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Assessment of managed aquifer recharge using GIS based modeling approach in West Coast, South Africa

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A thesis submitted in fulfillment of the requirements for the degree of **Doctor of Philosophy** in the Department of Earth Sciences, Faculty of Natural Sciences at the University of the Western Cape

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ABSTRACT

Due to climate change, rapid urbanization, and population expansion, the water demand and supply is showing increasing fluctuations, especially in the arid or semi-arid regions. One of the most important water resource management strategies to improve water security in these drought-prone areas is managed aquifer recharge (MAR), which is developed to recharge groundwater purposefully and increase its storage to overcome the temporal imbalance between local water demand and availability, thus improving water security of the water supply. Assessment of an MAR project requires the integration of many types of methods, data and information from many disciplines, which makes it a challenge. This thesis addressed a GIS based modeling approach for assessing the implementation of MAR in terms of suitable sites as well as appropriate scheme in drought-prone area. The West Coast of South Africa was studied as a case.

Langebaan Road aquifer system (LRAS) and the Elandsfontein aquifer system (EAS) are the two main aquifer systems in West Coast. The most important aquifer units in the study area are the upper unconfined aquifer unit (UAU) and the (semi) confined lower aquifer unit (LAU). The conceptual model of groundwater flow was developed based on the understanding of the hydrogeological condition of the West Coat. The UAU is recharged directly from precipitation, a recharge mound for LRAS and EAS has been postulated at southwest of Hopefield. Groundwater flow in UAU is topographically controlled and occurs from the recharge mound to the Berg River or the coastline. The distribution of aquitard clay between UAU and LAU is discontinuous, and several clay- missing areas are existed in study area. The “clay- missing windows” in the vicinity of the recharge mound would facilitate the downward percolation of the water into the LAU, then groundwater flows along the palaeochannels, and finally drains toward the Berg River or the coastline.

A GIS based analysis was adopted to select the preliminary suitable sites for implementing MAR, as well as to prepare the datasets for the following groundwater flow model. The Analytical Hierarchy Process (AHP) method was incorporated in GIS analysis to develop a three-level criteria tree based on the fact that MAR project is largely dependent on the factors of source water availability, infiltration capacity, and storage capacity, thus to assist the weights determination. The results showed that the areas of west of Hopefied and north of Berg River are the suitable sites with most possibility for the implementation of MAR in both UAU and LAU of West Coast.

A modeling approach was followed to verify and optimize suitable sites which are screened out by GIS based analysis, as well as to discuss the appropriate scheme of the implementation of MAR based on the designed scenarios. Result showed that the implementation of MAR in UAU and LAU is quite different. The implementation of MAR in UAU is feasible, and the suitable sites are dependent largely on the recharging purpose. The estimated available space for MAR in LRAS and EAS is 366.2 million m^3 and 549.5 million m^3 separately. Infiltration pond is suggested to be adopted when implementing MAR in UAU, but borehole recharge is suggested to be adopted in the area where are distributed with Langebaan Formation. The clay-missing area (natural recharge area) at west of Hopefield is suitable site for implementing MAR for LAU. However, the present piezometric surface is much higher than the top of the clay layer (confining-layer), therefore there's little space in LAU to store water when implementing MAR at present. It was also concluded that GIS is very useful tool to prepare the datasets for modeling, as well as to screen out the suitable sites for the implementation of MAR. However, the role of GIS based analysis is suggested to be a preliminary tool to suitable sites assessment, and the results of which need to be verified by modeling.

On the basis of the present study, combining the GIS with groundwater flow modeling into a three- phase GIS based modeling approach that includes the conceptual model, the GIS-based analysis for selection of suitable sites for MAR supported by numerical modelling provides a reliable solution to assess the implementation of MAR in drought-prone area with water stress.

KEYWORDS

Aquifer; Artificial recharge; Geographic information systems; Implement scheme; Modeling; South Africa West Coast; Suitable sites

DECLARATION

I declare that "**Assessment of managed aquifer recharge using GIS based modeling approach in West Coast, South Africa**" is my own original work which has not been submitted to any other institution for similar purposes, and that all the sources I have used or quoted have been indicated and acknowledged as complete references.

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December, 2019
Date

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CHAPTER 1: General introduction

1.1 Study overview

The present study argues that i) suitable sites and appropriate scheme are important issues that influence the implementation of managed aquifer recharge (MAR) as solution to water shortage problems; ii) GIS based analysis is useful in the suitable sites evaluation for the implementation of MAR but results of which need to be verified and optimized by modeling; iii) modeling approach is helpful to analyze the suitable sites and implement scheme of MAR. The research seeks to develop a GIS based modeling approach for assessing the implementation of MAