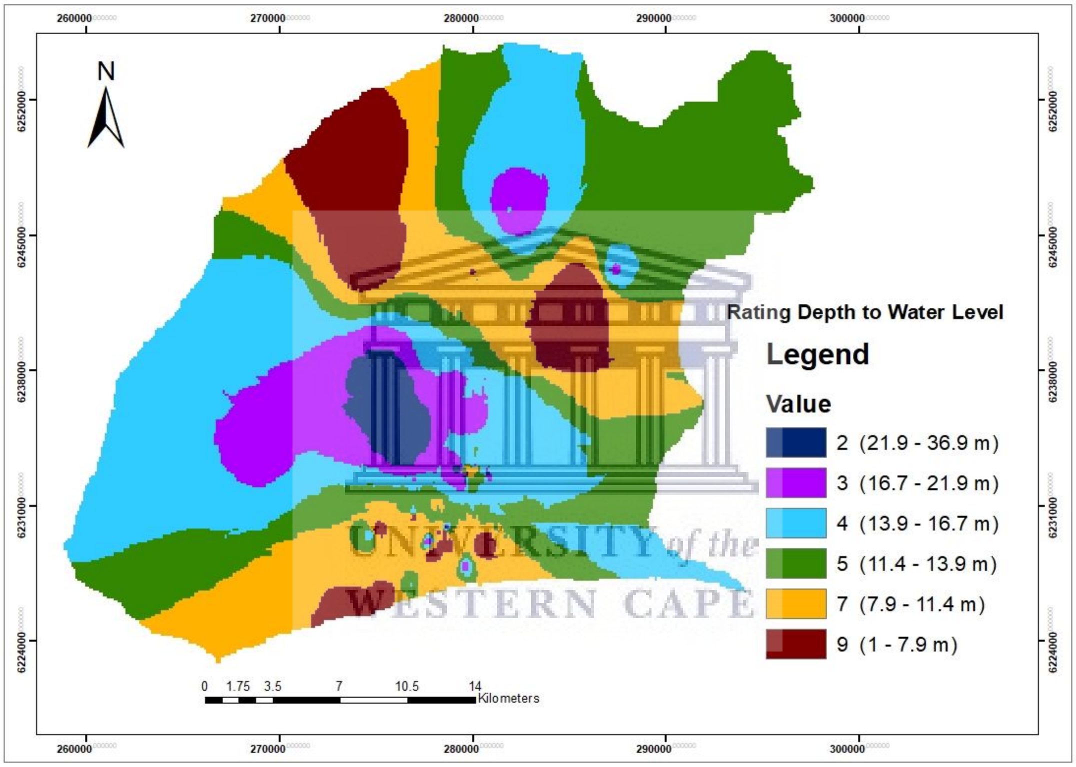


Fig. 6.1 Map of depth to water level (D) and assigned rates

6.1.2.2 Net recharge (R)

Net recharge (R) represents the amount of water added to the subsurface and serves as a transport agent for contaminants to groundwater. More recharge leads to greater contamination potential, as it can cause leaching and transport of contaminants from the ground surface to the water table (Lathamani et al., 2015). Recharge quantification is relatively complex. However, WaterWorld Policy Support approaches proposed by (Soesbergen and Mulligan, 2014b), were used in this research to estimate recharge. The developed map shows the spatial variation of recharge from 67 mm to 1200 mm per year in the study area (Fig. 6.2).

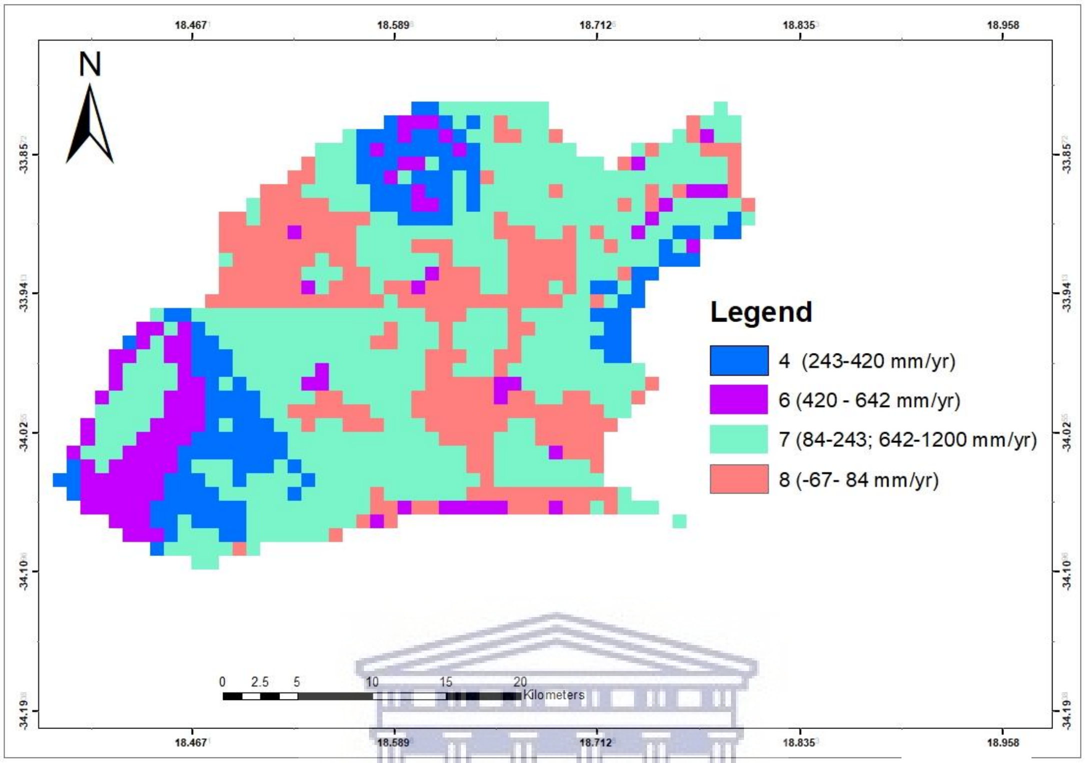


Fig. 6.2 Recharge map (R) and assigned rates

6.1.2.3 Aquifer medium (A)

Aquifer media (A) mainly discusses the type and properties of the aquifer material that control the pollution processes of the saturated zone (Kozlowski and Sojka, 2019b; Mondal et al., 2017). Determines the attenuation capacity of an aquifer to carry the contaminant based on the amount, size, and sorting of grains, lowering the grain size (Muhammad et al., 2015b). A large part of an aquifer is the unconsolidated, unconfined Cape Flats aquifer, followed by low-permeability shale and fine sedimentary units (Fig. 6.3). Based on the hydrostratigraphic units of the study, the area rating was assigned. First, sedimentary rocks have a value of 8. Second, fractured shale receives a value of 7, correlated with the vulnerability rating. In the Cape Flats catchment, the aquifer medium is mainly composed of permeable sandy units. In the rest of the catchment, the aquifer is mostly made up of calcrete, calcarenite, aeolianite, conglomerate, clay, and other rocks.

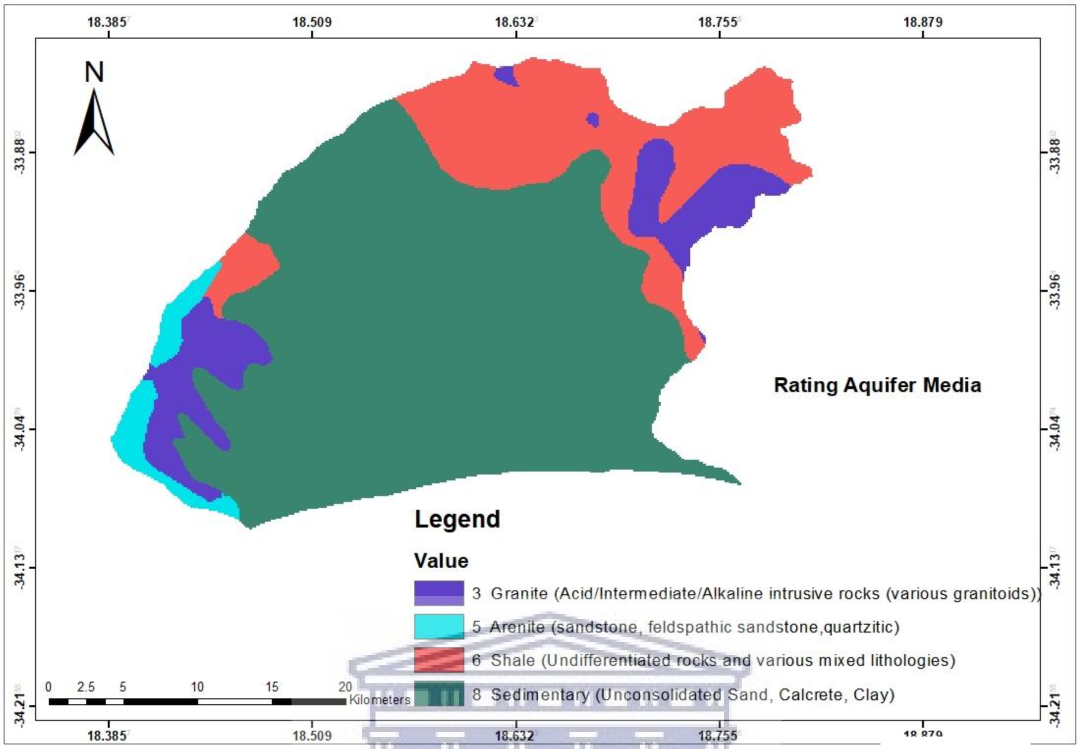


Fig. 6.3 Map of the aquifer media (A) and its rates assigned in the study area

6.1.2.4 Soil medium (S)

Soil media (S) is the upper layer and the weathered layer of the ground surface associated with the increased influence rate on the downward movement of contaminants (Voudouris et al., 2010). In the presence of fine material, infiltration decreases. Therefore, this presence also decreases the potential for pollution. Thus, soils with relatively low infiltration rates, such as clay soils, have a larger runoff component than sandy soils, which have a relatively higher infiltration rate (B. Mauck, 2015b). The value of variable S (Soil type) was obtained from soil classification maps produced by the Department of Geosciences of the South African Geological Survey (Musekiwa and Majola, 2011), and weights and ratings were assigned accordingly. In the study area, the soil was classified as sandy clay, sandy loam, and sand (Fig. 6.4). Based on the interpretation of the content of agricultural soil maps, sandy clays and sandy loam developed from sandy materials are the dominant soils in the area.

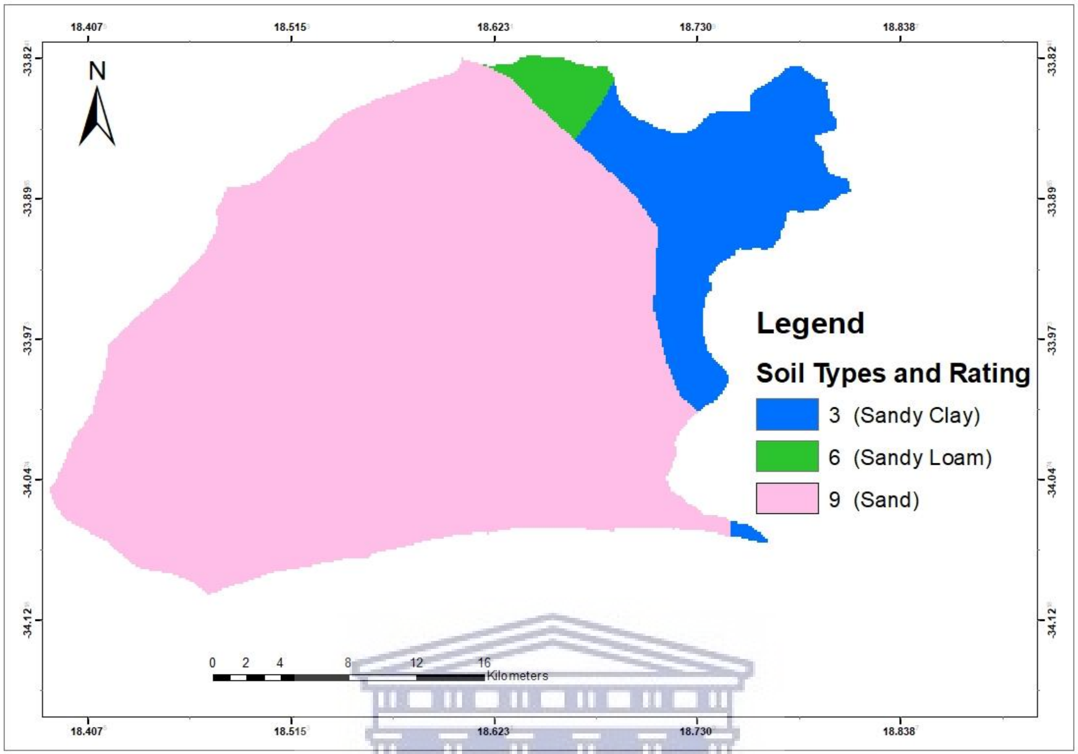


Fig. 6.4 Soil map (S) and rates assigned

6.1.2.5 Topography (T)

Topography (T) refers to the slope. Areas with a slope of a gentle topography and flat areas would allow more contaminants to move into the shallow groundwater aquifer easily. However, with a steep slope, contaminants tend to move with runoff and are less likely to infiltrate the vadose zone and enter groundwater. The slope was determined directly from the Digital Elevation Model (DEM). The DEM was downloaded from an authorized site (USGS) using the ArcGIS spatial analysis tool. Topography is specified by the percentage of slope (%) extracted from the DEM of 30 m. The slope in the study area is steep in the western zone and gently to low in the eastern and northern zones and the central zone, respectively, and varies from 4.9 to 89.9 degrees (Fig. 6.5). In the present study, the topography was subsequently rated using the DRASTIC, ranging from 1 to 10 (Fig. *6.5*).

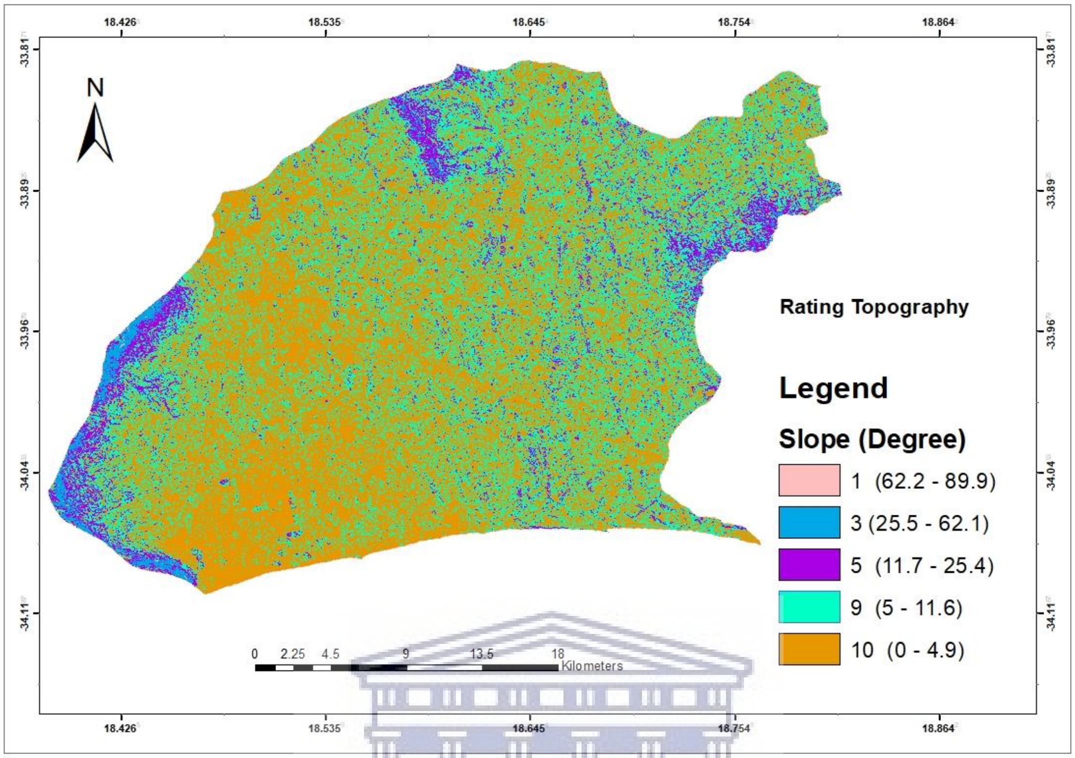


Fig. 6.5 Topography map (T) and its assigned rates

6.1.2.6 Impact of the vadose zone (I)

The thickness and properties of the unsaturated zone, among other hydrogeological factors, are important factors in assessing the likelihood of a contaminant reaching groundwater (Nezar et al., 2010). In this study, the influence of the unsaturated zone was calculated based on the location of each well and the dominant material using the AHP adjustment and the depth of the aquifer (Saida et al., 2017). The impact of the vadose zone map layer was prepared using the lithological formation of the Cape Flats and has been converted to raster data with a pixel resolution of 300 m. In the impact map of the vadose zone layer, the gravel and sandy alluvial deposits were assigned a high rating value of 8. Whereas the clayey gravel deposits and the Mesozoic sandstone were assigned a moderate score of 6. The low rating values of 2, 3, and 4 were assigned to clay and clay sand, respectively.

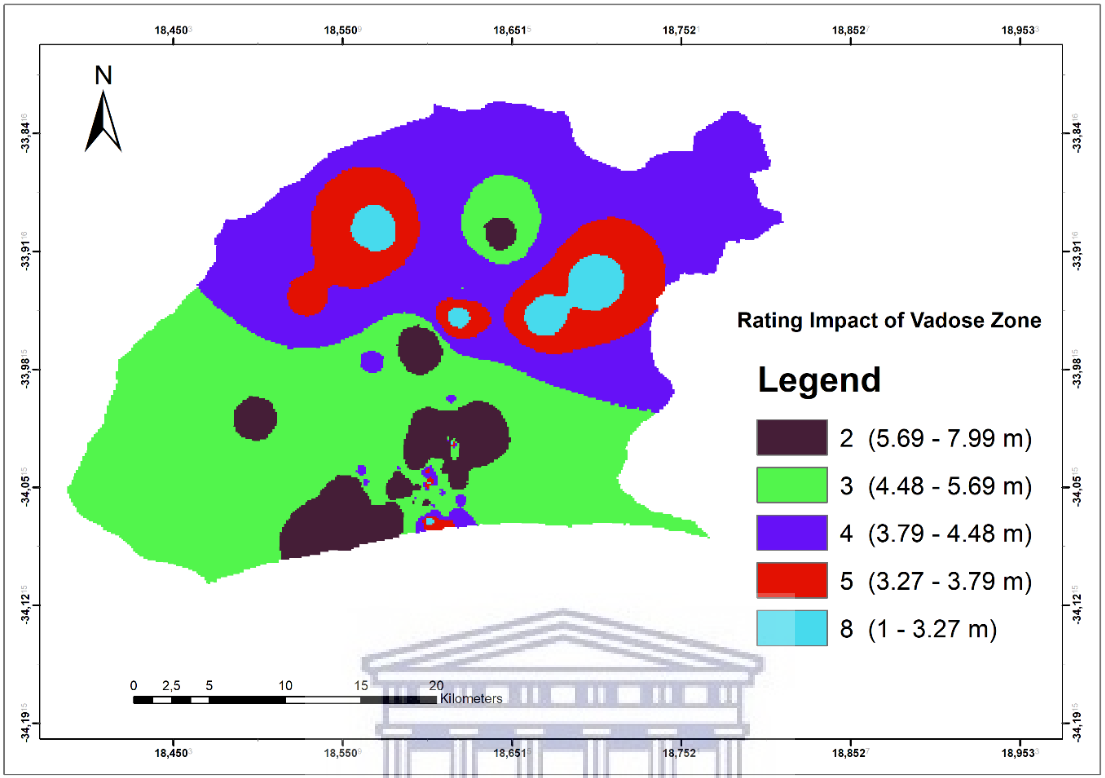


Fig. 6.6 Impact of the map of the vadose zone (I) and the assigned rates

6.1.2.7 Hydraulic Conductivity (C)

Hydraulic conductivity (C) determines the ability of the aquifer to transmit water (Machdar et al., 2018b). Aquifers with high conductivity have higher chances of contamination from sources that can easily move through the aquifer (Aller, 1987, as cited in (Muhammad et al., 2015). For the present study, hydraulic conductivity was calculated from pump test data and the spatial hydraulic conductivity map obtained from the hydrogeological analysis of the Cape Flats region by different scholars. Adelana et al. (2010) found that transmissivity values range from 50 to 650 m2 / day, with values between 200 and 350 m2/day due to well-sorted and rounded sands of the aquifers. In general, the defining characteristic of the Cape Flats area is high hydraulic conductivity. Therefore, a large part of the analysed area was assigned a maximum rating score of 7 (Fig. 6.7).

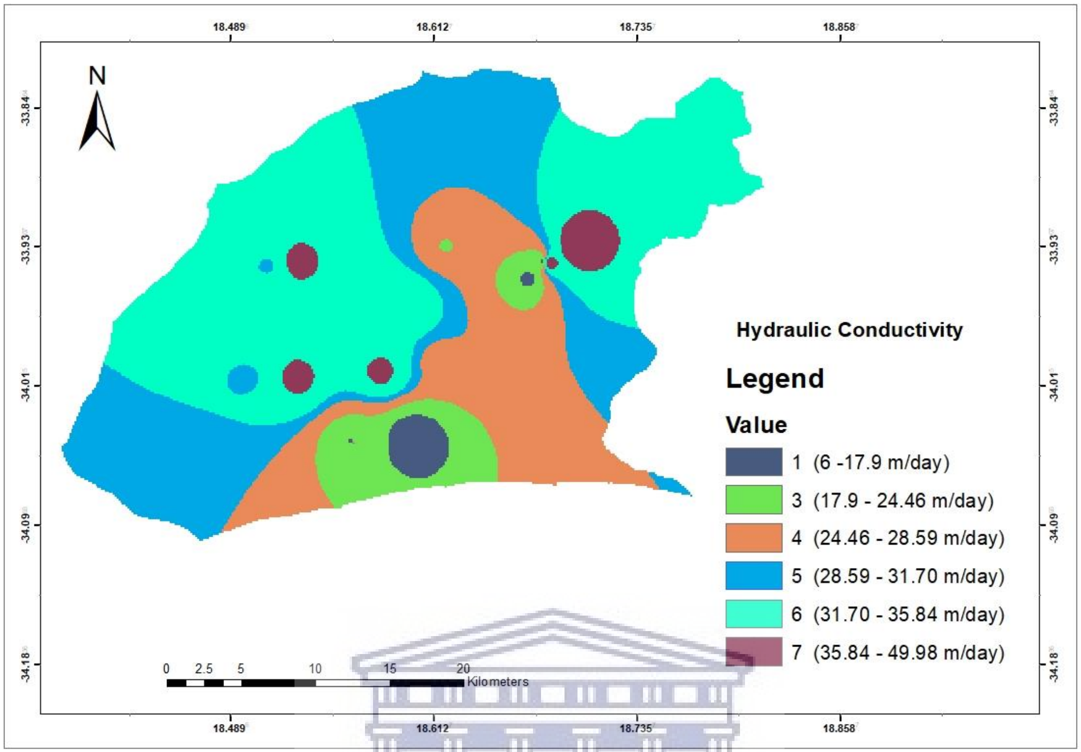


Fig. 6.7. Hydraulic Conductivity (C) Map and Rates Attributed

6.1.2.8 Land Use/Land Cover (Lu)

Land use has a potential impact on groundwater vulnerability and risk mapping, which were produced due to groundwater contamination. The precision of the DRASTIC technique can be combined with land use characteristics and other variables (Shrestha and Luo, 2018). The thematic map of land use/land cover (Lu) was prepared based on visual interpretation and classification of satellite images (Fig. 3.8). The land use map was divided into five classes, including the built-up area (60.5%), agriculture (13.6%), water bodies (2%) and vegetation (22.6%) for modified DRASTIC ratings, and the assumed DRASTIC weight of the land use parameter was 5 (Table 5.3). In general, each class was classified according to its effect on groundwater vulnerability scales ranging from 1 to 10 (Fig. 6.8).

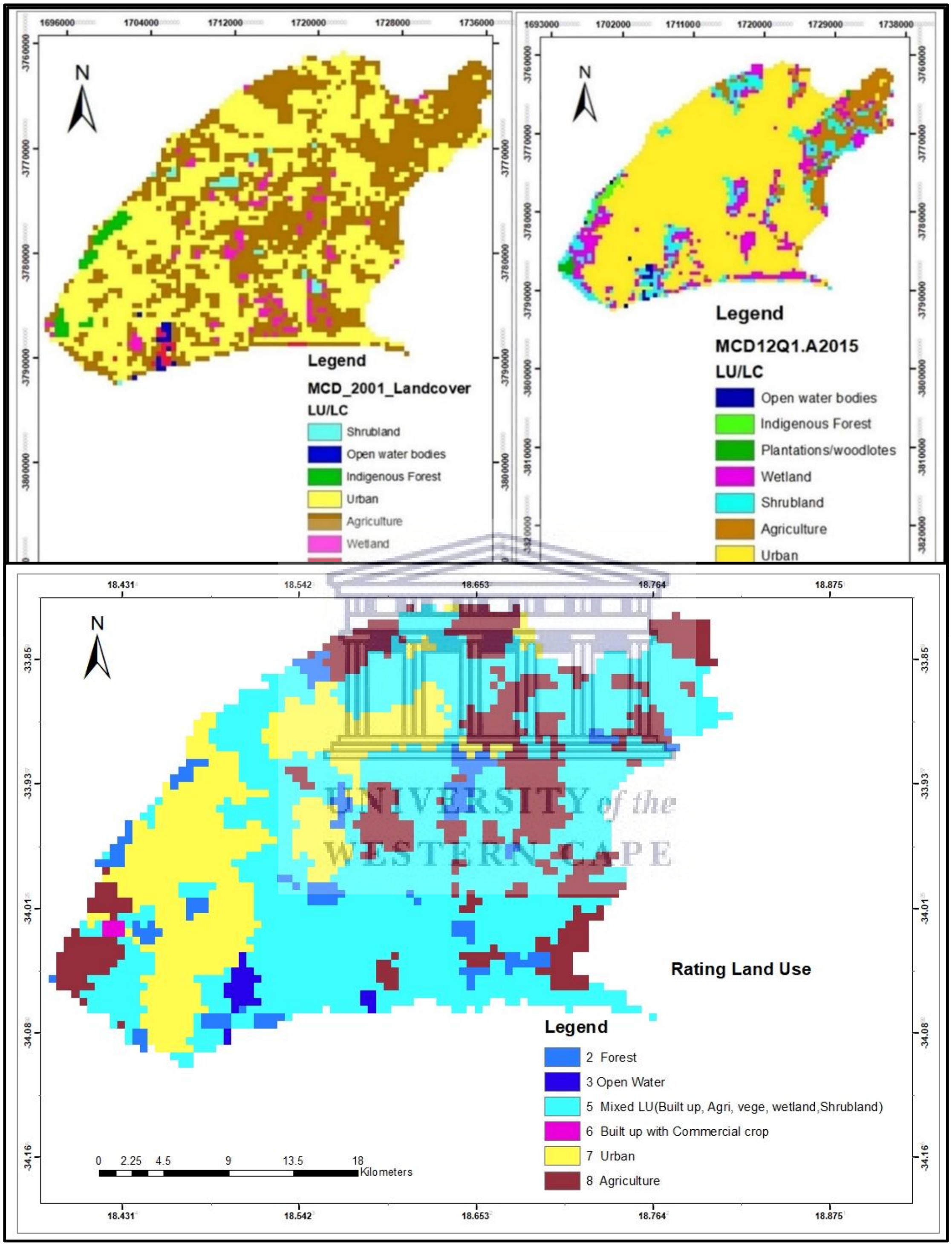


Fig. 6.8. Land Use/Cover Change Maps (LU/LC) and Aggregated Rates

6.1.3 *Groundwater Vulnerability Mapping*

6.1.3.1 Drastic Vulnerability Index

The vulnerability of groundwater was prepared by overlaying thematic maps using ArcGIS 10.3 software. The DRASTIC index (DI) was calculated as the weighted overlay analysis and the sum of the parameters. The DI theoretically ranges from 1 to 10. Small values of DI indicate a low vulnerability potential, while high values are related to a high pollution potential (Abdeslam et al., 2017). The groundwater vulnerability map was created based on seven hydrogeological parameters that were evaluated and recommended by the DRASTIC model. The DRASTIC rating index map of the study area was developed to show values between 117 and 220 (Fig. 6.9). The map compiled is divided into five vulnerability zones showing high (18%), moderate (28%), and low (54%) vulnerability zones.

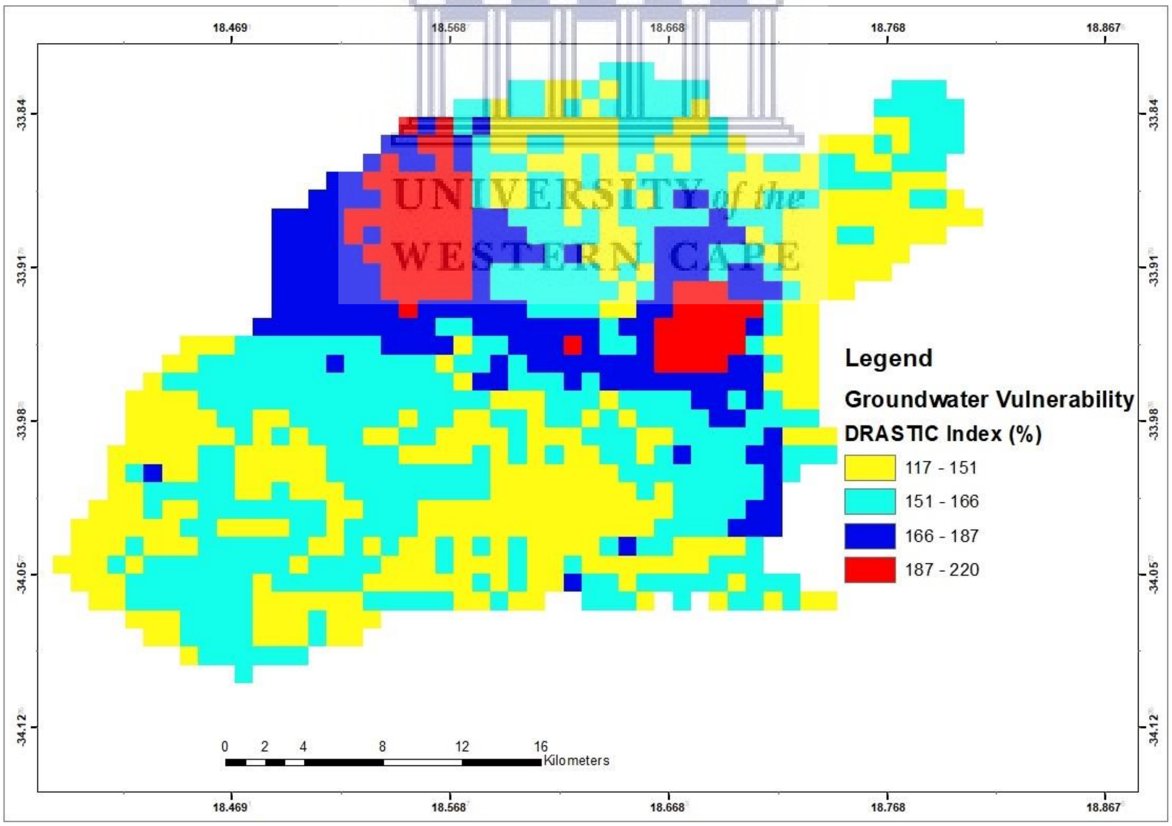


Fig. 6.9. Groundwater vulnerability map produced by the conventional DRASTIC model

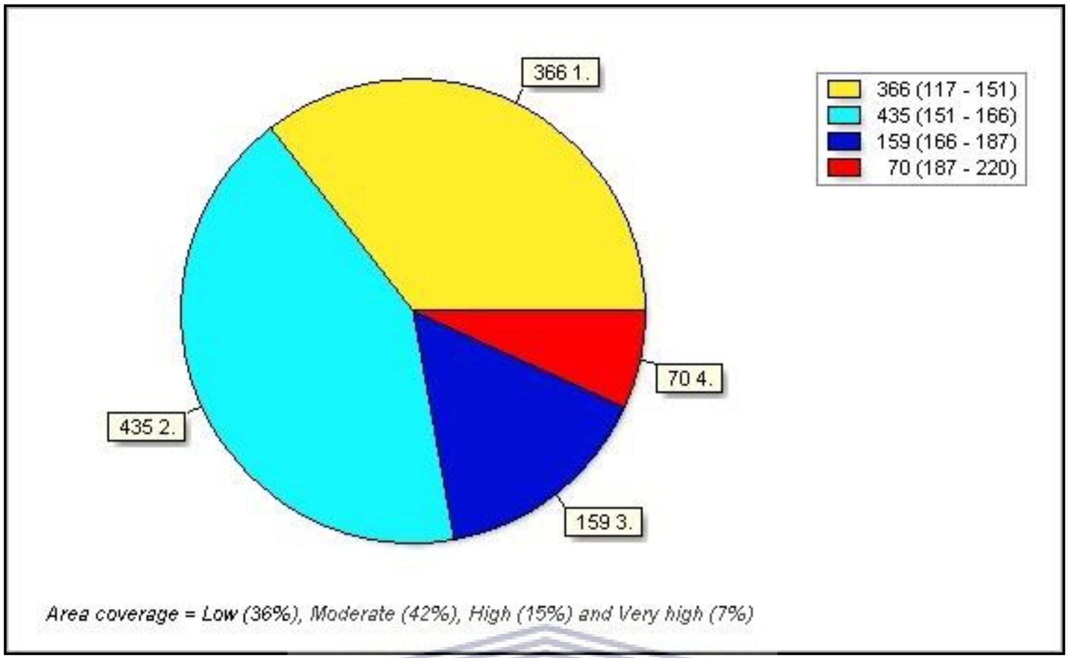


Fig. 6.10 Coverage of vulnerability zones (DRASTIC model)

Table 6.1 Classification of the DRASTIC vulnerability index

DRASTIC indices	DRASTIC range	Area (Km^2)	Percentage
Low	117 – 151	366	36
Moderate	151 – 166	435	42
High	166 – 187	159	15
Very high	187 – 220	70	7

6.1.3.2 Modified DRASTIC Index

The original DRASTIC model was modified by adding the parameter that describes the type of land use, which is important for assessing the vulnerability of shallow groundwater. The land use parameter used to modify the assumed weight rate of DRASTIC was 5 (Anp, 2019). The types of land use considered contained the following: wetland, settlement, agriculture, and forest, with scores of 8, 7, 5, 3, and 2, respectively. The rating was achieved using GIS, the analytical hierarchy process and spatial interpolation techniques based on inverse distance weighting (IDW) to develop thematic maps of groundwater contamination. After creating all the necessary layers, the vulnerability maps were obtained by overlaying the thematic maps on ArcGIS 10.3, and the DI was calculated as the weighted sum of the parameters. Overall, the DRASTIC Index (DI) ranges between 23 and 226 (Koz\lowski and Sojka, 2019), theoretically. The most obvious small values show a low vulnerability potential, and high values are related to the high contamination potential of groundwater to allow a better groundwater vulnerability assessment. In Table 6.1 the analytic hierarchy process was used to determine how important each parameter was when comparing two things at the same time (AHP).

The primary means of comparing the parameters to determine the contribution to the vulnerability index is the depth to the water table, which is (mean = 31) and the net recharge, which is (mean = 24). The aquifer and soil media have mean values of 11 and 10, which are the third and fourth significant parameters. Because the vadose zone and land use have a mean value of 5, these things do not play a large role in contaminating the aquifer.

Table 6.1. Standard and modified weight values are used in the different DRASTIC models.

Parameter	**Weight**		
	Standard DRASTIC	Modified DRASTIC	Modified DRASTIC AHP
Depth to water (D)	5	5	0.313
Recharge (R)	4	4	0.244
Aquifer medium (A)	3	3	0.11
Soil medium (S)	2	2	0.099
Topography (T)	1	1	0.093
Impact of the vadose zone (I)	5	5	0.049
Hydraulic conductivity (C)	3	3	0.057
Land use/land cover (Lu)	-	5	0.035

Source (After Aller et al., 1987)

The results of this analysis classified the vulnerability map into different ranges of levels, from low to high vulnerability indices. The results are expressed in the coverage of areas of different vulnerability zones in percent, including high (12%), moderate (47%), and low (41%). Compared to the results obtained using the modified DRASTIC method, the results indicate that the area described as a zone of high vulnerability has increased by 1%. The application of the modified DRASTIC method is demonstrated by the vulnerability index, which is between 109 and 222 (Fig. 6.10). These results show on the vulnerability map that a large area is dominated by low- and moderate-vulnerability zones, followed by a high zone, respectively.

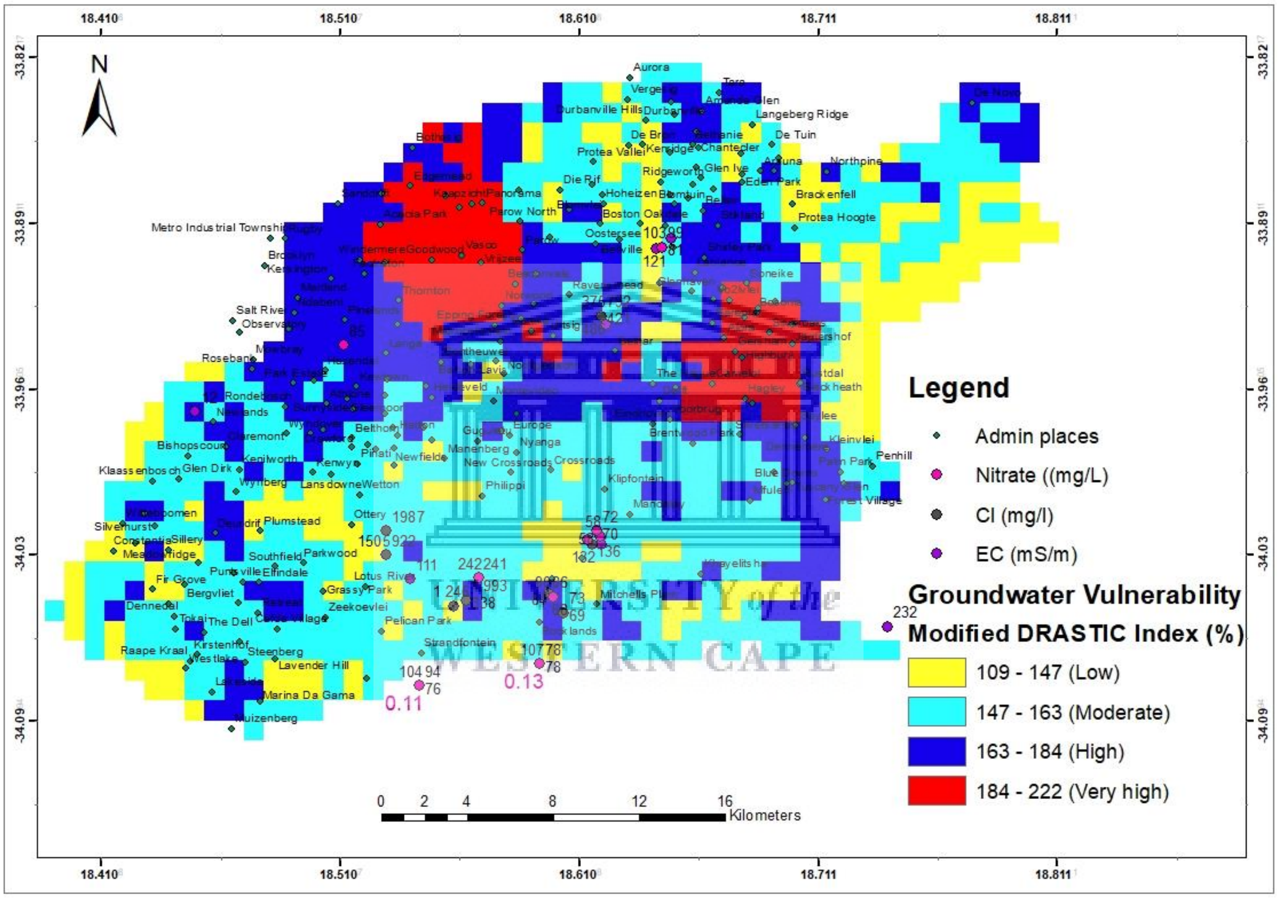


Fig. 6.11 Groundwater vulnerability map produced by the modified DRASTIC model

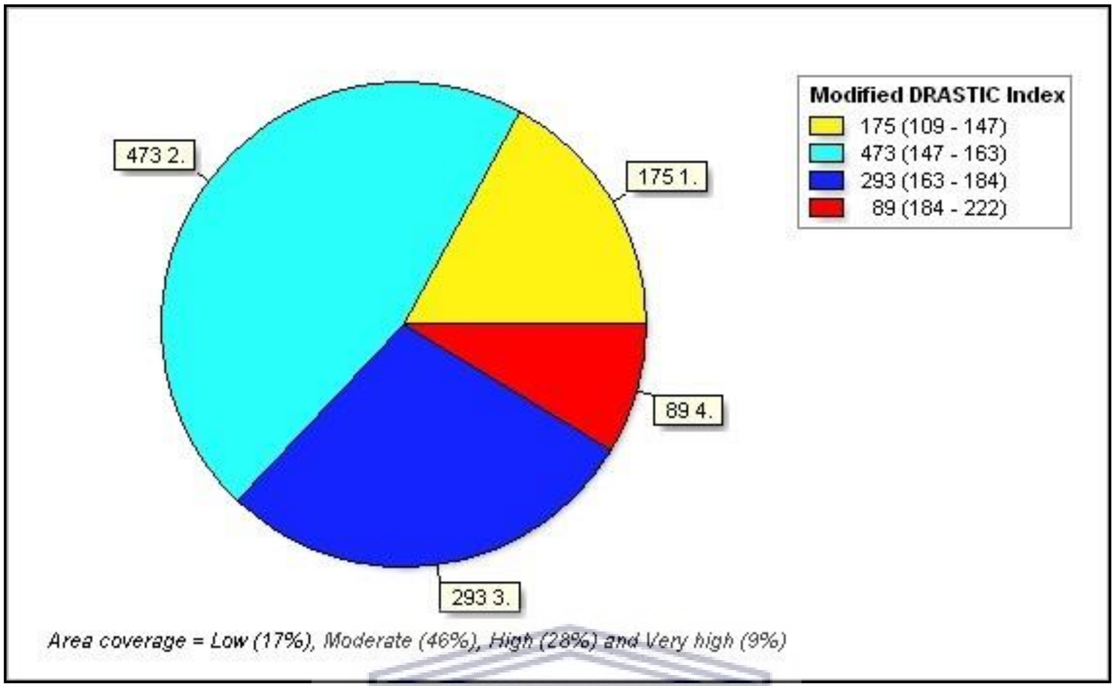


Fig. 6.12 Area of groundwater contamination risk map

Table 6.2 Classification of the modified DRASTIC vulnerability index

DRASTIC indices	DRASTIC range	Area (Km2)	Percentage
Low	109 – 147	175	17
Moderate	147 – 163	473	46
High	163 – 184	293	28
Very high	184 – 222	89	9

Land use parameters have been added to the DRASTIC method to increase its prediction accuracy. However, a statistical comparison reveals a 22.5% difference between the modified DRASTIC vulnerability map and the original DRASTIC model that shows the percentage distribution of the area that covers the predicted vulnerable zones, namely very high, high, moderate, low and very low, which are estimated from the groundwater vulnerability prediction maps produced. Fig. 6.12 illustrates that more than 46% of the area is in moderately vulnerable zones.

An important coastal water catchment's water quality was linked to land cover/use change. When the spatial heterogeneity of the catchments was altered by human or natural events, this was reflected in changes in water quality. The Cape Flats catchment in Cape Town was studied using a spatial and temporal analysis of historical catchment land use change (Fig. 6.13). The groundwater contamination risk index was examined to determine trends that correlated with changes in land use activities. In the Cape Flats catchment, chloride and electrical conductivity concentrations were higher in the cropland, bare land, and coastal vicinity and were correlated with low recharge.

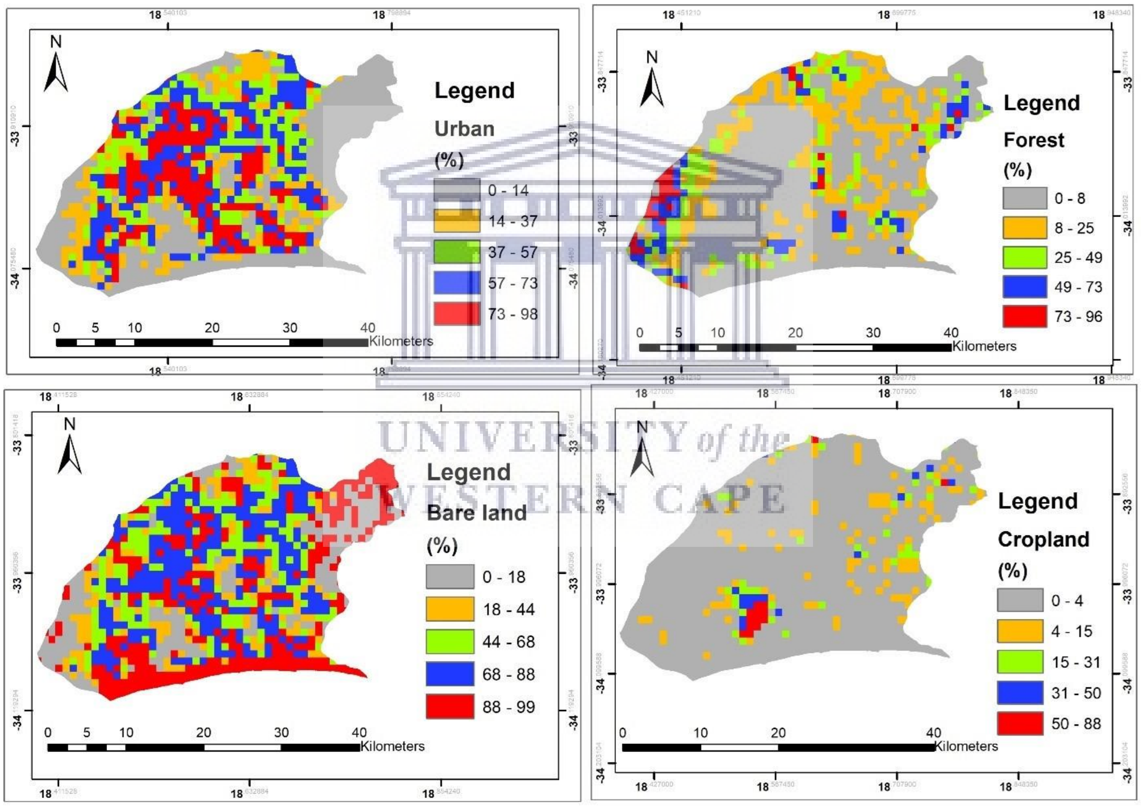


Fig. 6.13. Land use land cover distribution in the Study Area

6.1.4 Interpretation of the results of the assessment of groundwater vulnerability of coastal aquifers

The Cape Flats aquifer is under pressure from population growth, urbanization, industrialization, and agricultural activities. The study area is characterized by many sources of pollution that threaten groundwater quality. The modified DRASTIC model was used to assess the vulnerability of groundwater to pollution in the Cape Flats aquifer. Low to moderate vulnerability is in the central part of the study area. Very high vulnerability values are recorded in a large part of the aquifer and are associated with shallow aquifers without great depth in the vadose zone. Regional assessment of groundwater vulnerability is a useful tool for groundwater resource management and protection zoning. The results provide important information, and the vulnerability maps could be used by local authorities and decision makers alike to make timely policy decisions in this area.

Groundwater vulnerability was prepared by overlaying the thematic maps using ArcGIS 10.3 software. The DRASTIC index (DI) was calculated as a weighted overlay analysis and the sum of parameters. The DI theoretically ranges from 1 to 10. Small values of DI indicate a low vulnerability potential, while high values are related to a high pollution potential (Abdeslam et al., 2017). The groundwater vulnerability map was created based on seven hydrogeological parameters that were evaluated and recommended by the DRASTIC model. The DRASTIC rating index map of the study area was developed to show values between 117 and 220 (Fig. 6.9). The map compiled is divided into five vulnerability zones showing high (18%), moderate (28%), and low (54%) vulnerability zones on land.

The results of this analysis classified the vulnerability map into different ranges of levels, from low to high vulnerability indices. The results are expressed in the coverage of areas with different vulnerability zones in percent, which included high (12%), moderate (47%), and low (41%). Compared to the results obtained using the modified DRASTIC method, the results indicate that the area described as a zone of high vulnerability has increased by 1%. The application of the modified DRASTIC method demonstrated that the vulnerability index is between 109 and 222 (Fig. 6.11). These results show on the vulnerability map that a large area is dominated by low and moderate vulnerability zones, followed by a high zone, respectively.

6.1.5 Comparative assessment of the results on groundwater vulnerability of coastal aquifers

Compared to the present study, most previous studies were smaller and did not investigate vulnerability assessment on spatial and temporal scales at the local level. They also discovered higher levels of chloride concentration in the wells in the study area. Additionally, the findings are compared to similar areas of research(Table 7.2). Adelana (2010) used the input parameters with the CALOD model, which include clay layer thickness (C), aquifer media character (A), lateritic layer thickness (L), overlying layer character (O), and depth to groundwater level (D). According to (Kaliraj et al., 2015), the results of the DRASTIC groundwater vulnerability assessment show index values that range from 120 to 159 (intermediate pollution susceptibility) to 160 to 167 (high susceptibility). Their results confirmed the classification of the assessment of groundwater vulnerability of the study area into four zones. First, a very low risk zone with a risk index of 120 to 128. Second, a low groundwater vulnerability risk zone with a risk index of 128.1–135. Third, a moderate groundwater vulnerability risk zone with a risk index of 135.1 to 140. Fourth, there are high-vulnerability risk zones. In general, the modified DRASTIC model result was also compared with the result derived from the original DRASTIC method. The optimized-DRASTIC method thought that there were more catchments in the higher index range than the original-DRASTIC method thought there were.

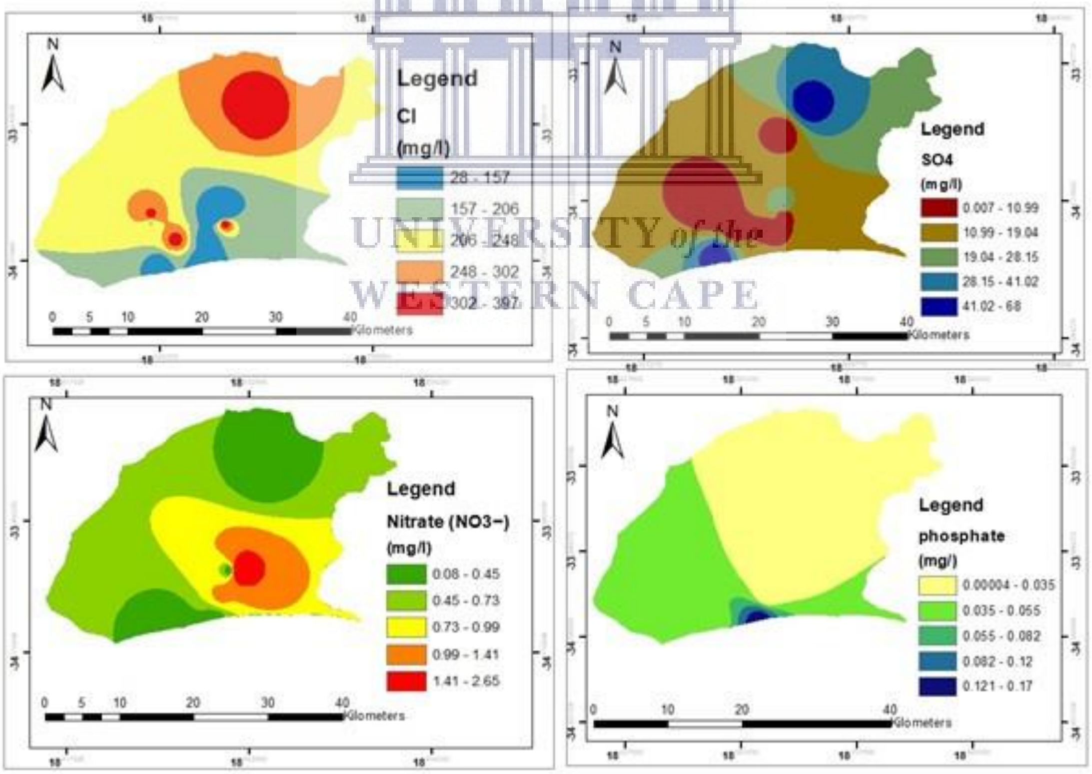
6.1.6 Implication of results in the assessment of groundwater vulnerability of coastal aquifers

This study indicates that the GIS technique could provide an efficient way to deal with the large amount of spatial data used in the DRASTIC model. This study demonstrates the use of remote sensing and GIS to assess the suitability of groundwater development for agricultural, industrial and domestic purposes. Remote sensing and GIS techniques have been used in the Cape Flats area to map risk zones of groundwater contamination. These methods are found to be cost-effective and enable quick decision-making for sustainable water resource management. Satellite data was combined with rain gauge data to create thematic layers of geology, land cover, slope, and rainfall, which were then assigned the appropriate weightage and scale and integrated into the GIS environment using the weighted index overlay method, which has proven to be very useful in preparing the groundwater contamination risk zone map for the study area. The results of this study are relatively unique and comparable to the findings of previous studies conducted in the Cape Flats catchment in spatial distributions of values of hydrological parameters. Vulnerability and integrated risk assessments on a larger scale, following a holistic approach, provide effective strategies to manage groundwater quality on a larger scale under changing environmental and uncertain future conditions. The results of this study would provide important information about land use and the effects of climatic variables on hydrological regimes and groundwater quality under certain scenarios of climatic variables and land use. This knowledge becomes strategic since it contributes to better informed and more sustainable water resource management. Locations with a high-risk index are those most vulnerable to contamination and consequently need to be managed more efficiently.

6.1.7 Results validation

The modified DRASTIC index was calculated, which ranged from 109 to 222. 28% of the study area was found to be highly vulnerable. Most of the study area is in moderate vulnerability zones, with index values ranging from 147 to 163. Maqsoom et al. (2021) previously conducted a study in Chitral, northern Pakistan, using a similar technique, which validates the current research. The modified DRASTIC index has been found to range from 140 to 160 in the moderate vulnerability class. Another study, Malik and Shukla (2019), estimated the DRASTIC index between 121 and 206 and found that approximately 27.39% were at high risk, which is similar to the current research result. Furthermore, the findings can be used to validate a previous study that used the WaterWorld model to model the effects of climate variability on groundwater quality in the study area. Adelana (2010) used the CALOD model with the following input parameters: clay layer thickness (C), aquifer nature (A), lateritic layer thickness (L), overlying layer nature (O), and depth of the water table (D) (D). Most previous studies have not adequately examined the assessment of hazards on a spatial scale as thoroughly as in the current study.

The water quality data for the research area was plotted using existing borehole laboratory findings and literature. Four variables (Nitrate (NO3-), electrical conductivity (EC), and chloride (Cl-)) were chosen as indicators of overall water quality. Sulfate (SO42-) is a mining impact indicator and chloride (Cl) indicates the presence of leaching from the soil due to landfill infiltration and other anthropogenic activities. Nitrate (NO3-), electrical conductivity (EC) and chloride (Cl-) are the variables chosen. Electrical conductivity (EC) (mS/m) as an indicator of salinization and chloride (Cl) (mg / l) to represent agricultural impact, discharge of wastewater effluent, and industrial waste. Electrical conductivity (EC) was assessed to highlight temporal changes in water quality. The available observation water quality data from previous studies was used to compare the results and validate the model results against observed data (Adelana et al., 2014; 2010; Davis et al., 2011; Gnandji et al., 2013). The chemical analysis of groundwater in the study area revealed high levels of nitrates and chlorides. It was found that the mapping of groundwater quality parameters using the GIS technique was in close agreement with the available point source water quality laboratory data.



Figs. 6.14a-14d Validation of DRASTIC vulnerability using chosen hydrochemical indicators

The water quality parameters are shown in Figs. 6.14a-14d to verify the spatial variation of the risk of contamination. The presence of nitrate in groundwater easily indicates the potential for contamination of contaminants, as nitrate is generally not present in groundwater under natural conditions (Jang et al., 2017). Chloride (Cl^-) is an indicator of salinity, with a concentration ranging from 28 to 397 mg/l in shallow aquifers. Chloride and nitrate concentrations were all above the target maximum (Adelana and Xu, 2006; Gnandji et al., 2013b).

Use the Geostatistical Analyst extension of ArcGIS 10.3 software to determine the statistical relationship between nitrate concentration and groundwater vulnerability. The correlation factor for the original DRASTIC technique was 0.81, while it was 0.83 for the updated model, as seen in Fig. 6.15a and b. The vulnerability map developed with the updated DRASTIC approach is more accurate than the original, according to the results. According to the results, the vulnerability map made with the updated DRASTIC method is more accurate than that made with the original DRASTIC method.

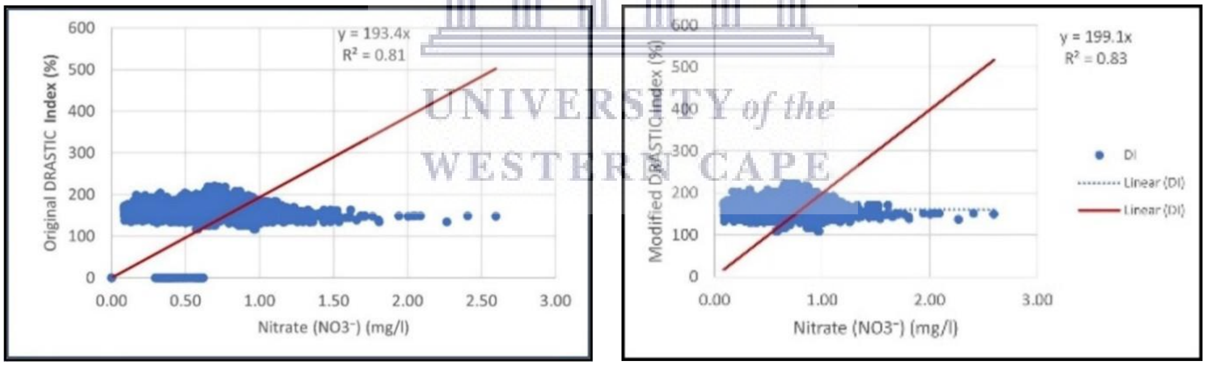
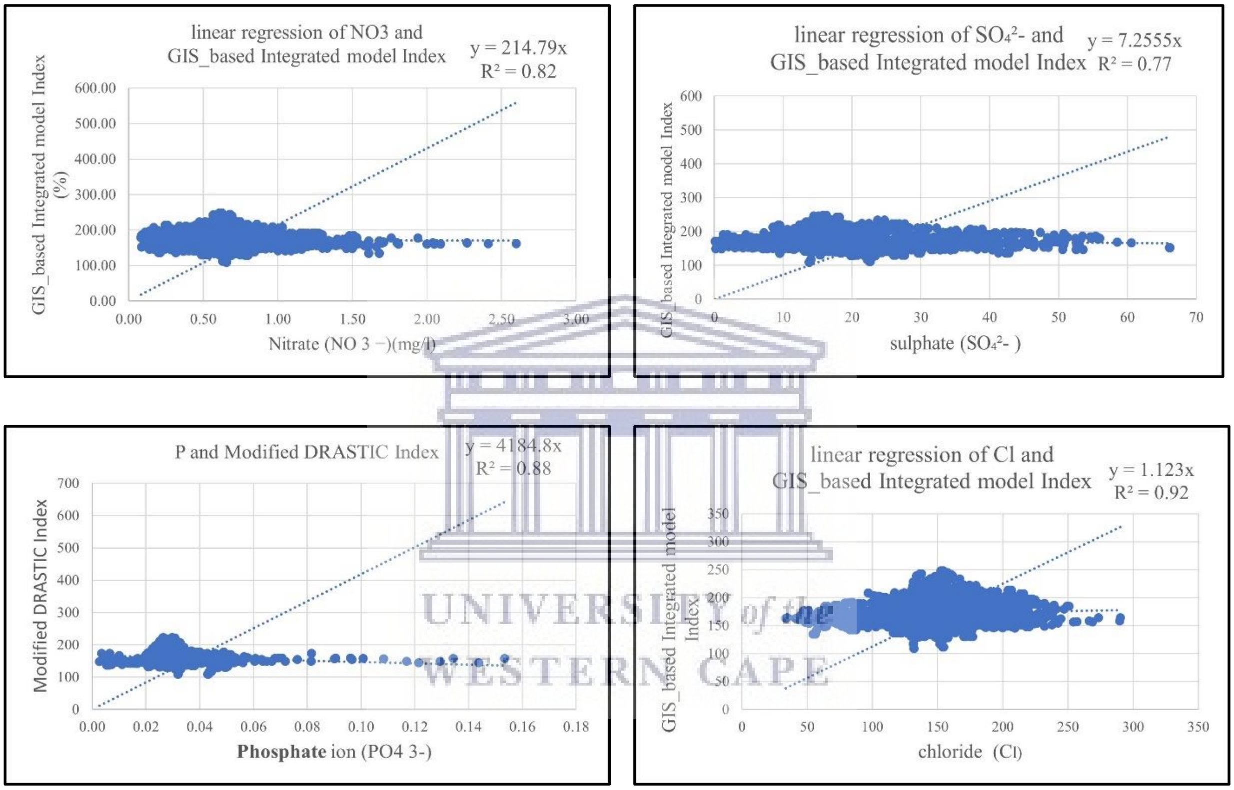


Fig. 6.15. a) Correlation between the DRASTIC index and nitrate concertation and b) the modified DRASTIC index and nitrate concertation in the Cape Flats aquifer.

In the Cape Flats aquifer, there is a correlation between the DRASTIC index and nitrate concertation, as well as a correlation between the modified DRASTIC index and nitrate concertation. The following factors charts demonstrate the link between the GIS-based integrated model index and several water quality indicators.



Figs 16a-d. Correlation plots of data showing the relationship between the GIS based integrated model index and various water quality parameters.

Chapter 7: Using a GIS-based integrated model to assess the risk of groundwater contamination in the Cape Flats aquifer, South Africa.

7.1 Introduction

Groundwater contamination risk assessment is a useful tool for groundwater management. The third objective was to evaluate the risk of groundwater contamination in coastal aquifers in urban hydrogeological areas. The research also aims to develop a risk of groundwater contamination using an integrated method that incorporates geospatial and hydrological modelling techniques. Value-weighted risk maps were created by overlaying risk and vulnerability maps. Cape Flat aquifers were classified as high to very high contamination risk 37% of the time. Mostly, the central portions of Cape Flat were at the highest risk and had the highest groundwater values. There was a significant and strong correlation between the contamination risk index and the measured groundwater quality values. GIS-based analytical tools provide practical and actionable information on measures that would improve groundwater security in the face of climate variability and change in land use.

7.2 Descriptive and inferential statistical analysis of groundwater contamination risk mapping and modelling

The Geographic Information System (GIS) was successfully integrated with hydrological and hydrogeologic models to provide a better assessment of groundwater quality. Risk assessment of groundwater contamination is widely used worldwide for sustainable groundwater management. The study describes a groundwater contamination risk assessment method that integrates a modified DRASTIC model, GIS, and analytical hierarchy process. First, we evaluate the risk of contamination from climate variability using a hydrological model in a GIS environment. Second, to determine groundwater vulnerability using a modified DRASTIC model. Also, an integrated distributed hydrological model and a modified DRASTIC model were coupled with a spatial chemical water quality analysis in a GIS environment. The value-weighted risk map was created by overlaying the base risk map and the groundwater value map. Risk maps represent the contamination risk based on the integration of different models within a GIS platform (Fig. 7.1).

The final results are presented on a risk map derived from the overlay of the WaterWorld model and the hazard map (obtained from the modified model DRASTIC).

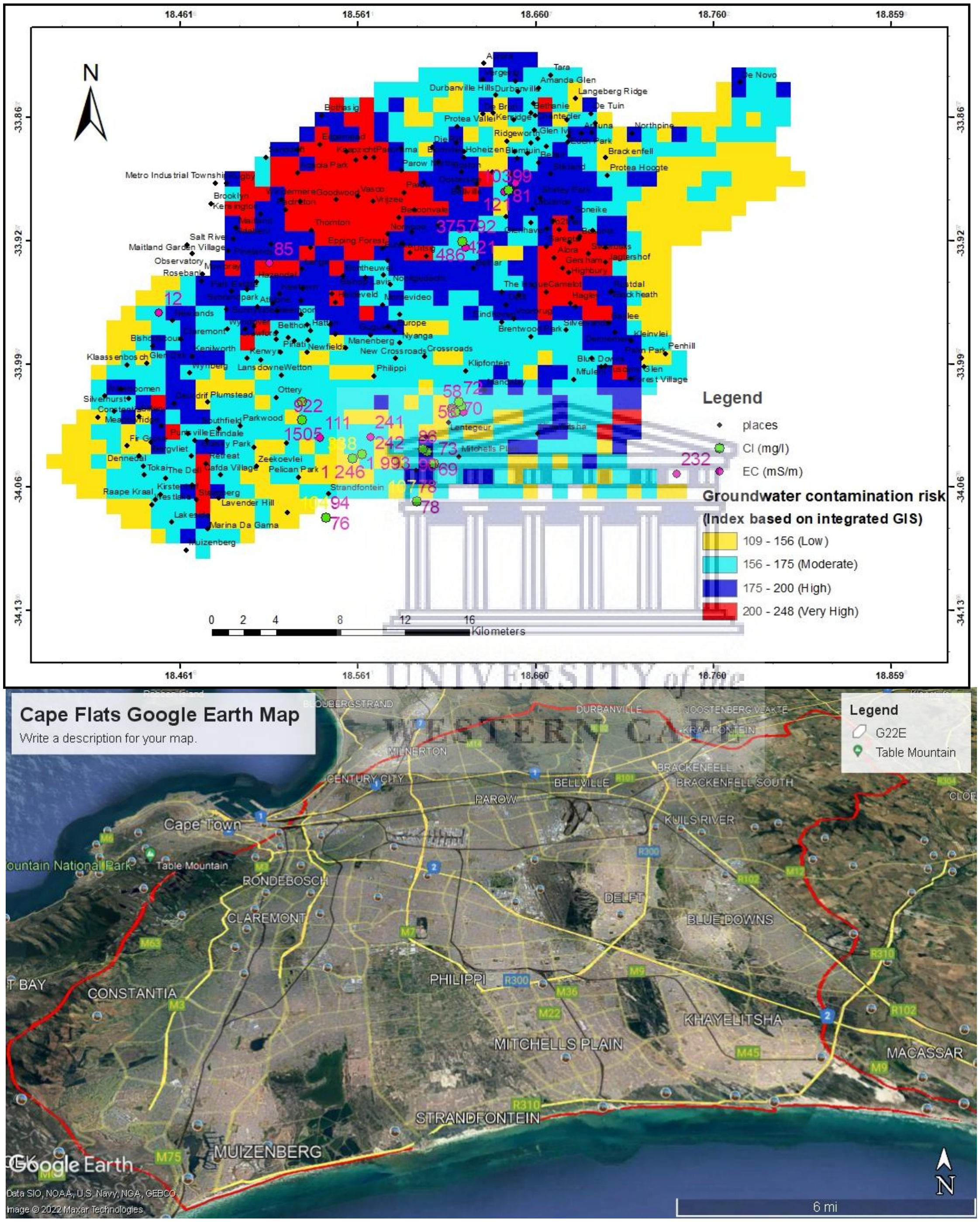
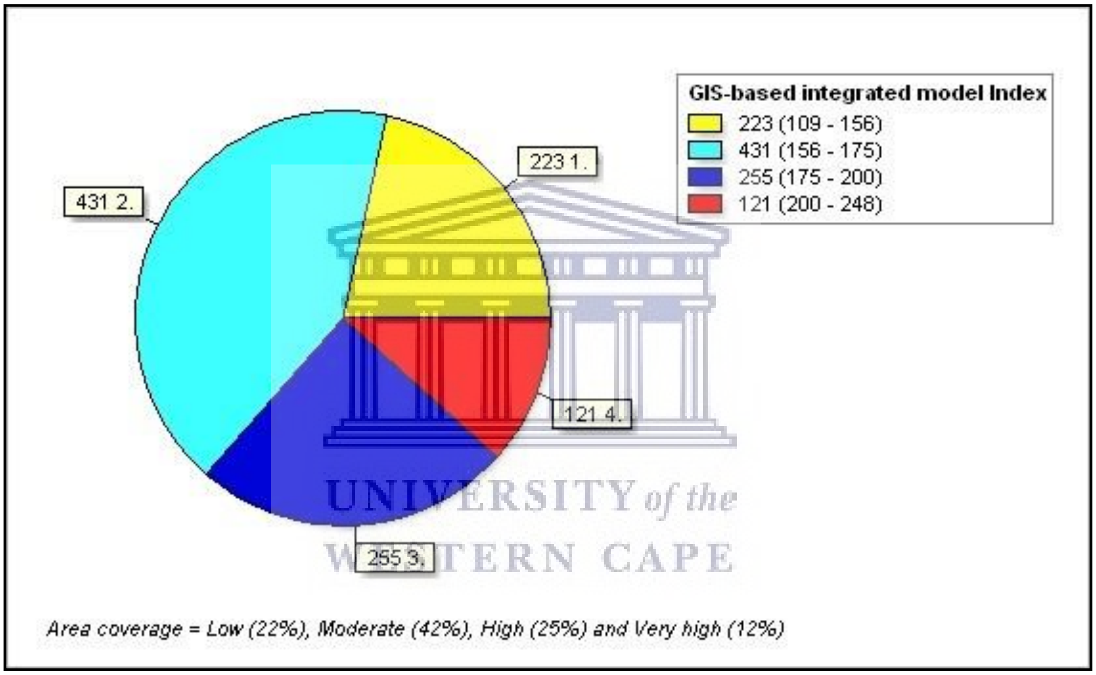


Fig. 7.1. Groundwater Contamination Risk Map

The western and northern plains were the most vulnerable, with the highest groundwater values, indicating that they should be the most concerned. Because hazards change over time, thematic maps should be updated frequently. Also, GIS technology was required to complete the assessment. An excellent tool for land planning and groundwater management is the assessment of groundwater contamination risk. The final vulnerability index is required for decision-making. The GIS platform also allows for easy overlaying of elements and expressing evaluation results. It was a good place to conduct research, manage data and create maps.



Area coverage = Low (22%), Moderate (42%), High (25%) and Very high (12%)

Fig. 7.2 Risk map showing an area of groundwater contamination

Table 7.1 Classification of the contamination risk index of integrated models based on GIS

DRASTIC indices	Index range	Area (Km^2)	Percentage
Low	109 – 156	223	22
Moderate	156 – 175	431	42
High	175 – 200	225	25
Very high	200 – 248	121	12

7.3 Interpretation of the results: Groundwater Contamination Risk Model

The main outputs of the spatially resolved methodology include GIS-based vulnerability and groundwater contamination risk maps that are described in the steps of the methodology. These maps identify protection hotspot areas and provide a basis for groundwater resources for monitoring and managing pollution within the case study area. The risk index and the vulnerability factors identified for the case study area are represented in raster GIS layers, which allow the analysis and visualisation of their spatial distribution in the case study area. Therefore, the outputs of the risk assessment are raster maps that represent the spatial distribution of the vulnerability and the risk index.

7.4. Comparative assessment of the results on mapping and modelling groundwater contamination risk

Table 7.2 Comparison of vulnerability and contamination risk index

Index ranges	WaterWorld model	DRASTIC Model	Modified DRASTIC Model	GIS integrated model	CALOD Index (Adelana, 2010)	Optimized-DRASTIC methods (Shrestha and Luo, 2018b)	DRASTIC (Voudouris et al., 2010b)
Very low.						103 – 110	
Low		117 – 151	109 – 147	109 – 156		111 – 128	< 100
Moderate	17.6 – 33	151 – 166	147 – 163	156 – 175	42 – 60	129 – 147	100 – 120
High	33 – 74.9	166 – 187	163 – 184	175 – 200		147 – 163	120 – 140
Very high		187 – 220	184 – 222	200 – 248	70 – 76	163 – 193	>140

7.5 Implications of the Findings for Mapping and Modeling the Risk of Groundwater Containment

The results of this study are comparable to the findings of previous studies conducted in the CFA. Geospatial-related approaches possess all the relevant functionalities needed for the assessment and management of coastal issues caused by climatic variables and human activities. The results of this study would provide important information about the effects of land use and climatic variables on hydrological regimes and groundwater quality under certain climatic variables and land use scenarios. This knowledge becomes strategic as it contributes to better informed and more sustainable water resource management. The high-risk index represents the possible cases that need to be considered here for more efficient management.

7.6 Validation

7.6.1 Developing a Groundwater Quality Index (GWQI) Map

Deteriorating groundwater quality due to natural and anthropogenic factors has made sustainable groundwater use difficult. Land use and climate change are commonly highlighted as the key human-induced factors influencing groundwater quality. because agriculture, industries, urbanization, and human settlements affect groundwater degradation. The groundwater quality index (GWQI) and geostatistics were used to investigate the characteristics and factors that influence groundwater quality for drinking water supply in shallow aquifers in the coastal Cape Flats catchment area in Cape Town. Combining hydrochemical studies and GIS with factor analysis can help people make better decisions about how to keep groundwater clean.

In this study, the water quality parameters are shown in Fig. 7.3a-d to Fig. 7.4a-d were multiplied with the resultant vulnerability map to verify the spatial variation of the contamination risk. Chloride (Cl^-) is an indicator of salinity, with a concentration ranging from 28 to 397 mg/l in shallow aquifers. Nitrate in groundwater indicates the presence of contaminants, as nitrate is not naturally present in groundwater (Jang et al., 2017). The nitrate content of groundwater is high, at 2.65 mg/l. Lands with a high nitrate content in groundwater, such as farmland, development land, industry, and mining, have seen extensive misuse of land assets. In some areas, groundwater is extremely salinized, containing nitrate and chloride. The vulnerability map shows the highest concentration zone mostly in the study area's northern part.

Finally, to validate the model, the arranged guide was compared with a sorted WQI map. The results show that the zones with higher DRASTIC scores match those with higher WQI estimates. The maps were spatially correlated with the nitrate (NO3-) concentration records of each well. The spatial distribution patterns of Na and Cl are comparable, and high chloride levels have been recorded in coastal wells and wells near the False Bye in the Cape Flats catchment. In the study area, SO_4^{2}- has a spatial distribution like Cl, with high concentrations in wells near the coast and the Cape Flats aquifer.

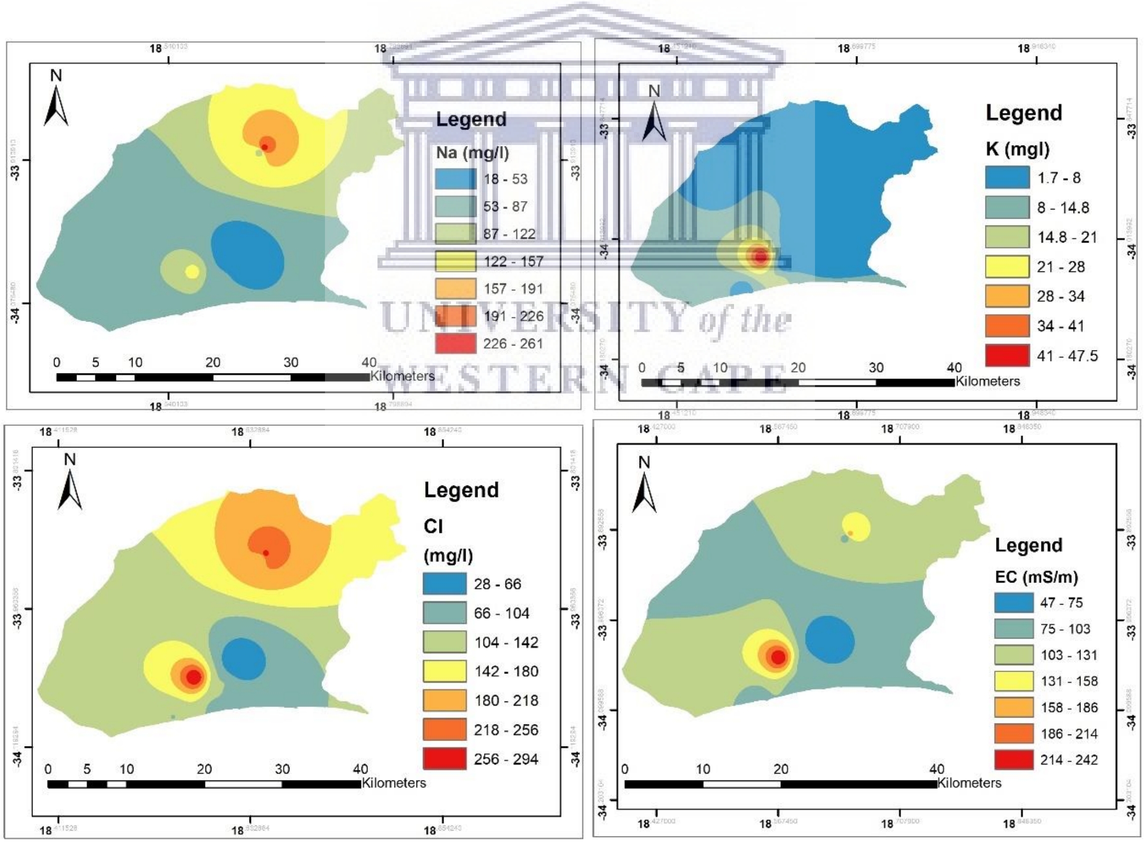
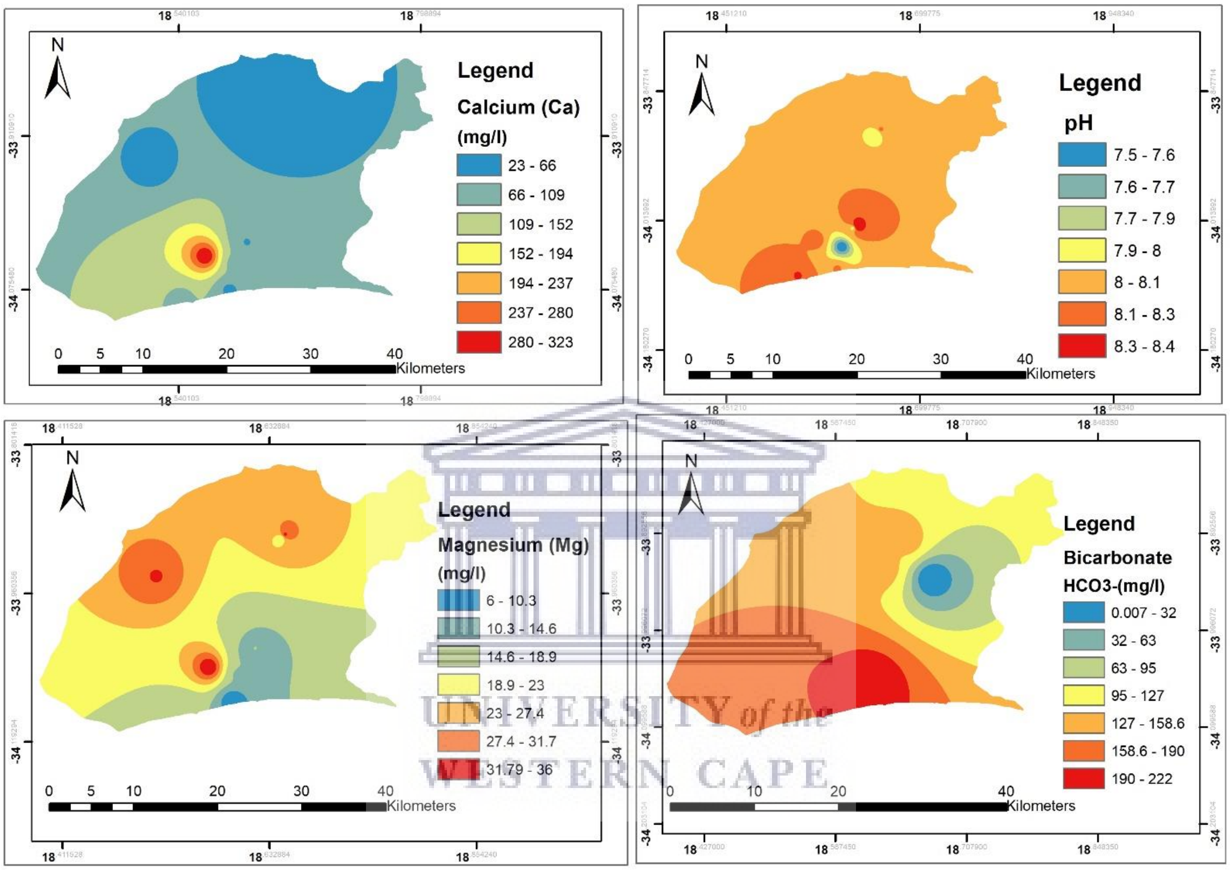
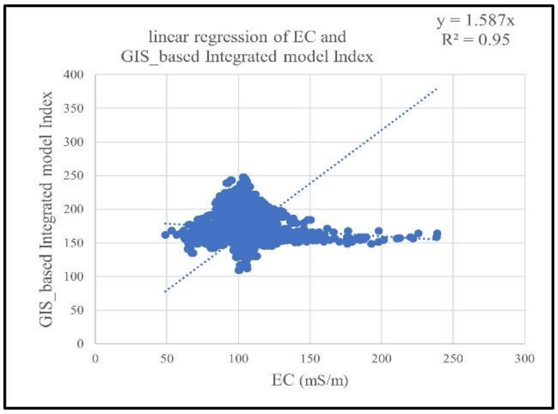


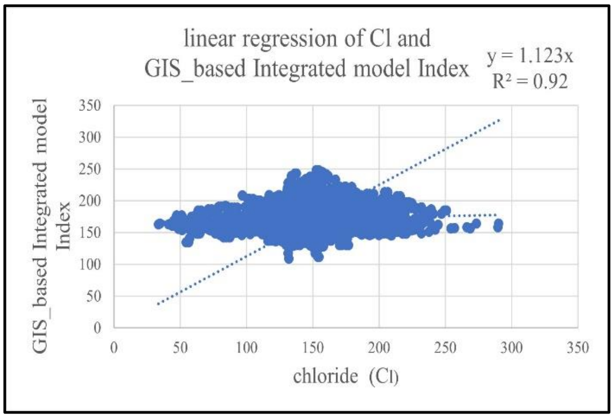
Fig. 7.3a- d Validation using chosen hydrochemical parameters (Na, Cl, K)

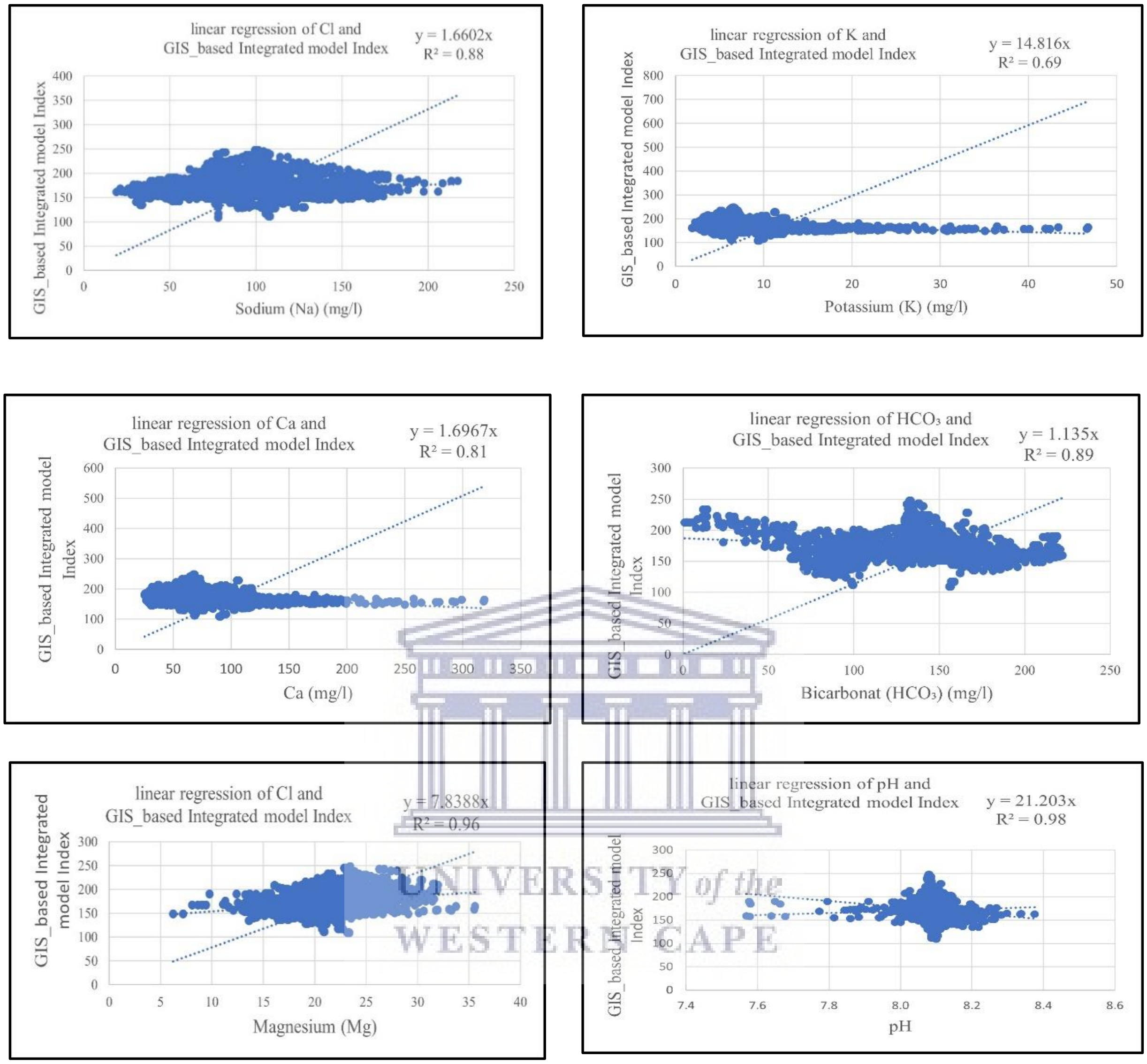
Studies suggest an increased prevalence of water quality evaluations for the protection and sustainable management of groundwater resources, which are vulnerable to human and climatic variables / variables. Chloride, nitrate, sulfate, phosphate (and electrical conductivity), as well as the mean annual values of these chemical parameters, were used to group the values of the water quality index.



Figs. 7.4a-d Validation using chosen hydrochemical parameters (Ca, Mg, $P^{H,}$ HCO_3)







Figs. 7.5a-h. The integrated model index based on GIS and several water quality parameters are shown in correlation plots.

The correlation graphs depict the relationship between the GIS-based integrated model index and a number of water quality parameters. There is a substantial association between all chemical water quality measures, demonstrating deterioration of groundwater quality due to natural and anthropogenic factors. Land use and climate change are commonly highlighted as the key human-induced factors that influence groundwater quality because agriculture, industries, urbanization, and human settlements affect groundwater degradation.

Around the world, the groundwater quality index (GWQI) is frequently used to monitor water quality changes. The GWQI is a valuable tool for assessing water quality. In this study, "GWQI" refers to groundwater quality indices based on selected chemical water quality indicators (EC, P, Na+, Ca2+, Cl, SO42, HCO3+). GWQI and geostatistics were used to explore the characteristics and factors influencing groundwater quality for drinking water supply in shallow aquifers in the coastal Cape Flats catchment area. GIS and factor analysis combined with hydrochemical investigations can help decision makers manage groundwater quality. For spatial-temporal comparisons, the WQI coordinates the various water quality parameters. The WQI of the research area ranges from 56 to 142 (Fig.). Drinking water quality classes were characterized as excellent (12 %), good (89%), and low (19%) by the water quality index (GWQI). On the groundwater quality index, more than 75% of the study region was deemed potable. Overall, the water quality of the research area was rated as "excellent to good" for potable purposes for the study area.

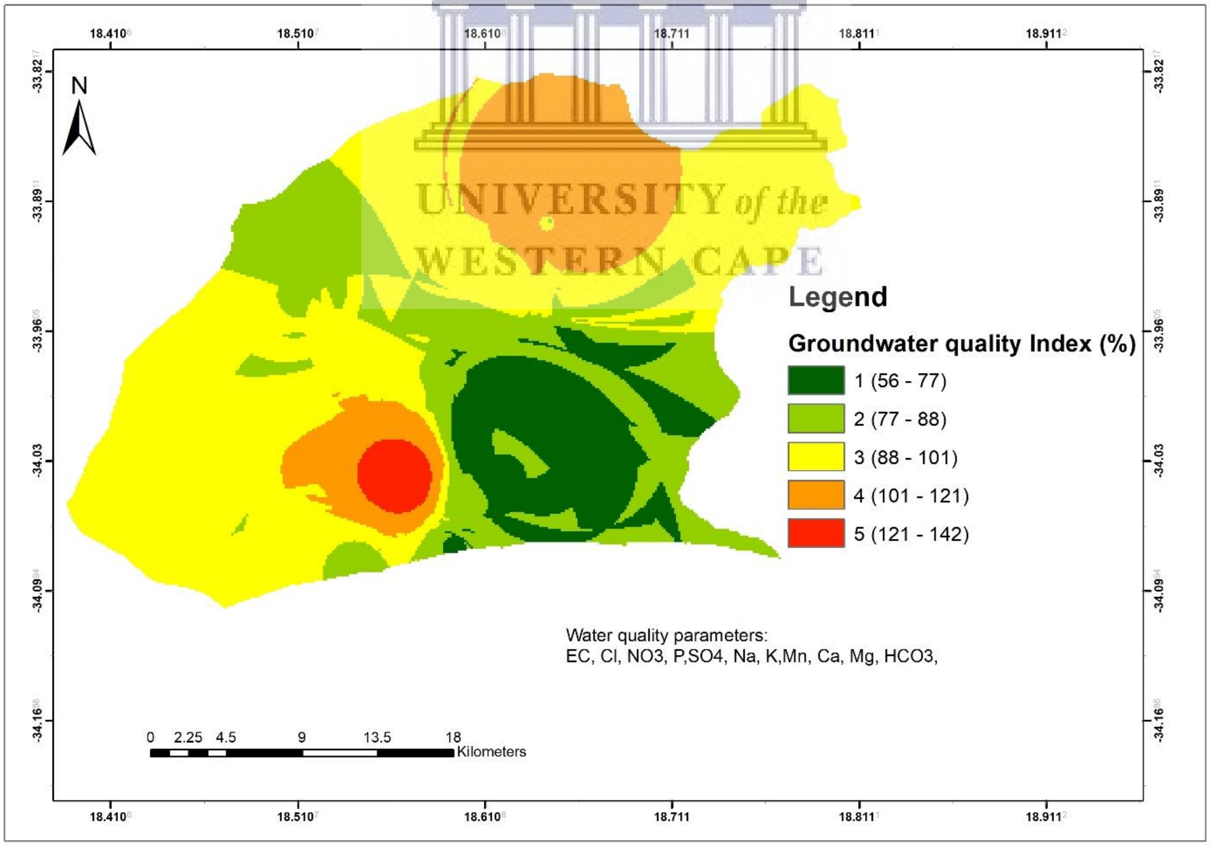


Fig. 7.5 Map of the groundwater quality index in the study area.

The water quality index (WQI) method is widely used throughout the world to assess changes in water quality over time and space, to help design strategies and protect aquatic resources. It is one of the best ways to tell if water is polluted and a simple way to classify water (Table).

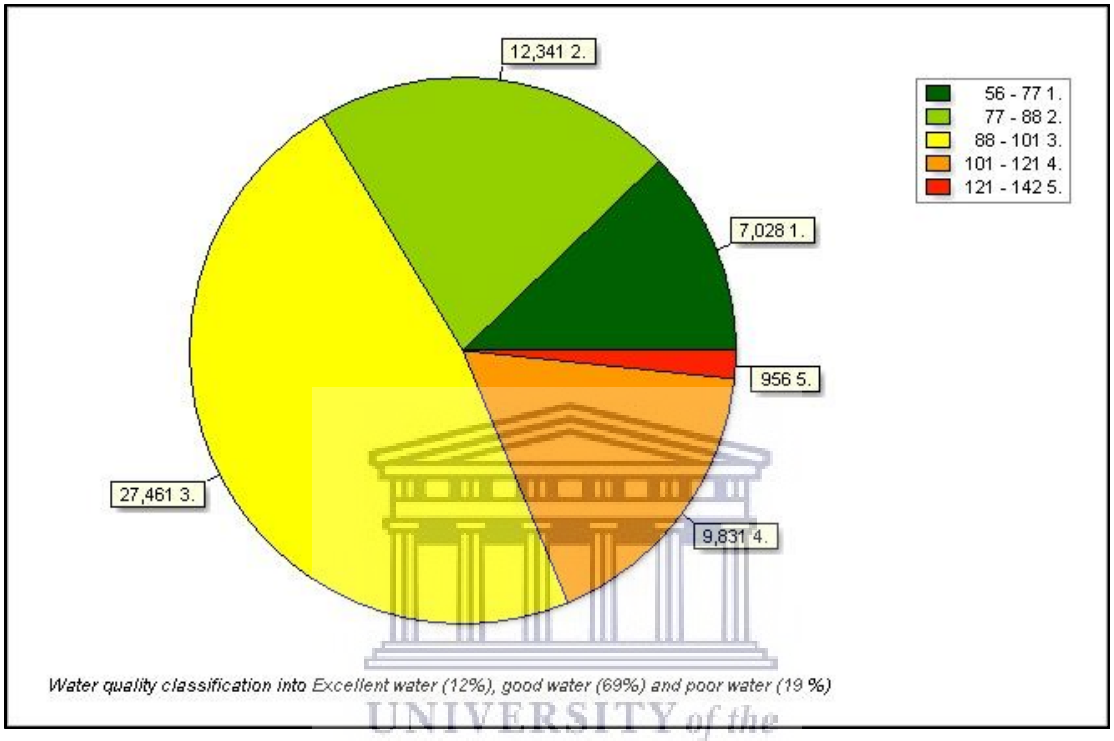


Fig. 7.4 Risk map showing an area of groundwater contamination

Table 7.3 Water quality classification ranges and types of water based on WQI values (Abbasnia et al., 2018).

WQI value	**Area (Km2)**	**Explanation**
<50	Excellent	Good for human health
50–100	Good	Fit for human consumption.
100–200	Poor	Water not in good condition
200–300	Very poor.	Need attention before use
>300	Inappropriate	Need too much attention?

Source (Kumar and James, 2013; Rao and Nageswararao, 2013)

The correlation between nitrate concentration and groundwater vulnerability was assessed using linear regression analysis to validate contamination risk based on integrated GIS methods (Fig. 7.5). The contamination risk index and the measured groundwater quality values had a significant and strong correlation (R2 = 0.96).

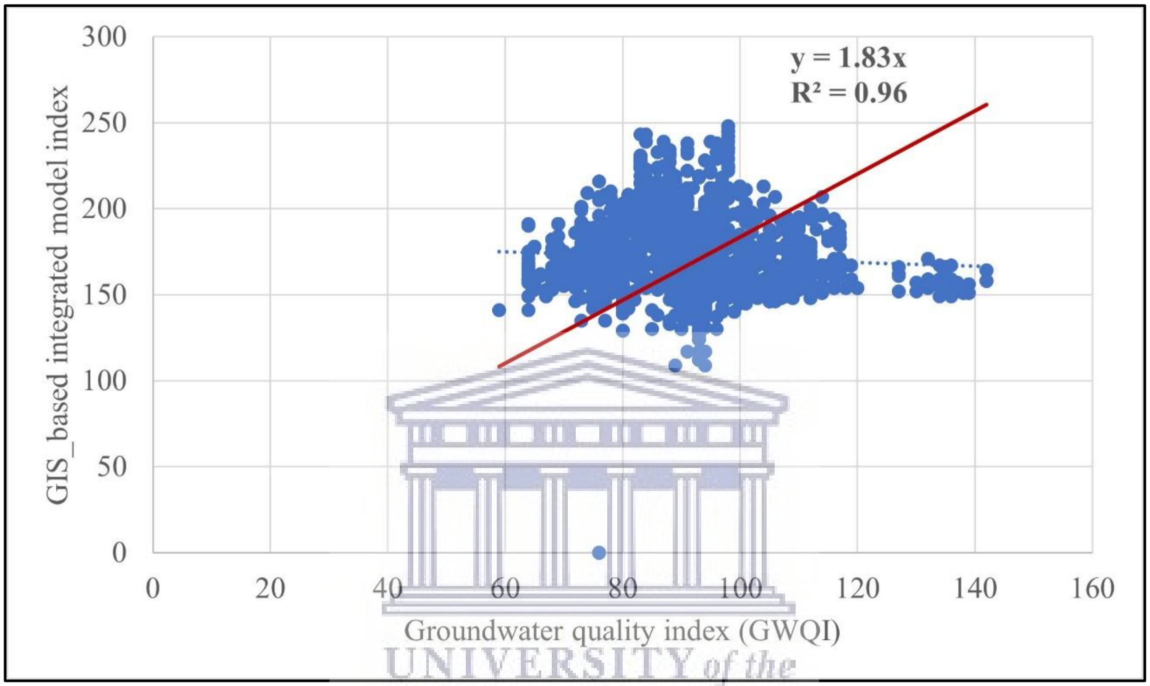


Fig. 7.5. represents the relationship between the modified DRASTIC and the groundwater quality index (GWQI).

Integrated predictive modelling within GIS of climate and land use change provides the most effective means of quantifying contamination, land use, and climate change and are often cited as the most important human-induced factors affecting groundwater quality. Because groundwater degradation is influenced by agriculture, industry, urbanization, and human settlements. Based on the water quality index, it was concluded that groundwater in the Cape Flats aquifer is at an increasing potential risk of contamination.

7.2 Evaluation of the study

In this study, the integrated model GIS was developed and applied to assess the vulnerability of the Cape Flats aquifer and the risk of groundwater contamination. GIS-based modelling using downscaling techniques was used to link climate models and hydrological models at the watershed scale. In this study, the WaterWorld model and a modified DRASTIC model were integrated into a GIS framework to map the potential risk of groundwater contamination in the Cape Flats aquifer in South Africa. Water quality data from existing wells in the study area was also used to validate the resulting groundwater contamination risk map. An integrated model based on GIS for the occurrence of contamination in the study region was briefly developed in the last part of this chapter. Furthermore, a combination of the modified DRASTIC and the pollution risk map could provide a useful tool to assess groundwater vulnerability to point source contamination and seawater intrusion for shallow, unconfined, low-lying coastal aquifers (Section 5.4). The modified DRASTIC model combined with the GIS based method is the main innovation for vulnerability mapping and visualization. An analytical hierarchy process (AHP) is used in the study to determine the weighting value for each of the hydrogeological parameter values. The comparison of water quality (in the form of a GWQI map) and the DRASTIC index was performed using GIS tools. The links between the vulnerability map and the underlying nitrate water quality were highlighted at the local level. In addition, this chapter describes the groundwater vulnerability model implementation process and a suite of ArcGIS tools developed to support implementation. The chapter addresses the problem of limited studies. This finding will help to better understand the mechanisms affecting groundwater quality due to changes in climate and land use in the Cape Flats aquifer in the context of coastal aquifers in urban areas. In addition, two papers scheduled for publication were presented. Consistent land use and land cover classification and mapping was performed in conjunction with predictive land use transition models to quantify and characterise the actual land use and land cover changes. Geospatial approaches can be used to solve and solve problems on the coast caused by climate changes and human activities.

Studies of how groundwater will respond to climatic variables associated with human activities are limited. The challenges of understanding the effects of climate variables on groundwater are unique because climate variables can affect hydrogeologic processes and groundwater resources in complex ways. Physically based climate models provide the most likely estimates of scenarios for climatic variables such as precipitation and temperature. It appears that the application of integrated GIS-based methods generally provides useful advances in the assessment of rare groundwater quality considering land use and climatic variables.

7.3 Summary chapter on the results and discussion

This doctoral thesis examines the state of the art in evaluating the potential effects of climate variables and land use on coastal aquifers in urban areas. It was an experimental research study that examined the effects of changes in climate and land use on groundwater quality, particularly nearshore aquifer systems in metropolitan areas.

First, this study used climate change simulations with a geomodel to simulate impacts on groundwater quality in the Cape Flats aquifer in South Africa. The link between information on climate variables and hydrological simulations is key to understanding future potential changes in the hydrological cycle and the resulting degradation of aquifer systems. Second, this work used GIS -based overlay and index methods to determine the vulnerability of coastal aquifers using the modified DRASTIC model. Third, this work uses the integrated model based on GIS to analyse the effects of changes in groundwater quality at the basin scale as a function of climatic variables and land use. This research was implemented in several evaluation steps (i.e., vulnerability and risk overlay analysis) to identify potential risks for groundwater contamination.

The results have revealed a new perspective on the spatial distribution of vulnerability throughout the study area. Groundwater vulnerability and risk assessments on a larger scale using a holistic approach provide practical strategies for managing groundwater quality on a broad scale under changing environmental conditions and uncertain future conditions. The results and findings will be useful to decision makers in formulating appropriate strategies for managing water resources in social and environmental data to understand the distributional consequences of a changing climate for people and the environment.

A study concludes that groundwater in the Cape Flats Aquifer (CFA) is at increased potential risk of contamination. The Pearson correlation between the contamination risk index and the electrical conductivity in the CFA showed a strong and positive relationship (R2 = 0.84). Geospatial approaches have all the relevant functionalities needed to assess and manage coastal problems caused by climatic variables and human activities. Climate variables can affect hydrogeological processes and groundwater resources in complex ways. This work examines the potential impacts of climate variables and land use on coastal aquifers in urban areas. The results will be useful to decision makers in developing appropriate water resource management strategies.

Chapter 8: ***CONCLUSIONS AND RECOMMENDATIONS***

8.5 CONCLUSIONS

The results and discussion of groundwater contamination risk modelling and assessment in urban coastal aquifers were presented in Chapters 5, 6 and 7. This chapter concludes the findings and recommendations of the previous chapters and closes with a hydrological model based on physical evidence (WorldWater model), a local scale GCM, a modified DRASTIC model, and a geostatistical water quality index (GWQI) were used to assess the impacts of climate variability and change in land use on groundwater quality in the Cape Flats catchment, South Africa. The hydrologic impact of climate variables was assessed using a 1 km2 validated WaterWorld Policy Support model. Climate scenarios using the NRC GCM and RCP 8.5 emission scenarios have rainfall totals between 2041 and 2060 downscaled from the baseline (1950 to 2000). The results show an increase in temperatures, but a decrease in rainfall and recharge. The area's evapotranspiration is expected to increase by 100%, resulting in an 8.6% decrease in water balance. The WaterWorld model appears to be well suited to watersheds with sparse data and high variability in rainfall patterns. It was also used to model future climate changes and their impacts on sea level rise in TerrSet Geospatial Monitoring and Modelling Software. The region's climate projections predict seasonal decreases in precipitation and seasonal increases in temperature. The area could warm by 2.1 ° C by the 2060s. The increase in temperatures affects the hydrological cycle by increasing evaporation. In the 2060s, the seasonal precipitation decrease will be up to 23%. This will exacerbate the problem of seasonal water distribution. floods in the wet season and droughts in the dry season. Sea level is expected to increase in 12 to 58% of coastal areas by 2060. There are many ways to connect local groundwater vulnerability and climate change, but geospatial modelling seems to be the best way to do it.

The second goal of this thesis was to assess the vulnerability of groundwater using the modified DRASTIC model (GIS). Zones of very high, high, moderate, and low groundwater vulnerability were studied. However, 46% of the study area is moderately prone to groundwater contamination. Modifying the model by LU increases the very high-risk zone by 26% and decreases the low-risk zone by 52%. High and very high contamination risk areas are concentrated on lower slopes and water tables. In addition, shallow coastal aquifers are more vulnerable to depth of water level, hydraulic conductivity, and aquifer media. A map of aquifers with moderate vulnerability in relation to highly urbanized and industrialized areas. The inclusion of land use, land cover, and AHP improved the CFA's depiction of groundwater vulnerability because intensive agricultural activities and industrial development were classified as more vulnerable. The results highlight the value of the DRASTIC model in GIS-based groundwater vulnerability analysis. The modified DRAST IC method maps groundwater vulnerability better. In the Cape Flats, the findings may help protect and manage groundwater.

The third goal of the thesis was to develop a risk of groundwater contamination using an integrated method that included GIS-based DRASTIC modelling, land use modification, downscaling of GCM to local scale, a hydrological modeling technique based physically (WorldWater Model), and a groundwater quality index (GWQI). This study's main goal is to assess the risk of groundwater contamination in urban coastal aquifers. The Cape Flats aquifer in South Africa was used to create thematic maps. The models' results are superimposed on a risk map. Groundwater resource maps identify high-risk areas for protection and are used to monitor and manage groundwater resources in the case study area. The overlap of risk and hazard maps created value-weighted risk maps. The DRASTIC index method was used to assess groundwater vulnerability using publicly available high-resolution datasets. 37 percent of Cape Flat's aquifers are contaminated. Many of these were in the large metropolitan area, on broad plains with hot spots. GIS produced index-based groundwater risk maps with a 30 m spatial resolution. Due to the low risk of groundwater contamination, GIS was critical for the evaluation work. The most vulnerable areas of the Cape Flats plain were found to be the western and northern parts, which had the highest groundwater values. The contamination risk index and the measured groundwater quality correlated strongly ($R^2 = 0.99$). GIS-based analytical tools can help people improve groundwater security in the face of climate change and changes in land use.

The GWQI was calculated to quantify overall water quality and validate the resulting groundwater pollution risk map. Using a geographic information system, the study area's water quality parameters (GIS) were mapped. The quality of drinking water was classified as excellent (12%), good (69%) or poor (19%) in the study. Some characteristics of water quality are strongly correlated with the contamination risk index. The nearshore aquifer of the Cape Flats watershed is generally good. Exceeding the drinking water standards (WHO and SA Drinking Water Standards) indicates contaminants from both anthropogenic and natural sources. The highest concentration zone is in the northern part of the study area. The findings of this study are in line with previous research warnings of groundwater contamination. GIS mapping of groundwater quality parameters was well matched with laboratory data. The results of the integration of the groundwater vulnerability assessment method provided additional information. There was a strong and significant relationship between water quality and contamination risk in Cape Flats. These were electrical conductivity, chloride, and nitrate. Therefore, the study recommends more monitoring and improvement plans to protect groundwater quality. The study found that spatial modelling can be used to determine how land use and climate change affect groundwater resources.

8.2. Unanswered Questions/surprising Results/ Recommendations

The findings of this study may help to assess the risk of groundwater contamination in urban coastal aquifers. Data can also be used to revise management systems to help water resource managers restore this depleted resource. The modified DRASTIC model, combined with a GIS-based method, is the main innovation for vulnerability mapping. The study uses an AHP to determine the weighting value for each hydrogeological parameter. GIS tools were used to compare water quality (GWQI map) and the DRASTIC index. Locally, the vulnerability map and water nitrate levels were linked. The results of the DRASTIC method can be applied to the development of aquifer protection and management plans. If this scenario proves true, the local agencies responsible for managing groundwater resources will save both time and money. The GIS-based model was also successful in assessing the hydrology of the Cape Flats watershed. Long-term, this would improve decision-making and increase water production in the metropolitan area of Cape Town. The study shows the value of AHP as a spatial decision support tool for future groundwater vulnerability assessments. To assess groundwater quality, the study applied hydrogeologic concepts and parameters. The use of GIS-based analytical tools can help improve urban groundwater security by assessing climate-related impacts at the local level. Using integrated models as an analytical framework for regional climate change modelling is a good idea to demonstrate its effectiveness. The thesis identifies important research areas to improve water resource protection, management, and adaptability. This work presents a simple and efficient model for analysing large amounts of spatial data. The findings of this study will help local officials and decision makers maintain a regulated groundwater management system in the Cape Flats watershed. In addition, municipal officials could use the findings of the study to develop effective water quality monitoring measures. The study found that the Cape Flats basin is sensitive to both climate and human activity.

The nitrate concentration correlated with the DRASTIC vulnerability index. So the modified DRASTIC method may be more reliable. Including land use in the vulnerability map identifies areas at risk of groundwater contamination. We developed a new method to predict how hydrologic processes and water quality will affect future land use and climate. To determine intervention priorities and long-term adaptation strategies, assessing potential impacts of land use and climate change on groundwater resources is critical. Anthropogenic and climate change pressures on coastal aquifers are studied. It aims to make coastal aquifer vulnerability easier to grasp. A spatially resolved methodology can identify coastal groundwater-human interactions. Researchers used scientific knowledge in land use planning and climate change adaptation policies. Local climate change impact assessment is required. Water resources and land use planning should consider future land use and climate change scenarios to protect coastal aquifers. GIS and remote sensing aid in understanding coastal groundwater contamination risks. A validation study of DRASTIC parameters and groundwater protection zone mapping is needed. Finally, this research is original, and all sources used or quoted are cited.

The findings of this study will add to existing knowledge about the Cape Flats watershed and will have a significant impact on water resource management in similar watersheds around the world.

In data-poor watersheds with highly variable precipitation, the Waterld model's results support water resource management efforts and provide an evaluation of physically based hydrologic models.

References

Abbas, N., Wasimi, SA and Al-Ansari, N. (2016). Assessment of the impacts of climate change on the water resources of khabour in Kurdistan, Iraq using a swat model. *Journal of Environmental Hydrology, 24*, 716–732. https://doi.org/10.4236/eng.2016.810064

Abbasnia, A., Alimohammadi, M., Mahvi, A. H., Nabizadeh, R., Yousefi, M., Mohammadi, A. A., Pasalari, H. and Mirzabeigi, M. (2018). Evaluation of groundwater quality and evaluation of the scaling and corrosive potential of drinking water samples in villages of Chabahr city, Sistan, and Baluchistan province in Iran. *Data in Brief*, *16*, 182–192.

Abdeslam, I., Fehdi, C. and Djabri, L. (2017). Application of a drastic method for determining the vulnerability of an alluvial aquifer: Morsott—El Aouinet northeast of Algeria: Using an arcgis environment. *Energy Procedia*, *119*, 308–317. https://doi.org/10.1016/j.egypro.2017.07.114

Adelana, M., Victoria, S. G., and Xu, Y. (2014). *Hydrogeochemical Characterization of the Cape Flats Aquifer (South Africa): H YDROGEOCHEMICAL C HARACTERISATION OF G ROUNDWATER IN THE C APE F LATS A REA , S OUTH A FRICA : C ONSTRAINTS FOR. November*.

Adelana, S.M.A. (2010). *Evaluation and protection of groundwater resources in the Cape Flats, South Africa*.

Adelana, M. M., Xu, Y., and Vrbka, P. (2006). *Hydrogeochemical Characterisation of Groundwater in the Cape Flats Area, SOuth Africa: Constraints for Water Supply Augmentation*.

Adelana, S., and Xu, Y. (2006). Contamination and protection in the Cape Flats aquifer, South Africa. In *Groundwater Pollution in Africa* (pp. 279–292). CRC Press.

Adelana, S., Xu, Y., and Vrbka, P. (2010). A conceptual model for the development and management of the cape flats aquifer, South Africa. *Water SA*, *36*(4), 461–474. https://doi.org/10.4314/wsa.v36i4.58423

Adelana, Yongxin, X., and Shafick, A. (2010). *Identifying Sources and Mechanisms of Groundwater Recharge in the Cape Flats, South Africa: Implications for Sustainable Resources Management*. *May 2016*, 1–13. http://en.cgs.gov.cn/Achievement/The34thCongress/Ecology/18320.htm

Aduah, M. S., Jewitt, G. P. W., and Toucher, M. L. W. (2017). Scenario-based impacts of land use and climate change on the hydrology of a lowland rainforest catchment in Ghana, West Africa. *Hydrology and Earth System Sciences Discussions*, *October* 1 to 27. https://doi.org/10.5194/hess-2017-591

Ahjum, F., Hughes, A., and Fant, C. (2015). *Climate, land, energy and water strategies in the City of Cape Town*.

Aizebeokhai. (2011). *Potential impacts of climate change and variability on groundwater resources in Nigeria*. *5*(October), 760–768.

Alaween, M. A., Al-kuisi, M. M. and Al-manaseer, N. M. (2013). *GIS-Based Model of Groundwater Vulnerability and Contamination Risk of Wadi Kufrinja Catchment Area, Jordan Faculty of Science, University of Jordan*. *24*(5), 570–581. https://doi.org/10.5829/idosi.wasj.2013.24.05.13210

Aza-Gnandji, CDR, Xu, Y, Raitt, L, and Levy, J. (2013). Salinity of irrigation water in the Philippi farming area of the Cape Flats, Cape Town, South Africa. *Water SA*, *39*(2), 199–210.

Cheng, C., Yang, Y. C. E., Ryan, R., Yu, Q., and Brabec, E. (2017). Landscape and Urban Planning Assessing Climate Change-induced Flood Mitigation for Adaptation in the Charles River Watershed of Boston, USA. *Landscape and Urban Planning*, *167*(May), 25–36. https://doi.org/10.1016/j.landurbplan.2017.05.019

Climate System Analysis Group. (2014). *Climate Science Input into Municipal Climate Adaptation Plans*. *August*.

Comte, J.-C., Cassidy, R., Obando, J., Robins, N., Ibrahim, K., Melchioly, S., Mjemah, I., Shauri, H., Bourhane, A., and Mohamed, I. (2016). Challenges in Groundwater Resource Management in Coast aquifers of East Africa: Investigations and lessons learnt in the Comoros Islands, Kenya, and Tanzania. *Journal of Hydrology: Regional Studies*, *5*, 179–199.

Conrad, J., Nel, J., and Wentzel, J. (2004). The Challenges and Implications of Assessing Groundwater Recharge A study in the northern Sandveld, Western Cape, South Africa. *Water SA*, *30*(5), 623–629.

Davis, C., Aza-Gnandji, R., Yongxin, X., and Raitt, L. (2011). *SALINITY OF IRRIGATION WATER IN THE PHILIPPI FARMING AREA OF THE CAPE FLATS, CAPE TOWN, SOUTH AFRICA.*

Dawes, W., Ali, R., Varma, S., Emelyanova, I., Hodgson, G., Mcfarlane, D., and Engineering, R. (2012). *Modelling the effects of climate and land cover change on groundwater recharge* *in the south-west of Western Australia*. 2709–2722. https://doi.org/10.5194/hess-16-2709-2012

Db, D., Holman, I., Audsley, E., Berry, P., Brown, C., Bugmann, H., Clarke, L., Cojocaru, G., Dunford, R., Fronzek, S., Harrison, P. A., Honda, Y., Janes, V., Kovats, S., Lafond, V., Lobanova, A. and Sloth, M. (2017). *Modelling Climate Change Impacts, Adaptation and Vulnerability in Europe*. 1–100.

Demlie, M. (2015). Evaluation and estimation of groundwater recharge for a catchment located in a tropical highland climate in central Ethiopia using catchment soil water balance (SWB) and chloride mass balance (CMB) techniques. *Environmental Earth Sciences*, 1137–1150. https://doi.org/10.1007/s12665-015-4099-y

Duah, A. A., and Xu, Y. (2013). Sustainable Utilisation of Groundwater Resources Under Climate Change: A Case Study of the Table Mountain Group Aquifer of South Africa. *CLIMATE CHANGE: RELATIES, IMPACTS ON THE ICE CAP, SEA LEVEL AND RISKS*, 191.

Dwarakish, G., and Ganasri, B. (2015). Impact of land use change on hydrological systems: A review of current modeling approaches. *Cogent Geoscience*, *1*(1), 1115691.

Fan, M., and Shibata, H. (2015). Simulation of watershed hydrology and stream water quality under scenarios of land use and climate change in the Teshio River watershed, northern Japan. *Ecological Indicators*, *50*, 79–89.

FAO-ONU. (2017). The future of food and agriculture: Trends and challenges. In the *Food and Agriculture Organization of the United Nations*. https://doi.org/10.4161/chan.4.6.12871

Farjad, B., Gupta, A., and Marceau, D. J. (2016). Annual and Seasonal Variations of Hydrological Processes Under Climate Change Scenarios in Two Sub-Catchments of a

Complex Watershed. *Water Resources Management*, *30*(8), 2851–2865. https://doi.org/10.1007/s11269-016-1329-3

Fitch, P., Brodaric, B., Stenson, M., and Booth, N. (2016). Integrated groundwater data management. In *Integrated Groundwater Management: Concepts, Approaches and Challenges*. https://doi.org/10.1007/978-3-319-23576-9_26

Goderniaux, P., Brouyere, S., Blenkinsop, S., Burton, A., Fowler, H. J., Orban, P., and Dassargues, A. (2011). Modeling the impacts of climate change on groundwater resources using stochastic transient climatic scenarios. *Water Resources Research*, *47*(12).

Gxokwe, S., and Xu, Y. (2017). *Conceptualization of Urban Hydrogeology within the context of Water-Sensitive Urban Design: Case study of Cape Flats Aquifer*. *May*. http://etd.uwc.ac.za/

Hagemann, S., Chen, C., Clark, D. B., Folwell, S., Gosling, S. N., Haddeland, I., Hanasaki, N., Heinke, J., Ludwig, F., Voss, F. and Wiltshire, A. J. (2013). Impact of climate change on available water resources obtained using multiple global climate and hydrology models. *Earth System Dynamics*, *4*(1), 129–144. https://doi.org/10.5194/esd-4-129-2013

Hansen, M. C., Potapov, P. V., Goetz, S. J., Turubanova, S., Tyukavina, A., Krylov, A., Kommareddy, A., and Egorov, A. (2016). Mapping tree height distributions in sub-Saharan Africa using Landsat 7 and 8 data. *Remote Sensing of Environment*, *185*, 221–232.

Hartnady, C., and Rogers, J. (1990). The scenery and geology of the Cape Peninsula. *Guidebook Geocongress, 90*, 1–76.

Hay, R., McGibbon, D., Botha, F., and Riemann, K. (2015). *Cape flats aquifer and false bay - Opportunities to change*. Conference paper.

Hosseini, N., Johnston, J., and Lindenschmidt, K. E. (2017). Impacts of climate change on the water quality of a regulated prairie river. *Water (Switzerland)*, *9*(3), 1–15. https://doi.org/10.3390/w9030199

IPCC. (2007). Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Summary for policymakers. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, 996. https://doi.org/10.1038/446727a

Jakeman, A. J., Barreteau, O., Hunt, R. J., Rinaudo, J.D. and Ross, A. (2016). Integrated groundwater management: Concepts, approaches, and challenges. In *Integrated Groundwater Management: Concepts, Approaches and Challenges*. https://doi.org/10.1007/978-3-319-23576-9

Jang, W. S., Engel, B., Harbor, J., and Theller, L. (2017). *Aquifer vulnerability assessment for sustainable groundwater management using DRASTIC*. https://doi.org/10.3390/w9100792

Jun, XIA, Shubo, C., Xiuping, HAO, Rui, XIA and Xiaojie, LIU (2010). *Potential Impacts and Challenges of Climate Change on Water Quality and Ecosystem Case Studies in Representative Rivers in China*. *1*(200801001), 31–35. https://doi.org/10.3969/j.issn.1674-764x.2010.01.004

Jun, X., Shubo, C., Xiuping, H., Rui, X., and Xiaojie, L. (2010). Potential impacts and challenges of climate change on water quality and ecosystem: Case studies in representative rivers in China. *Journal of Resources and Ecology*, *1*(1), 31–35.

Kaliraj, S., Chandrasekar, N., Peter, T. S., Selvakumar, S. and Magesh, N. S. (2015). Mapping of the vulnerable zone of the coastal aquifer in the southwest coast of Kanyakumari, South India, using the GIS-based DRASTIC model. *Environmental Monitoring and Assessment*, *187*(1). https://doi.org/10.1007/s10661-014-4073-2

Khan, H. H., Khan, A., Ahmed, S., and Perrin, J. (2011). GIS-based impact assessment of land-use changes on groundwater quality: Study from a rapidly urbanized region of South India. *Environmental Earth Sciences*, *63*(6), 1289–1302.

Khatami, S. and Khazaei, B. (2014). Benefits of GIS application in hydrological modeling: A summary. *Journal of Water Management and Research*, *70*(1), 41–49.

Kozlowski, M. and Sojka, M. (2019). Applying a modified DRASTIC model to assess groundwater vulnerability to pollution: A case study in central Poland. *Polish Journal of Environmental Studies*, *28*(3), 1223–1231. https://doi.org/10.15244/pjoes/84772

Kumar, C.P. (2010). Impact of climate change on groundwater resources. *Change*, *247–667*, 1–14. papers2://publication/uuid/DB98AC5D-B9B5-4D29-B550-B7FD0036B079

Kumar, C. P. (2012). Climate Change and its Impact on Groundwater Resources. *International Journal of Engineering and Science*, *1*(5), 43–60. http://www.researchinventy.com/papers/v1i5/F015043060.pdf

Lathamani, R., Janardhana, M. R., Mahalingam, B., and Suresha, S. (2015). Evaluation of aquifer vulnerability using a dynamic model and GIS: A Case Study of Mysore City, Karnataka, India. *Aquatic Procedia*, *4*(Icwrcoe), 1031–1038. https://doi.org/10.1016/j.aqpro.2015.02.130

Li, R., and Merchant, J. W. (2013). Modeling vulnerability of groundwater to pollution under future scenarios of climate change and biofuel-related land use change: A case study in North Dakota, USA. *Science of the Total Environment*, *447*, 32–45.

Machdar, I., Zulfikar, T., Rinaldi, W., and Alfiansyah, Y. (2018). *Assessment of groundwater vulnerability using DRASTIC Model and GIS: A case study of two subdistricts in the city of Banda Aceh, Indonesia*. *334*(1), 012032.

Machiwal, D., Cloutier, V., Güler, C., and Kazakis, N. (2018). A review of GIS-integrated statistical techniques for groundwater quality evaluation and protection. *Environmental Earth Sciences*, *77*(19), 1–30. https://doi.org/10.1007/s12665-018-7872-x

Malik, M.S. and Shukla, J. (2019). Assessment of the risk of groundwater vulnerability in the shallow aquifers of the Kandaihimmat watershed, Hoshangabad, Madhya Pradesh. *Journal of the Geological Society of India*, *93*(2), 199–206.

Malik, M. S., and Shukla, J. P. (2019). Assessment of the risk of groundwater vulnerability in the shallow aquifers of the Kandaihimmat watershed, Hoshangabad, Madhya Pradesh. *Journal of the Geological Society of India*, *93*(2), 199–206. https://doi.org/10.1007/s12594-019-1152-6

Mango, L. M., Melesse, A. M., McClain, M. E., Gann, D., and Setegn, S. (2011). Land use and climate change impacts on the hydrology of the upper Mara River Basin, Kenya: Results of a modeling study to support better resource management. *Hydrology and Earth System Sciences*, *15*(7), 2245–2258.

Maqsoom, A., Aslam, B., Alwetaishi, M., Awais, M., Hassan, U., Maqsoom, S., Alaloul, W. S., Musarat, M. A., Zerouali, B., and Hussein, E. E. (2021). A GIS-Based Groundwater Contamination Assessment Using Modified DRASTIC Geospatial Technique. *Water*, *13*(20), 2868.

Mauck, B. (2015). *Managed Aquifer Recharge (Mar) for Stormwater Management in the Cape Flats, Cape Town*. *November*.

Mauck, B. A. (2017). *The capacity of the Cape Flats aquifer and its role in water-sensitive urban design in Cape Town*. OpenUCT. http://hdl.handle.net/11427/27293

McGibbon, D. C., Hartnady, C. J. H., Buchanan, J., Wise, E., and Riemann, K. (2017). *Philippi Horticultural Area - Natural Resources Survey, [Socio-Economic Agricultural Plan for Existing PHA]*. *December*, 40.

McGill, B. M., Altchenko, Y., Hamilton, K.K., Kenabatho, P. K., Sylvester, S. R., and Villholth, K.G. (2019a). Complex interactions between climate change, sanitation, and groundwater quality: A case study from Ramotswa, Botswana. *Hydrogeology Journal*, *27*(3), 997–1015. https://doi.org/10.1007/s10040-018-1901-4

Meyer, R. and de B., JH. (1981). A geophysical study of the Cape Flats aquifer. *South African Journal of Geology*, *84*(2), 107–114.

Miller, J. D., and Hutchins, M. (2017). Journal of Hydrology: Regional Studies The Impacts of Urbanisation and Climate Change on Urban Fl ooding and Urban Water Quality: A review of the evidence concerning the United Kingdom. *Journal of Hydrology: Regional Studies*, *12*(June), 345–362. https://doi.org/10.1016/j.ejrh.2017.06.006

Mogaji, K. A. (2018). Application of vulnerability modeling techniques in groundwater resource management: A comparative study. *Applied Water Science*, *8*(5), 1–24. https://doi.org/10.1007/s13201-018-0770-2

Mohammadi Ghaleni, M., and Ebrahimi, K. (2015). Effects of human activities and climate variability on water resources in the Saveh plain, Iran. *Environmental Monitoring and Assessment*, *187*(2). https://doi.org/10.1007/s10661-014-4243-2

Montenegro, S., and Ragab, R. (2012). Impact of possible climate and land use changes in the semi-arid regions: A case study from Northeast Brazil. *Journal of Hydrology*, *434*, 55–68.

Muhammad, A. M., Zhonghua, T., Dawood, A. S., and Earl, B. (2015). Evaluation of local groundwater vulnerability based on the DRASTIC index method in Lahore, Pakistan. *Geofisica Internacional*, *54*(1), 67–81. https://doi.org/10.1016/j.gi.2015.04.003

Mulligan, M. (2015). *Climate change and food-water supply from Africa's drylands: Local impacts and teleconnections through global commodity flows*. *0627*. https://doi.org/10.1080/07900627.2015.1043046

Murray-Rust, D. H., and Fakhruddin, S. H. M. (2014). *An Assessment of Groundwater Management: Climate change and water resources in West Africa*. *March*, 67.

Musekiwa, C. and Majola, K. (2011). *Map of groundwater vulnerability for South Africa*. *27*(0), 1–29.

Musekiwa, C. and Majola, K. (2013). Map of groundwater vulnerability for South Africa. *South African Journal of Geomatics*, *2*(2), 152–162.

Nabizadeh, R., Amin, M. V., Alimohammadi, M., Naddafi, K., Mahvi, A. H., and Yousefzadeh, S. (2013). Development of innovative computer software to facilitate the setup and computation of the water quality index. *Journal of Environmental Health Science and Engineering*, *11*(1), 1-4.

Nashwan, M. S. and Shahid, S. (2020). A novel framework for selecting general circulation models based on spatial patterns of climate. *International Journal of Climatology*, *40*(10), 4422–4443. https://doi.org/10.1002/joc.6465

Nezar, H. A., Hammouri, A., Zunic, F., and Salameh, E. (2010). *Intrinsic Vulnerability Assessment for the Alluvial Aquifer in the Northern Part of the Jordan Valley*. 3461–3485. https://doi.org/10.1007/s11269-010-9615-y

Olivier, D. W., and Xu, Y. (2019). Making effective use of groundwater to avoid another water supply crisis in Cape Town, South Africa. *Hydrogeology Journal*, *27*(3), 823–826. https://doi.org/10.1007/s10040-018-1893-0

Osei, M. A., Amekudzi, L. K., Wemegah, D. D., Preko, K., Gyawu, E. S., and Obiri-Danso, K. (2019). The impact of climate and land use changes on the hydrological processes of the Owabi catchment from SWAT analysis. *Journal of Hydrology: Regional Studies*, *25*, 100620.

Panwar, S. and Chakrapani, G. J. (2018). *Climate change and its influence on groundwater resources*. *105*(1), 37–46.

Pasini, S., Torresan, S., Rizzi, J., Zabeo, A., Critto, A., and Marcomini, A. (2012). Science of the total environment Climate change impact assessment in the groundwater of the Veneto and Friuli Plain. Part II: A spatially resolved regional risk assessment. *Science of the Total Environment, The*, *440*, 219–235. https://doi.org/10.1016/j.scitotenv.2012.06.096

Pervez, M. S. and Henebry, G. M. (2015). Assessing the impacts of climate and land use and change in land cover on freshwater availability in the Brahmaputra River basin. *Journal of Hydrology: Regional Studies*, *3*, 285-211

Peter, A., Mujuru, M. and Dube, T. (2018). An assessment of land cover changes in a protected nature reserve and possible implications on water resources, South Africa. *Physics and Chemistry of the Earth, Parts A/B/C*, *107*, 86–91.

Pouget, L., Escaler, I., Guiu, R., Mc Ennis, S. and Versini, PA (2012). Global Change Adaptation in Water Resources Management: The Water Change project. *Science of the Total Environment*, *440*, 186–193.

Ramaraju, A. V. and Krishna, V. (2017). Evaluation of groundwater vulnerability using the DRASTIC method using GIS. *International Journal of Geo Informatics and Geological Science*, *4*(2), 6–13.

Rawal, D., Vyas, A., and Rao, S.S. (2016). Application of Gis and groundwater modelling techniques to identify perched aquifers to mark water logging conditions in parts of Mehsana. *ISPRS Annals of Photogrammetry, Remote Sensing, and Spatial Information Sciences*, *III–8*(November), 173–180. https://doi.org/10.5194/isprsannals-iii-8-173-2016

Reid, D., * Erlank, AJ*, and Rex, DC**. (1991). Age and correlation of the False Bay dolerite dyke swarm, South West Cape, Cape Province. *South African Journal of Geology*, *94*(2), 155–158.

Report, S. I. (2019). *Hydrologic site assessment for passive treatment of groundwater nitrogen with permeable reactive barriers, Cape Cod, Massachusetts Scientific Investigations Report 2019 – 5047*.

Rogers, J. (1982). Quaternary sedimentology of the Bot River Lagoon. *JOINT GEOLOGICAL SURVEY/UNIVERSITY OF CAPE TOWN*, 72.

Ruben Aza-Gnandji, C. D., Xu, Y., Raitt, L., and Levy, J. (2013). Salinity of irrigation water in the Philippi farming area of the Cape Flats, Cape Town, South Africa. *Water SA*, *39*(2), 199–210. https://doi.org/10.4314/wsa.v39i2.3

Rudd, M. A., Moore, A. F. P., Rochberg, D., Bianchi-Fossati, L., Brown, M. A., D'Onofrio, D., Furman, C. A., Garcia, J., Jordan, B., Kline, J., Risse, L. M., Yager, P. L., Abbinett, J., Alber, M., Bell, J. E., Bhedwar, C., Cobb, K. M., Cohen, J., Cox, M., … Worley, A. N. (2018). Climate research priorities for policy makers, practitioners and scientists in Georgia, USA. *Environmental Management*, *62*(2), 190–209. https://doi.org/10.1007/s00267-018-1051-4

Saatsaz, M., Sulaiman, WNA, Eslamian, S., and Mohammadi, K. (2011a). GIS DRASTIC model for groundwater vulnerability estimation of Astaneh-Kouchesfahan Plain,

Saida, S., Tarik, H., Abdellah, A., Farid, H. and Hakim, B. (2017). Assessment of Groundwater Vulnerability to Nitrate Based on Optimized DRASTIC Models in the GIS Environment (Case of Sidi Rached Basin, Algeria). *Geosciences*, *7*(2), 20. https://doi.org/10.3390/geosciences7020020

Salvadore, E., Bronders, J., and Batelaan, O. (2015). Hydrological modelling of urbanized catchments: A review and future directions. *Journal of Hydrology*, *529*(P1), 62–81. https://doi.org/10.1016/j.jhydrol.2015.06.028

Saraswat, C., Kumar, P., Dasgupta, R., Avtar, R., and Bhalani, P. (2019). Sustainability assessment of groundwater quality in western India to achieve urban water security. *Applied Water Science*, *9*(4), 1–17.

Segun, A. M., Yongxin, X., and Shafick, A. (2006). *Identifying sources and mechanism of groundwater recharge in the Cape Flats, South Africa: Implications for sustainable resource management*.

Shamir, E., Megdal, B.B., Carrillo, C., Castro, C. L., Chang, H. I., Chief, K., Corkhill, F. E., Eden, S., Georgakakos, K. P., Nelson, K.M. and Prietto, J. (2015). Climate change and water resource management on the Upper Santa Cruz River, Arizona. *Journal of Hydrology*, *521*, 18–33. https://doi.org/10.1016/j.jhydrol.2014.11.062

Shirazi, M. M., Imran, H. and Akib, S. (2012). GIS-based DRASTIC method for groundwater vulnerability assessment: A review. *Journal of Risk Research*, *15*(8), 991–1011.

Shrestha, A., and Luo, W. (2018). Assessment of Groundwater Nitrate Pollution Potential in the Central Valley Aquifer Using Geodetector-Based Frequency Ratio (GFR) and Optimized-DRASTIC Methods. *ISPRS International Journal of Geo-Information*, *7*(6), 211. https://doi.org/10.3390/ijgi7060211

Soesbergen, A. J. J. V. and Mulligan, M. (2014). *Modelling multiple threats to water security in the Peruvian Amazon using the WaterWorld policy support system*. 55–65. https://doi.org/10.5194/esd-5-55-2014

Srivastava, P. K., Han, D., Gupta, M., and Mukherjee, S. (2012). Integrated framework for monitoring groundwater pollution using a geographical information system and multivariate analysis | Cadre intégré for the monitoring of eaux souterraines pollution with the help of a system of geographic information and analysis. *Hydrological Sciences Journal*, *57*(7), 1453–1472. https://doi.org/10.1080/02626667.2012.716156

Theron, J. (1984). The geology of Cape Town and its environs, explanation of sheets 3318CD and DC and 3418 AB, AD and BA. *Geological Survey of South Africa, Pretoria*.

Theron, J., Gresse, P., Siegfried, H., and Rogers, J. (1992). The geology of the Cape Town area: Explanation of sheet 3318, scale 1: 250 000. *Geological Survey of South Africa, Department of Mineral and Energy Affairs, Pretoria*.

Tredoux, G., Ross, W., and Gerber, A. (1980). The potential of the Cape Flats aquifer for the storage and abstraction of reclaimed effluents (South Africa). *Zeitschrift Der Deutschen Geologischen Gesellschaft*, 23–43.

Tsihrintzis, V. A., Hamid, R., and Fuentes, H. R. (1996). Use of Geographic Information Systems (GIS) in Water Resources: A review. *Water Resources Management*, *10*(4), 251–277. https://doi.org/10.1007/BF00508896

Ugwu, C.C. (2019). *EVALUATING THE IMPACT OF CLIMATE CHANGE ON THE QUALITY OF GROUND WATER: CASE STUDY OF A COAL ENRICHED ENVIRONMENT IN ENUGU URBAN*. *August*, 536–550.

Van Soesbergen, A. J. J., and Mulligan, M. (2014). Modelling multiple threats to water security in the Peruvian Amazon using the WaterWorld policy support system. *Earth System Dynamics*, *5*(1), 55–65. https://doi.org/10.5194/esd-5-55-2014

Velazquez, J. A., Schmid, J., Ricard, S., Muerth, M., Gauvin St-Denis, B., Minville, M., Chaumont, D., Caya, D., Ludwig, R. and Turcotte, R. (2013). An ensemble approach to assess the contribution of hydrological models to uncertainties in the analysis of the impact of climate change on water resources. *Hydrology and Earth System Sciences*, *17*(2), 565–578.

Victorine Neh, A., Ako, A., Richard Ayuk, A., and Hosono, T. (2015). DRASTIC-GIS model to assess vulnerability to pollution of phreatic aquiferous formations in Douala-Cameroon.

Journal of African Earth Sciences, *102*, 180–190. https://doi.org/10.1016/j.jafrearsci.2014.11.001

Voudouris, K., Kazakis, N., Polemio, M., and Kareklas, K. (2010). Evaluation of intrinsic vulnerability using the DRASTIC model and GIS in the Kiti aquifer, Cyprus. *European Water*, *1968*, 13–24.

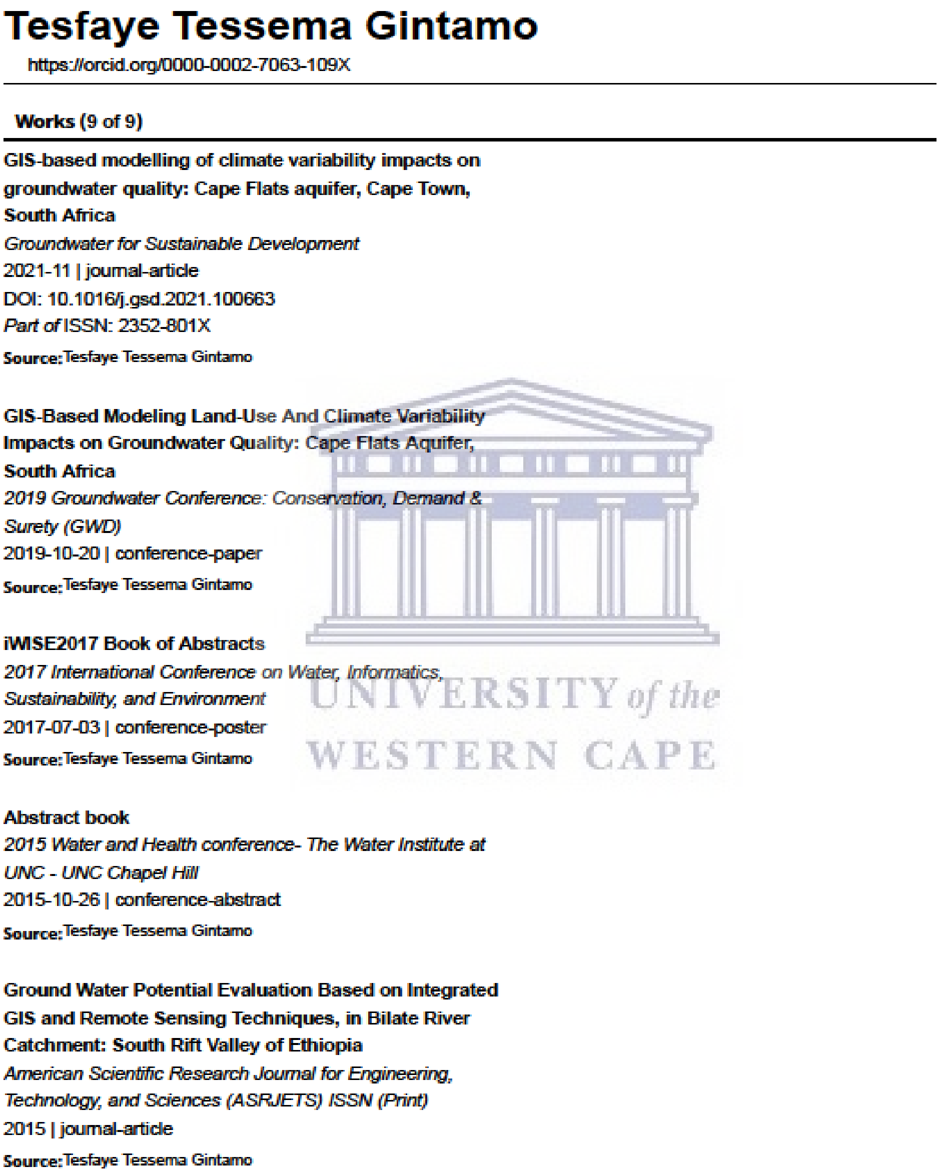
Zhang, L., Nan, Z., Xu, Y., and Li, S. (2016). Hydrological impacts of change in land use and climate variability in the headwater region of the Heihe River basin, northwest China. *PLoS ONE*. https://doi.org/10.1371/journal.pone.0158394

Zhou, Y., Lai, C., Wang, Z., Chen, X., Zeng, Z., Chen, J. and Bai, X. (2018). Quantitative evaluation of the impact of climate change and human activity on runoff change in the Dongjiang River Basin, China. *Water (Switzerland)*, *10*(5). https://doi.org/10.3390/w10050571

Zhu, T., and Ringler, C. (2010). *Implications of climate change for water resources in the Limpopo River Basin*. International Food Policy Research Institute (IFPRI).

Appendix

Appendix A: List of publications



Tesfaye Tessema Gintamo

https://orcid.org/0000-0002-7063-109X

Works (9 of 9)

GIS-based modelling of climate variability impacts on groundwater quality: Cape Flats aquifer, Cape Town, South Africa

Groundwater for Sustainable Development

2021-11 | journal-article

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2019 Groundwater Conference: Conservation, Demand & Surety (GWD)

2019-10-20 | conference-paper

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2017 International Conference on Water, Informatics, Sustainability, and Environment

2017-07-03 | conference-poster

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Abstract book

2015 Water and Health conference- The Water Institute at UNC - UNC Chapel Hill

2015-10-26 | conference-abstract

Source: Tesfaye Tessema Gintamo

Ground Water Potential Evaluation Based on Integrated GIS and Remote Sensing Techniques, in Bilate River Catchment: South Rift Valley of Ethiopia

American Scientific Research Journal for Engineering, Technology, and Sciences (ASRJETS) ISSN (Print)

2015 | journal-article

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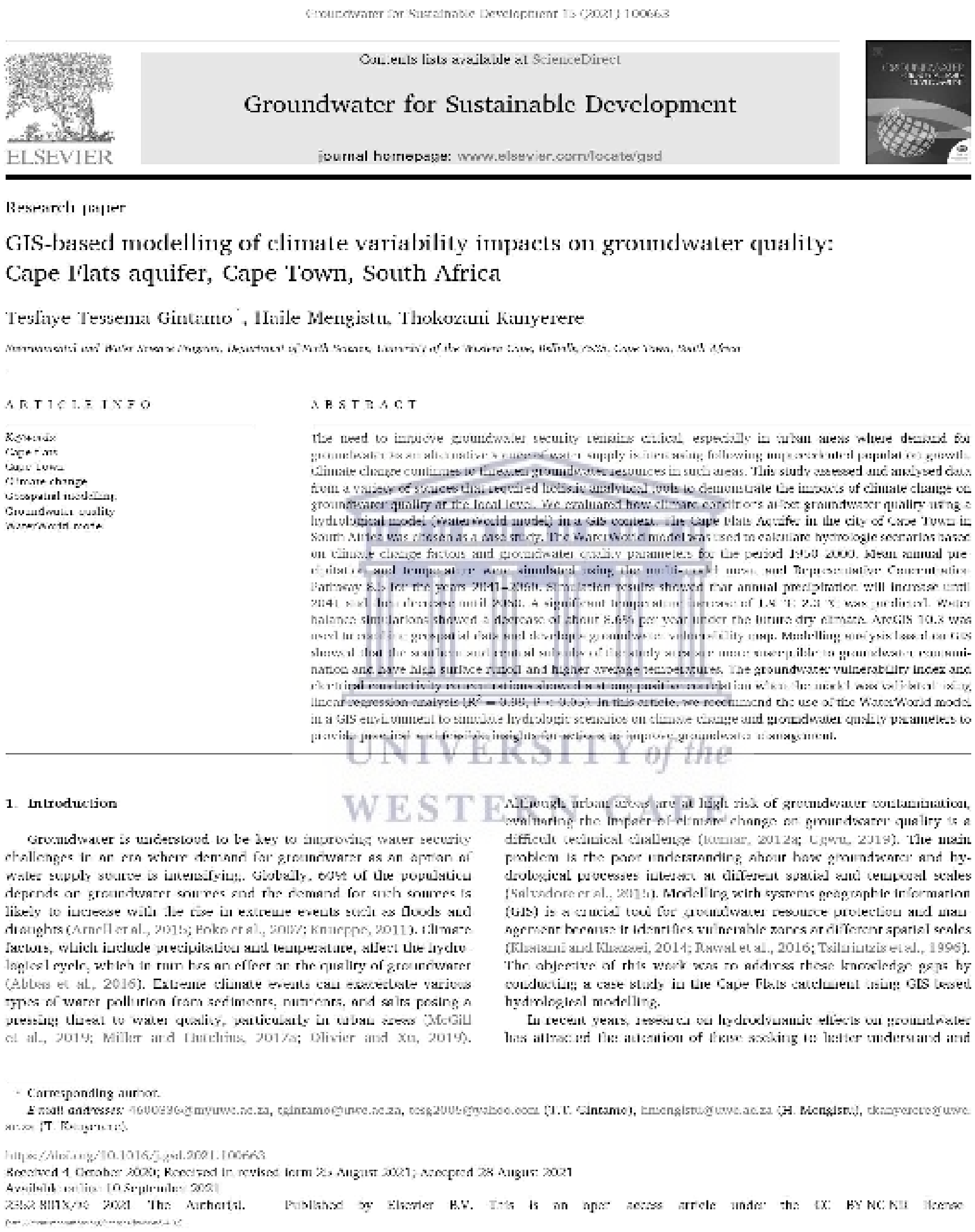
Paper 1



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Research paper

GIS-based modelling of climate variability impacts on groundwater quality: Cape Flats aquifer, Cape Town, South Africa

Tesfaye Tessema Gintamo *, Haile Mengistu, Thokozani Kanyerere

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WaterWorld model

ABSTRACT

The need to improve groundwater security remains critical, especially in urban areas where demand for groundwater as an alternative source of water supply is increasing following unprecedented population growth. Climate change continues to threaten groundwater resources in such areas. This study assessed and analysed data from a variety of sources that required holistic analytical tools to demonstrate the impacts of climate change on groundwater quality at the local level. We evaluated how climate conditions affect groundwater quality using a hydrological model (WaterWorld model) in a GIS context. The Cape Flats Aquifer in the city of Cape Town in South Africa was chosen as a case study. The WaterWorld model was used to calculate hydrologic scenarios based on climate change factors and groundwater quality parameters for the period 1950–2000. Mean annual precipitation and temperature were simulated using the multi-model mean and Representative Concentration Pathway 8.5 for the years 2041–2060. Simulation results showed that annual precipitation will increase until 2041 and then decrease until 2060. A significant temperature increase of 1.8 °C–2.3 °C was predicted. Water balance simulations showed a decrease of about 8.65% per year under the future dry climate. ArcGIS 10.3 was used to combine geospatial data and develop a groundwater vulnerability map. Modelling analysis based on GIS showed that the southern and central suburbs of the study area are more susceptible to groundwater contamination and have high surface runoff and higher average temperatures. The groundwater vulnerability index and electrical conductivity concentrations showed a strong positive correlation when the model was validated using linear regression analysis ($R^2 = 0.98$, $P < 0.05$). In this article, we recommend the use of the WaterWorld model in a GIS environment to simulate hydrologic scenarios on climate change and groundwater quality parameters to provide practical and feasible insights for actions to improve groundwater management.

1. Introduction

Groundwater is understood to be key to improving water security challenges in an era where demand for groundwater as an option of water supply source is intensifying. Globally, 60% of the population depends on groundwater sources and the demand for such sources is likely to increase with the rise in extreme events such as floods and droughts (Arnell et al., 2015; Foko et al., 2007; Knüppe, 2011). Climate factors, which include precipitation and temperature, affect the hydrological cycle, which in turn has an effect on the quality of groundwater (Abbas et al., 2016). Extreme climate events can exacerbate various types of water pollution from sediments, nutrients, and salts posing a pressing threat to water quality, particularly in urban areas (McGill et al., 2019; Miller and Hutchins, 2017a; Olivier and Xu, 2019). Although urban areas are at high risk of groundwater contamination, evaluating the impact of climate change on groundwater quality is a difficult technical challenge (Kumar, 2012a; Ugwu, 2019). The main problem is the poor understanding about how groundwater and hydrological processes interact at different spatial and temporal scales (Salvadore et al., 2015). Modelling with systems geographic information (GIS) is a crucial tool for groundwater resource protection and management because it identifies vulnerable zones at different spatial scales (Khosravi and Khezzei, 2014; Rawal et al., 2016; Tsihrintzis et al., 1996). The objective of this work was to address these knowledge gaps by conducting a case study in the Cape Flats catchment using GIS based hydrological modelling.

In recent years, research on hydrodynamic effects on groundwater has attracted the attention of those seeking to better understand and

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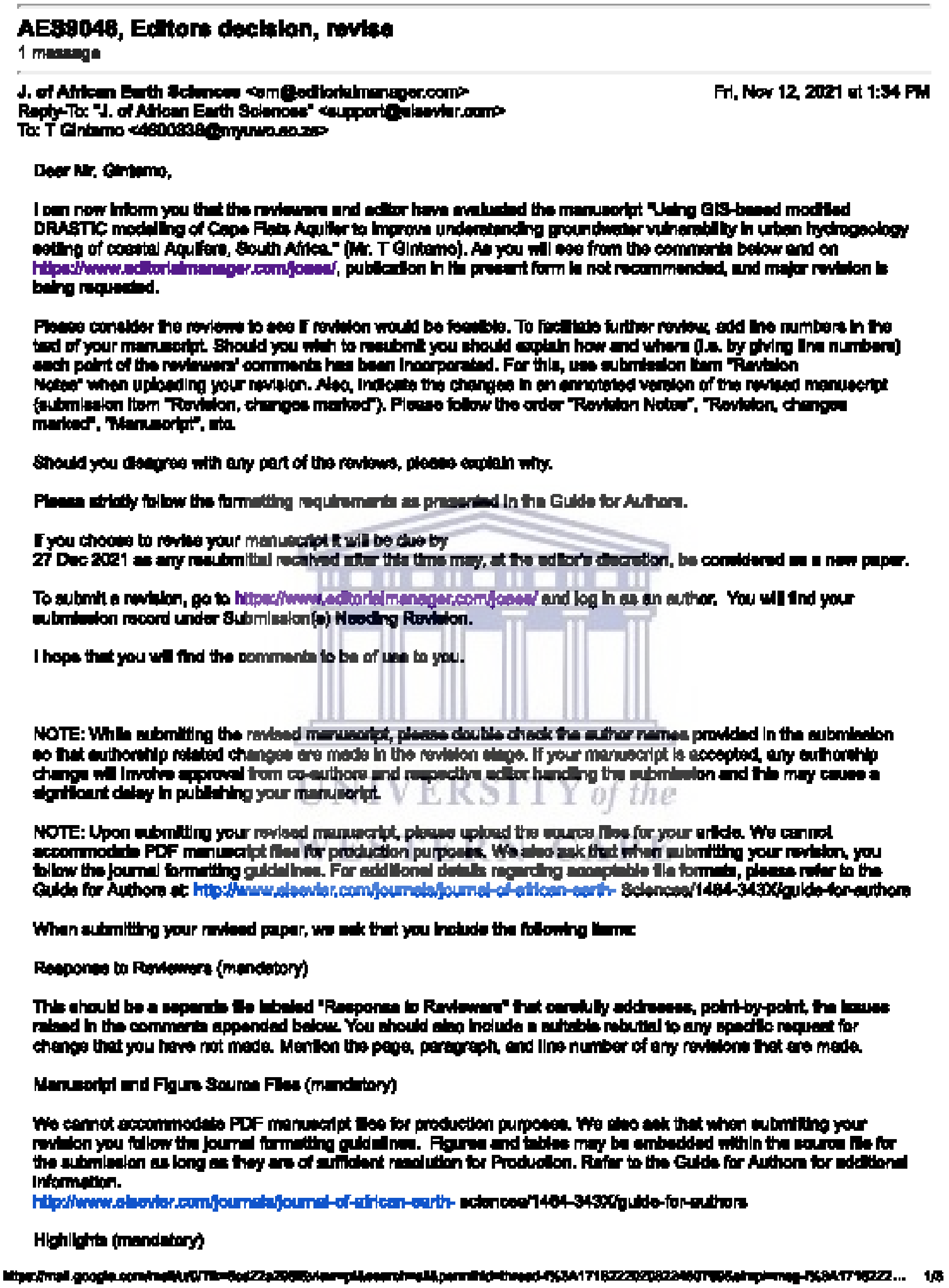
Manuscript 2



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1 message

J. of African Earth Sciences <em@editorialmanager.com> Fri, Nov 12, 2021 at 1:34 PM
Reply-To: "J. of African Earth Sciences" <support@elsevier.com>
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Dear Mr. Gintamo,

I can now inform you that the reviewers and editor have evaluated the manuscript "Using GIS-based modified DRASTIC modelling of Cape Flats Aquifer to improve understanding groundwater vulnerability in urban hydrogeology setting of coastal Aquifers, South Africa." (Mr. T Gintamo). As you will see from the comments below and on https://www.editorialmanager.com/jaes/, publication in its present form is not recommended, and major revision is being requested.

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Highlights (mandatory)

Paper 2.pdf

Appendix B: Depth to Water Level

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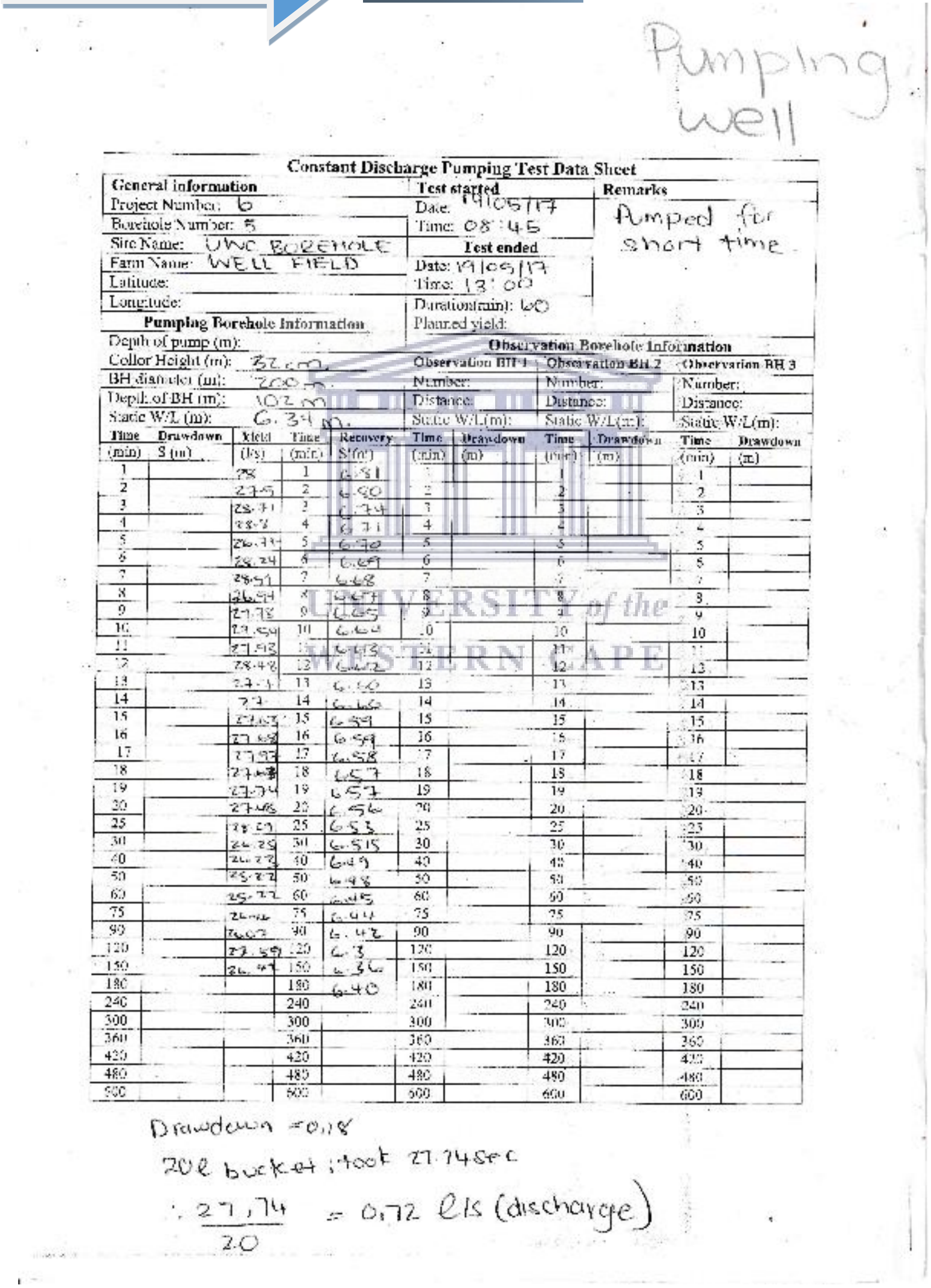
PDF

Depth to water and the salinity (EC)_WU



Pumping well

Constant Discharge Pumping Test Data Sheet

General information	**Test started**	**Remarks**
Project Number: 6	Date: 19/05/17	Pumped for short time
Borehole Number: 5	Time: 08:45	
Site Name: UWC BOREHOLE	**Test ended**	
Farm Name: WELL FIELD	Date: 19/05/17	
Latitude:	Time: 13:00	
Longitude:	Duration(min): 60	
Pumping Borehole Information	Planned yield:	

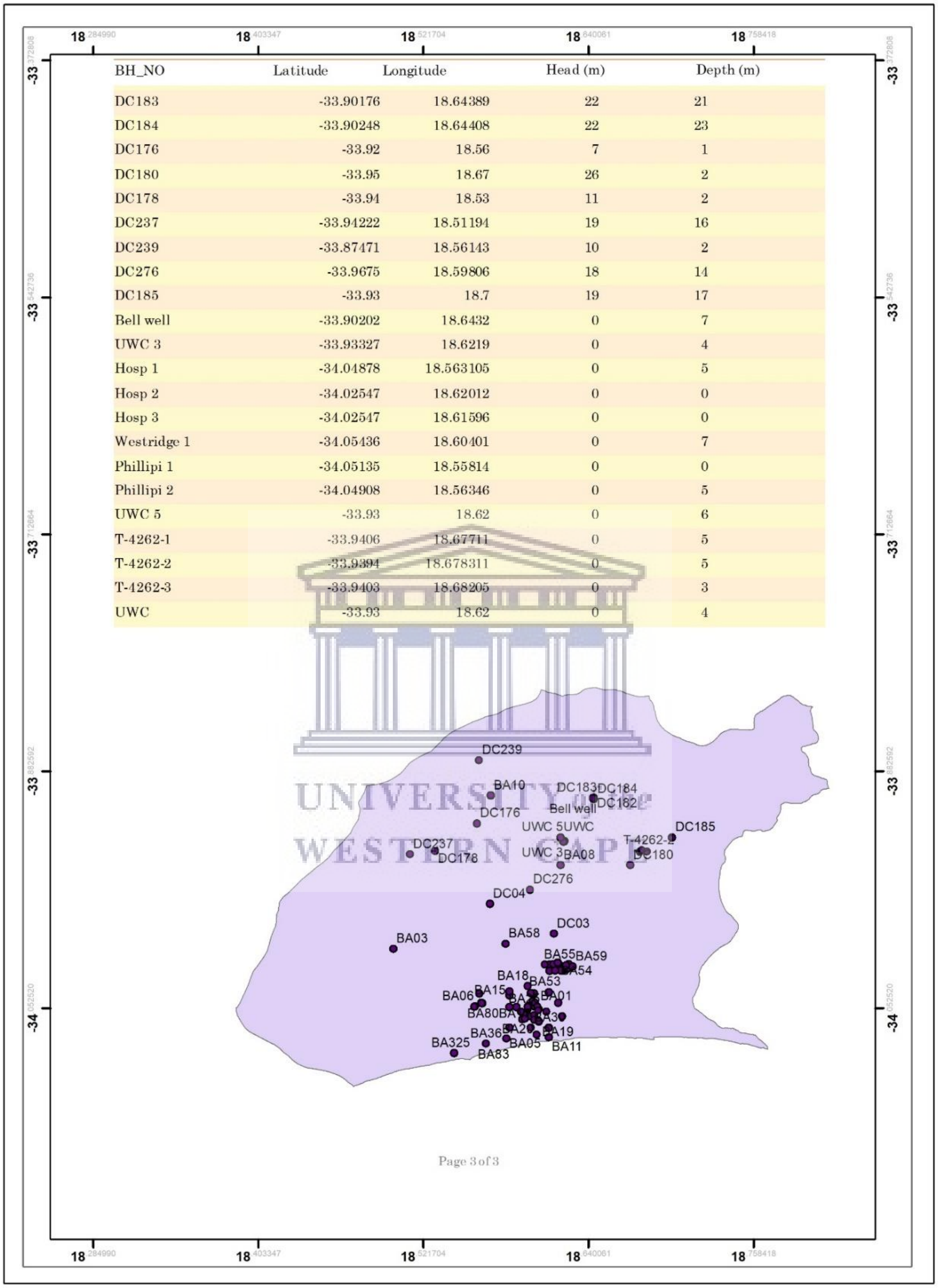
Depth of pump (m):	**Observation Borehole Information**		
Collor Height (m): 32 cm.	Observation BH 1	Observation BH 2	Observation BH 3
BH diameter (m): 200 m.	Number:	Number:	Number:
Depth of BH (m): 102 m	Distance:	Distance:	Distance:
Static W/L (m): 6.34 m.	Static W/L(m):	Static W/L(m):	Static W/L(m):

Time (min)	Drawdown S (m)	Yield (l/s)	Time (min)	Recovery S'(m')	Time (min)	Drawdown (m)	Time (min)	Drawdown (m)	Time (min)	Drawdown (m)
1		28	1	6.81	1		1		1	
2		27.5	2	6.90	2		2		2	
3		28.71	3	6.74	3		3		3	
4		28.7	4	6.71	4		4		4	
5		26.73	5	6.70	5		5		5	
6		28.24	6	6.69	6		6		6	
7		28.51	7	6.68	7		7		7	
8		26.54	8	6.67	8		8		8	
9		27.78	9	6.65	9		9		9	
10		27.54	10	6.64	10		10		10	
11		27.93	11	6.63	11		11		11	
12		28.48	12	6.62	12		12		12	
13		27.41	13	6.60	13		13		13	
14		27.	14	6.60	14		14		14	
15		27.03	15	6.59	15		15		15	
16		27.68	16	6.59	16		16		16	
17		27.97	17	6.58	17		17		17	
18		27.08	18	6.57	18		18		18	
19		27.74	19	6.57	19		19		19	
20		27.06	20	6.56	20		20		20	
25		28.29	25	6.53	25		25		25	
30		26.29	30	6.515	30		30		30	
40		26.27	40	6.49	40		40		40	
50		25.27	50	6.48	50		50		50	
60		25.77	60	6.45	60		60		60	
75		26.06	75	6.44	75		75		75	
90		26.07	90	6.42	90		90		90	
120		27.59	120	6.3	120		120		120	
150		26.47	150	6.36	150		150		150	
180			180	6.40	180		180		180	
240			240		240		240		240	
300			300		300		300		300	
360			360		360		360		360	
420			420		420		420		420	
480			480		480		480		480	
600			600		600		600		600	

Drawdown = 0,18

20ℓ bucket : took 27.74sec

$\therefore \frac{27,74}{20} = 0,72$ ℓ/s (discharge)



BH_NO	Latitude	Longitude	Head (m)	Depth (m)
DC183	-33.90176	18.64389	22	21
DC184	-33.90248	18.64408	22	23
DC176	-33.92	18.56	7	1
DC180	-33.95	18.67	26	2
DC178	-33.94	18.53	11	2
DC237	-33.94222	18.51194	19	16
DC239	-33.87471	18.56143	10	2
DC276	-33.9675	18.59806	18	14
DC185	-33.93	18.7	19	17
Bell well	-33.90202	18.6432	0	7
UWC 3	-33.93327	18.6219	0	4
Hosp 1	-34.04878	18.563105	0	5
Hosp 2	-34.02547	18.62012	0	0
Hosp 3	-34.02547	18.61596	0	0
Westridge 1	-34.05436	18.60401	0	7
Phillipi 1	-34.05135	18.55814	0	0
Phillipi 2	-34.04908	18.56346	0	5
UWC 5	-33.93	18.62	0	6
T-4262-1	-33.9406	18.67711	0	5
T-4262-2	-33.9394	18.678311	0	5
T-4262-3	-33.9403	18.68205	0	3
UWC	-33.93	18.62	0	4

Depth to water level_CFA.pdf

CFA water level data.pdf

Appendix C: The average annual rainfall at the Cape Town International Airport meteorological stations for the period 1979 to 2018

Year	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**	**NOV**	**DEC**	**P (mm / year)**
1979	17.9	36	6.6	9.2	63.1	76.4	45.9	40.3	27.4	80.8	2.1	2.4	**408**
1980	12.7	15.9	0.6	52.3	113.4	75.9	29.6	39.6	23.7	21.2	62.7	29	**477**
1981	58.9	0.3	41.3	52.5	13.8	58.3	168.6	66.8	87.8	9.7	14.7	12.5	**585**
1982		6	12.2	44.7	42.4	65.6	58.3	91.2	12.7	29	27.7	27.8	**418**
1983	10.7	48.8	38.6	7.8	95.9	165.9	59.4	34.9	43.6	11.5	3.5	7.5	**528**
1984	14	5.5	31.9	22.4	133.3	45.5	48.3	30.7	86.9	80	2.2	70.5	**571**
1985	25.4	14.2	72.5	49.6	44.6	110.3	132.3	69.2	33.1	5.7	2.9	9.4	**569**
1986	11.4	7.9	37.5	31.6	52.7	130.2	100.8	116.1	29.9	37.5	20.5	8.3	**584**
1987	14.6	18.3	14.2	36.7	121.1	114	139.4	103.3	41.7	12.6	10	25.4	**651**
1988	0.7	0	33.4	40.8	60.5	46.3	95.5	77.2	40.7	20.9	1.9	7.7	**426**
1989	4.7	19.9	57.7	65.9	89.6	56.2	120.6	99.1	91	47.7	29.5	3	**685**
1990	14	31.2	0.7	142.1	69.2	110.1	124.3	43.8	27.5	3.5	18.2	18.8	**603**
1991	5.8	10.9	10.6	25.4	89.9	151.4	167.6	31.1	72.5	48.3	11.2	7.5	**632**
1993	4.7	38	3.8	178.9	136.9	78.5	142.5	63.2	9.1	3.8	2.3	29.4	**691**
1994	14.6	0.7	3.6	35	39.5	229.4	68.9	30.9	39.5	14.1	7.9	3.4	**488**
1995	9.9	1	5.8	17.9	68	109.8	96.7	75.1	19.7	88.9	23.1	34.5	**550**
1996	2.2	34.7	26.5	33	55.3	131.4	85	106.5	100.4	69.2	34	28.3	**707**

1997	9.6	2	1.9	40.5	74.4	105.6	14.9	81.7	8.3	24.6	47.8	11.5	**423**
1998	9.7	0.3	14.1	35.4	120.2	52.8	99.7	46	30.9	15	47.1	45.4	**517**
1999	1.2	0.9	0.4	57.2	34.8	83.3	40.7	105.2	98.2	1.4	15.6	2.6	**442**
2000	16.1	0	12.9	13.8	62.3	92.6	46.3	46.2	66.6	6.6	6.8	5.9	**376**
2001	8.3	4.7	2.5	39.4	80.6	62.3	207.8	97.3	47	26.3	12.7	6.4	**595.**
2002	60.9	14.9	9.3	28	71.9	76.4	98.2	65.7	26.1	32.5	22	15.9	**522**
2003	2.4	8.4	47.6	11.9	37.1	25	33.4	100.3	63.9	19.2	5.8	21.1	**376**
2004	5.8	0.2	9.2	63.1	3.8	91.1	64.7	169.7	25.1	98.9	3.4	9.2	**544**
2005	24.5	2	8.7	95.3	77.7	90.2	64.6	89.6	29.7	13.5	20.1	1.2	**517**
2006	0	13	4.7	30.1	121.8	34	71.4	56.2	20	37.2	37.7	10	**436**
2007	0.5	27.3	18.6	65.6	96	123.4	151.5	101.5	18.2	18.7	40.8	18.5	**681**
2008	6.8	13.9	5.2	15.2	51.4	63.2	182.4	79.6	137.8	12.4	53.1	7.8	**629**
2009	1.4	3.6	0.8	24	64.4	108.4	88.4	52	60.2	31.6	86.2	4.4	**525**
2010	3.4	7.9	6.4	12	95.4	70.2	40.3	32.2	24.4	31	27.8	18	**369**
2011	6.2	3.2	6	27.8	59.6	84.8	25	53.4	23.8	12.4	27.6	18.6	**348**
2012	3	5.6	23	44	39.8	78.2	92	82	55.2	34.2	8.2	1	**466**
2013	12.6	37.4	14.4	36.4	53.6	115.4	43.6	168	68	16	85.2	4.8	**655**
2014	23.2	2.2	43.8	24	61	109.4	105.6	91.4	27.6	4.8	21.2	2.6	**517**
2015	13.6	3	1.6	4.4	27	106.6	87.8	35.6	21.4	5.4	25.6	16.2	**348**
2016	9.4	3.2	35.6	48	17	58	89	60.8	29.6	9.2	3.6	19	**382**
2017	3.6	0.6	7.6	19.4	5.6	86	36	48	16.8	19	33.2	7.8	**284**
2018	5.4	8.8	9.2	54.4	66	77.4	49	55	65.4	9	8.8	14	**422**

Mean P (mm/month)	**11.8**	**11.6**	**17.5**	**41.9**	**66.9**	**91.0**	**87.6**	**72.7**	**44.9**	**27.3**	**23.5**	**15.1**

Appendix D: Temperature data at Cape Town International Airport meteorological stations for the period 1979 to 2018

CLS_Disclosure.pdf

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Total	Mean annual T(deg.C)
26.8	26.5	24	23.1	20.7	18.9	17.8	18.4	18.7	20.2	24.2	26.2	265.5	22.1
26.4	25.7	26.4	22.5	19.3	18.5	19.9	19.7	19.9	22	22.6	24.5	267.4	22.3
25.1	27.4	25.4	23.3	21.8	17.6	16.5	17	19.3	23.4	23.6	25.8	266.2	22.2
25.45	25.5	24.6	21.9	20.7	17.5	17.5	17.8	21.1	22.4	22.4	23.5	260.35	21.7
25.8	24.6	24.5	24.4	19.3	17.3	18	18.5	17.6	21.9	22.8	24.9	259.6	21.6
26.9	27	26.5	24.1	19.7	19.2	18.5	18.2	19.3	20.6	24.5	23.3	267.8	22.3
26.2	26.3	24.1	22.1	21	18.9	17.4	19.6	19.4	21.8	26.6	24.9	268.3	22.4
26.3	26.8	24.4	23	21.2	18.7	17.6	18.5	20.4	21.5	23.1	25.5	267	22.3
24.7	25	24.9	22.7	21.5	19.2	18.3	18.9	19.4	21.6	22.2	24	262.4	21.9
24.8	27.3	25	22	21.4	18.6	17.1	18.8	19.6	20.4	24	25.9	264.9	22.1
27	27.2	24.4	23.1	20.1	18	17.5	18.4	18.8	19.7	23.1	24.4	261.7	21.8
25.8	26.7	25.7	22	20.5	16.4	16.2	17.6	19.6	20.9	22.7	25.2	259.3	21.6
24.9	25	26.7	23.7	22.2	18.4	17.1	16.6	18.7	20.5	22	24.5	260.3	21.7
26.7	26.3	26.2	21.4	18.6	17.7	18.3	18.6	19.6	22.2	24.7	25.7	266	22.2
26.9	28	25.9	24.3	19.3	17.2	17.5	18.1	19.7	22.6	23.5	26.2	269.2	22.4
26.8	27.8	27	22.4	20.9	18.2	15.7	17.3	19.4	20.5	23.7	26.4	266.1	22.2
27.4	26.9	24.7	24.7	21.3	18.5	16.7	17.2	17.3	19.9	20.7	24.2	259.5	21.6
26.4	26	25.1	22.4	21.5	16.6	18.8	17.5	22.3	24.1	23.2	25.4	269.3	22.4
26.1	28.9	25.5	23.8	20.2	18.1	17.3	19	19.3	22.2	23.2	26.1	269.7	22.5
26.9	27.6	27.9	24.4	20.8	20.3	18.1	19.4	18.3	23.6	24.4	28.8	280.5	23.4
28.4	27.5	26	24.1	21.2	20.3	17.9	19	18.7	22.5	24.7	24.4	274.7	22.9
26.3	28	25.6	22.6	20.6	18.1	17.9	17	18.9	21.8	24.6	25.9	267.3	22.3
25.4	28.3	26.9	23.5	19.6	16.5	16.8	18.8	21.3	21.2	22.7	26.6	267.6	22.3

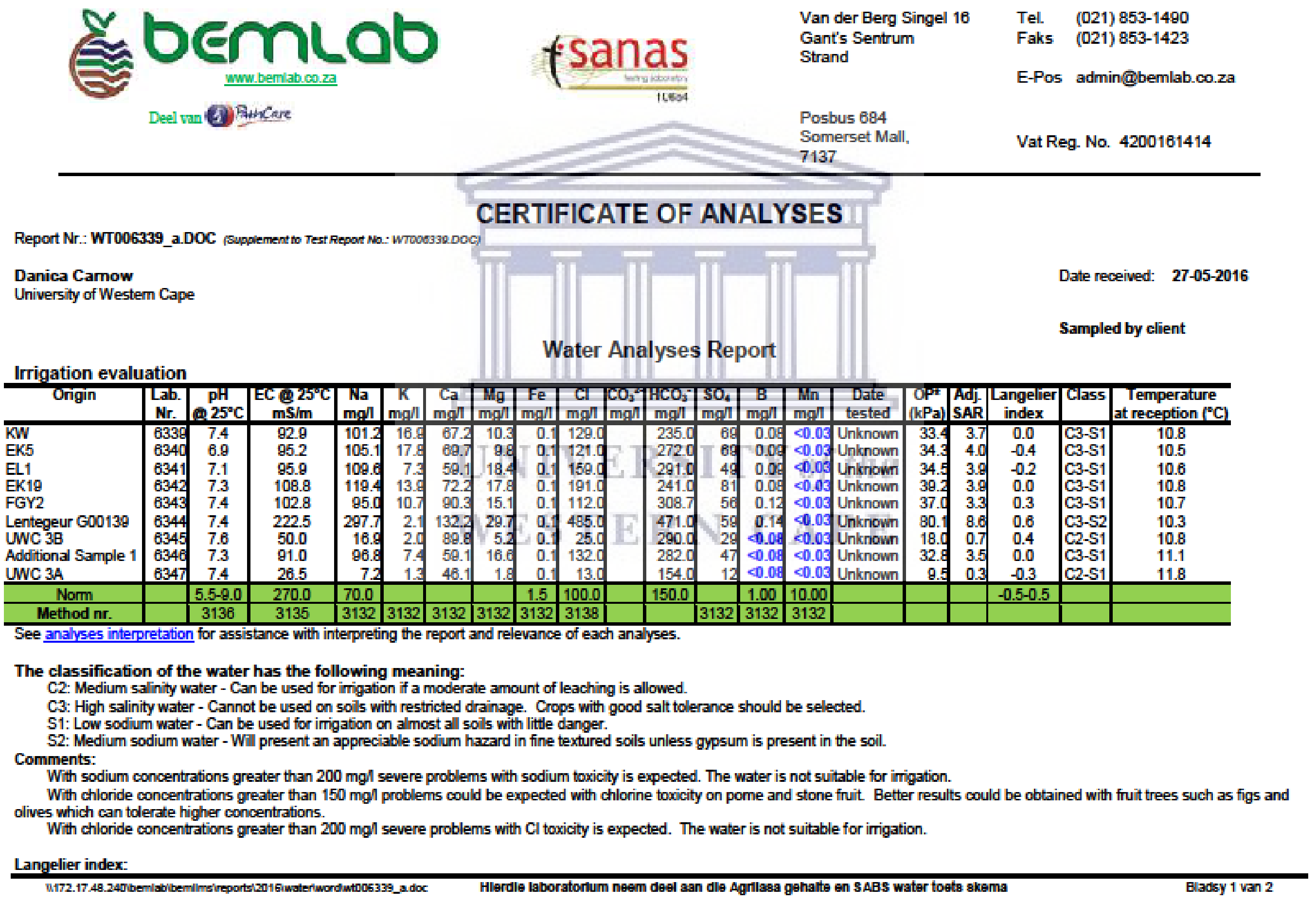
26.5	27.3	25.7	24.3	21.2	19.5	18	16.8	18.9	23.1	24.7	24.4	270.4	22.5
27.6	27.3	24.5	22.8	21.3	19.2	18.7	17.7	20.7	21.4	24.6	26.5	272.3	22.7
27.3	27.2	26.3	23.3	19.2	17.2	19.7	15.9	19.5	21.8	24.6	25	267	22.3
27.7	27.7	25.4	22.8	19.9	20.1	16.9	17.7	20.9	22.4	24.6	25	271.1	22.6
28.2	26.4	26.5	24	21.1	17.8	17.6	17.7	19.8	23.3	22.2	26.3	270.9	22.6
26.5	26.6	26.6	24.1	21.4	17.7	16.7	18.3	18.1	22	23.2	25.5	266.7	22.2
26.2	28.1	26.9	24	20.3	18.6	19.7	18.7	19.1	23	24.1	24.9	273.6	22.8
26.7	27.5	26.8	23	19.8	18.6	18.2	19.3	20	21.8	23.6	26.9	272.2	22.7
27.8	28.6	26.8	23.4	20.3	17.7	19.1	19	19.2	21.8	22.3	24.3	270.3	22.5
28.3	26.7	26.1	23	19.5	17.9	17.3	16.4	19	21.1	23.7	27.4	266.4	22.2
26.5	26.4	26.2	23.2	21.1	17.6	18.2	17.5	17.3	21.1	23.7	27	265.8	22.2
27	28.2	24	25.5	20.2	18	17.3	19.2	20.2	25	24.3	25.8	274.7	22.9
27.5	26.3	26.9	23.9	21.1	17.1	16.5	18.4	21	23.2	24.5	27	273.4	22.8
29.7	27.6	25.6	23.6	20.8	18.2	18	20	20	23.1	25.1	26.5	278.2	23.2
26.7	27.8	26.6	26.6	22.4	17.7	18.3	18.1	21.2	22.1	24.1	26.5	278.1	23.2
27.7	27.9	25.1	23.7	21.4	18.6	20.3	17.3	18.8	25.7	24.8	26	277.3	23.1
26.7	27.0	25.7	23.4	20.6	18.2	17.8	18.2	19.5	22.0	23.7	25.6		**22.4**

Appendix E: Mean monthly observed and simulated temperature at Cape Town based WaterWorld model

month	Max_1950-2000	Mean _1950-2000	Max_ 2041-2060	Mean_ 2041-2060
JAN	24	21	28	24
FEB	25	22	28	24
MAR	23	20	27	23
APR	20	17	23	20
MAY	20	17	20	16
JUN	14	12	17	14
JUL	13	11	16	13
AUG	14	12	18	14
SEP	16	14	20	16
OCT	19	16	23	19
NOV	21	19	25	21
DEC	23	20	27	23

Water quality laboratory data.pdf

Appendix F: Water Quality Data



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Vat Reg. No. 4200161414

CERTIFICATE OF ANALYSES

Report Nr.: **WT006339_a.DOC** *(Supplement to Test Report No.: WT006339.DOC)*

Danica Carnow
University of Western Cape

Date received: **27-05-2016**

Sampled by client

Water Analyses Report

Irrigation evaluation

Origin	Lab. Nr.	pH @ 25°C	EC @ 25°C mS/m	Na mg/l	K mg/l	Ca mg/l	Mg mg/l	Fe mg/l	Cl mg/l	CO_3^{2-} mg/l	HCO_3^- mg/l	SO_4 mg/l	B mg/l	Mn mg/l	Date tested	OP* (kPa)	Adj. SAR	Langelier index	Class	Temperature at reception (°C)
KW	6339	7.4	92.9	101.2	16.9	67.2	10.3	0.1	129.0		235.0	69	0.08	<0.03	Unknown	33.4	3.7	0.0	C3-S1	10.8
EK5	6340	6.9	95.2	105.1	17.8	69.7	9.8	0.1	121.0		272.0	69	0.09	<0.03	Unknown	34.3	4.0	-0.4	C3-S1	10.5
EL1	6341	7.1	95.9	109.6	7.3	59.1	18.4	0.1	159.0		291.0	49	0.09	<0.03	Unknown	34.5	3.9	-0.2	C3-S1	10.6
EK19	6342	7.3	108.8	119.4	13.9	72.2	17.8	0.1	191.0		241.0	81	0.08	<0.03	Unknown	39.2	3.9	0.0	C3-S1	10.8
FGY2	6343	7.4	102.8	95.0	10.7	90.3	15.1	0.1	112.0		308.7	56	0.12	<0.03	Unknown	37.0	3.3	0.3	C3-S1	10.7
Lentegeur G00139	6344	7.4	222.5	297.7	2.1	132.2	29.7	0.1	485.0		471.0	59	0.14	<0.03	Unknown	80.1	8.6	0.6	C3-S2	10.3
UWC 3B	6345	7.6	50.0	16.9	2.0	89.8	5.2	0.1	25.0		290.0	29	<0.08	<0.03	Unknown	18.0	0.7	0.4	C2-S1	10.8
Additional Sample 1	6346	7.3	91.0	96.8	7.4	59.1	16.6	0.1	132.0		282.0	47	<0.08	<0.03	Unknown	32.8	3.5	0.0	C3-S1	11.1
UWC 3A	6347	7.4	26.5	7.2	1.3	46.1	1.8	0.1	13.0		154.0	12	<0.08	<0.03	Unknown	9.5	0.3	-0.3	C2-S1	11.8
Norm		5.5-9.0	270.0	70.0				1.5	100.0		150.0		1.00	10.00				-0.5-0.5		
Method nr.		3136	3135	3132	3132	3132	3132	3132	3138			3132	3132	3132						

See analyses interpretation for assistance with interpreting the report and relevance of each analyses.

The classification of the water has the following meaning:

C2: Medium salinity water - Can be used for irrigation if a moderate amount of leaching is allowed.
C3: High salinity water - Cannot be used on soils with restricted drainage. Crops with good salt tolerance should be selected.
S1: Low sodium water - Can be used for irrigation on almost all soils with little danger.
S2: Medium sodium water - Will present an appreciable sodium hazard in fine textured soils unless gypsum is present in the soil.

Comments:

With sodium concentrations greater than 200 mg/l severe problems with sodium toxicity is expected. The water is not suitable for irrigation.

With chloride concentrations greater than 150 mg/l problems could be expected with chlorine toxicity on pome and stone fruit. Better results could be obtained with fruit trees such as figs and olives which can tolerate higher concentrations.

With chloride concentrations greater than 200 mg/l severe problems with Cl toxicity is expected. The water is not suitable for irrigation.

Langelier index:

\\172.17.48.240\bemlab\bemlims\reports\2016\water\word\wt006339_a.doc **Hierdie laboratorium neem deel aan die Agrilasa gehalte en SABS water toets skema** Bladsy 1 van 2

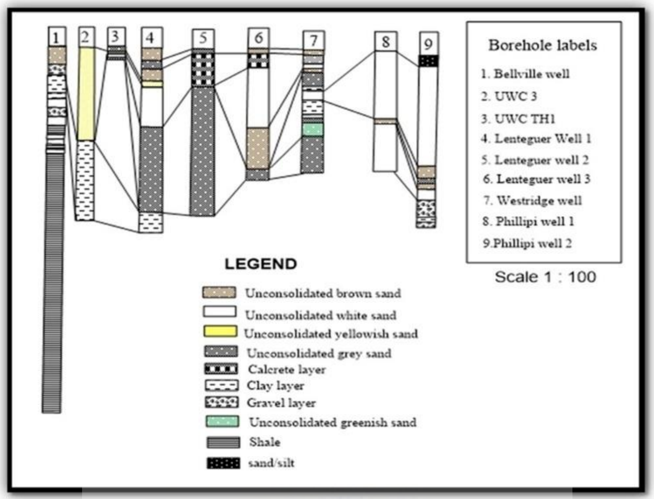
Appendix G: Lithological Units

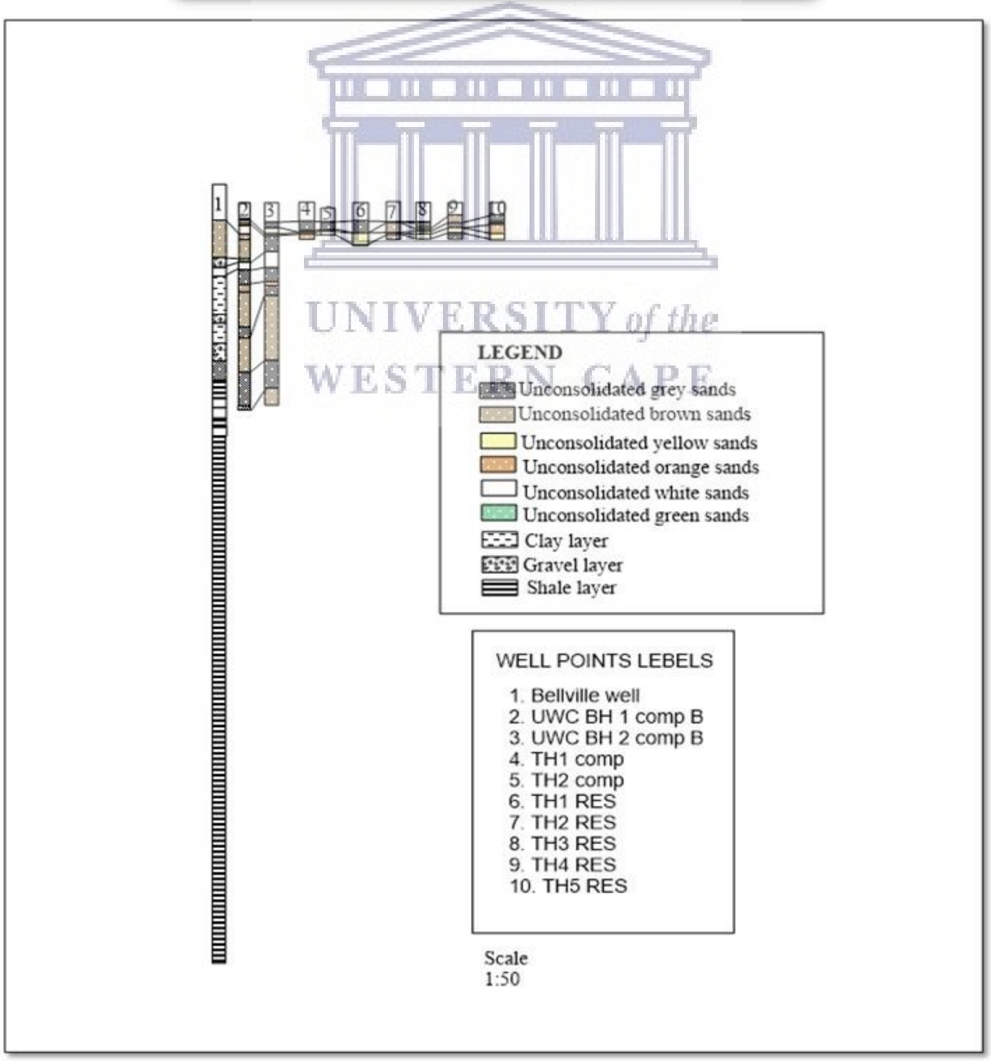
Geo, Water Affairs - Western Cape	3318DC00262	Well Point	-33.97828	18.59787	Lithology Depth	Lithology Name
Geo, Water Affairs - Western Cape	3318DC00262	Well Point	-33.97828	18.59787	0	Sand
Geo, Water Affairs - Western Cape	3318DC00262	Well Point	-33.97828	18.59787	3	Clay and Sand
Geo, Water Affairs - Western Cape	3318DC00262	Well Point	-33.97828	18.59787	0	Sand
Geo, Water Affairs - Western Cape	3318DC00262	Well Point	-33.97828	18.59787	3	Clay and Sand
Geo, Water Affairs - Western Cape	3318DC00262	Well Point	-33.97828	18.59787	0	Sand
Geo, Water Affairs - Western Cape	3318DC00262	Well Point	-33.97828	18.59787	3	Clay and Sand
Geo, Water Affairs - Western Cape	3318DC00262	Well Point	-33.97828	18.59787	0	Sand
Geo, Water Affairs - Western Cape	3318DC00261	Well Point	-33.97773	18.59926	0	Sand
Geo, Water Affairs - Western Cape	3318DC00261	Well Point	-33.97773	18.59926	4	Clay
Geo, Water Affairs - Western Cape	3318DC00261	Well Point	-33.97773	18.59926	0	Sand
Geo, Water Affairs - Western Cape	3318DC00261	Well Point	-33.97773	18.59926	4	Clay
Geo, Water Affairs - Western Cape	3318DC00264	Well Point	-33.97495	18.59732	0	Sand
Geo, Water Affairs - Western Cape	3318DC00264	Well Point	-33.97495	18.59732	3.5	Calcrete
Geo, Water Affairs - Western Cape	3318DC00264	Well Point	-33.97495	18.59732	0	Sand
Geo, Water Affairs - Western Cape	3318DC00264	Well Point	-33.97495	18.59732	3.5	Calcrete
Geo, Water Affairs - Western Cape	3318DC00264	Well Point	-33.97495	18.59732	0	Sand

Geo, Water Affairs - Western Cape	3318DC00264	Well Point	-33.97495	18.59732	3.5	Calcrete
Geo, Water Affairs - Western Cape	3318DC00264	Well Point	-33.97495	18.59732	0	Sand
Geo, Water Affairs - Western Cape	3318DC00264	Well Point	-33.97495	18.59732	3.5	Calcrete
Geo, Water Affairs - Western Cape	3318DC00265	Well Point	-33.97495	18.59759	0	Sand
Geo, Water Affairs - Western Cape	3318DC00265	Well Point	-33.97495	18.59759	0	Sand
Geo, Water Affairs - Western Cape	3318DC00265	Well Point	-33.97495	18.59759	0	Sand
Geo, Water Affairs - Western Cape	3318DC00265	Well Point	-33.97495	18.59759	0	Sand
Geo, Water Affairs - Western Cape	3318DC00267	Well Point	-33.97384	18.59454	0	Sand
Geo, Water Affairs - Western Cape	3318DC00267	Well Point	-33.97384	18.59454	3	Calcrete
Geo, Water Affairs - Western Cape	3318DC00267	Well Point	-33.97384	18.59454	0	Sand
Geo, Water Affairs - Western Cape	3318DC00267	Well Point	-33.97384	18.59454	3	Calcrete
Geo, Water Affairs - Western Cape	3318DC00267	Well Point	-33.97384	18.59454	0	Sand
Geo, Water Affairs - Western Cape	3318DC00267	Well Point	-33.97384	18.59454	3	Calcrete
Geo, Water Affairs - Western Cape	3318DC00267	Well Point	-33.97384	18.59454	0	Sand
Geo, Water Affairs - Western Cape	3318DC00267	Well Point	-33.97384	18.59454	3	Calcrete
				Rocklands Mitchells Plain		
Geo, Water Affairs - Western Cape	32987	Borehole	-34.06713	18.61068	0	NO SAMPLE
Geo, Water Affairs - Western Cape	32987	Borehole	-34.06713	18.61068	5	Sand
Geo, Water Affairs - Western Cape	32987	Borehole	-34.06713	18.61068	6	Sand

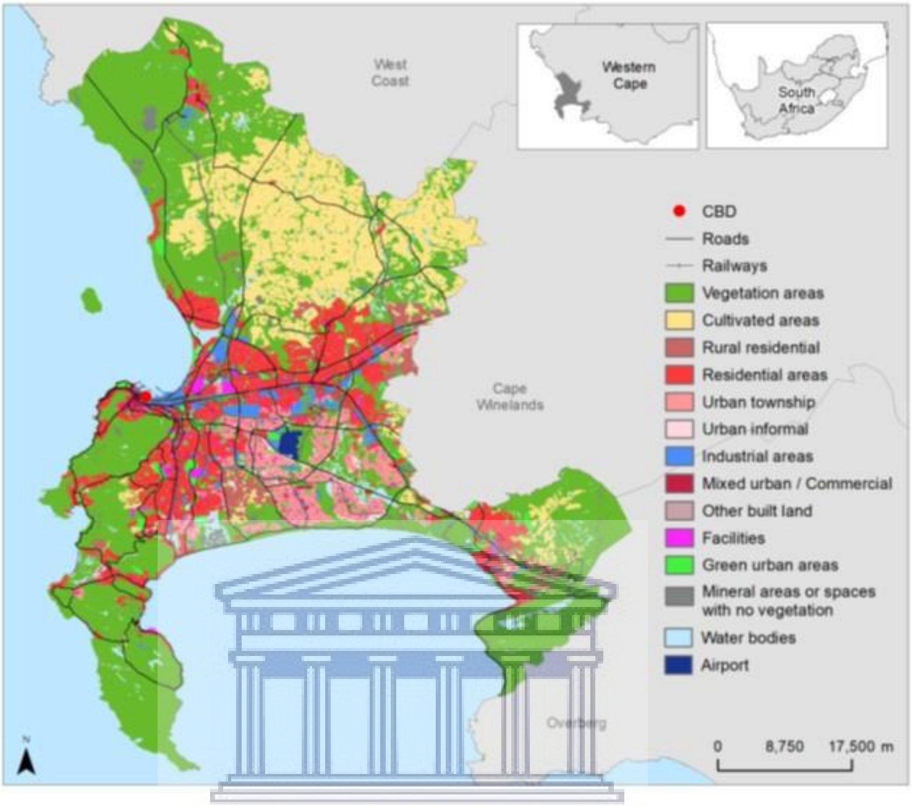
Geo, Water Affairs - Western Cape	32987	Borehole	-34.06713	18.61068	8	Sand
Geo, Water Affairs - Western Cape	32987	Borehole	-34.06713	18.61068	10	Sand
Geo, Water Affairs - Western Cape	32987	Borehole	-34.06713	18.61068	12	Sand
Geo, Water Affairs - Western Cape	32987	Borehole	-34.06713	18.61068	13	Sand
Geo, Water Affairs - Western Cape	32987	Borehole	-34.06713	18.61068	14	Sand
Geo, Water Affairs - Western Cape	32987	Borehole	-34.06713	18.61068	15	Sand
Geo, Water Affairs - Western Cape	32987	Borehole	-34.06713	18.61068	17	Sand
Geo, Water Affairs - Western Cape	32987	Borehole	-34.06713	18.61068	18	Sand
Geo, Water Affairs - Western Cape	32987	Borehole	-34.06713	18.61068	19	Sand
Geo, Water Affairs - Western Cape	32987	Borehole	-34.06713	18.61068	21	Sand
Geo, Water Affairs - Western Cape	32987	Borehole	-34.06713	18.61068	25	Sand
Geo, Water Affairs - Western Cape	32987	Borehole	-34.06713	18.61068	30	Sand
Geo, Water Affairs - Western Cape	32987	Borehole	-34.06713	18.61068	32	Sand
Geo, Water Affairs - Western Cape	32987	Borehole	-34.06713	18.61068	35	Sand

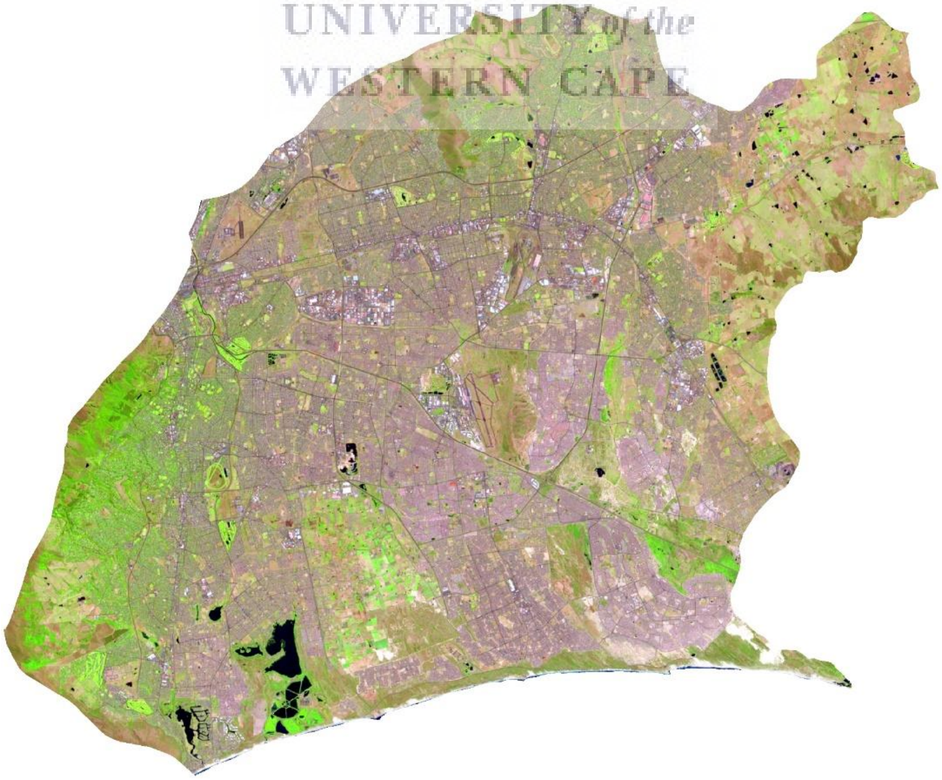
Geological logs



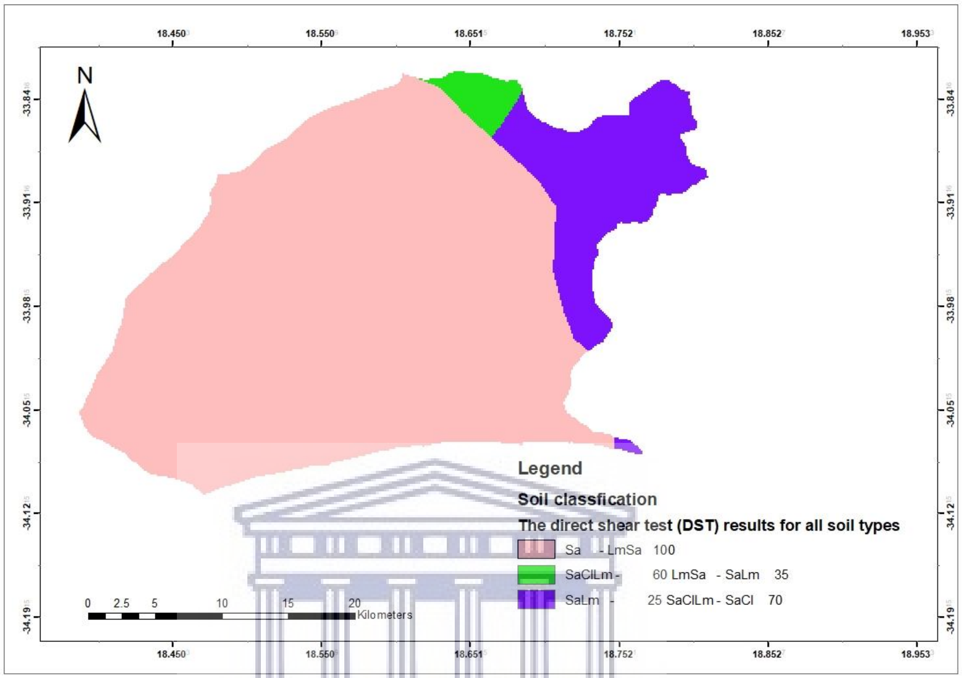


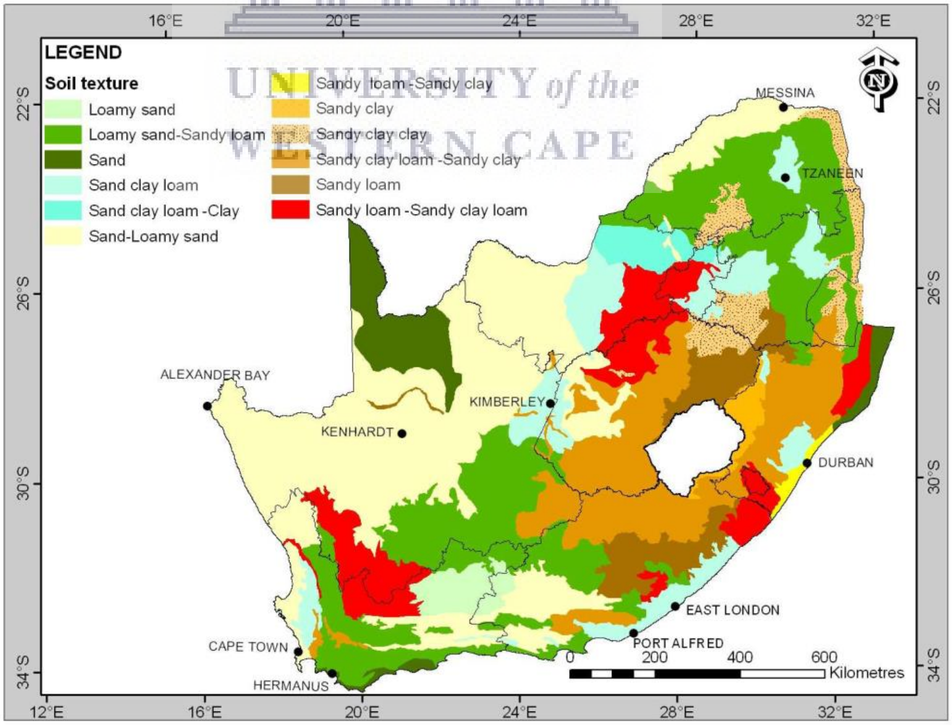
Appendix H: Land cover (Cape Town for verification)





Appendix I: Soil Data





Sources (Musekiwa and Majola, 2013)

Appendix K: Cape Flats Seawater Infiltration Monthly Flux Alteration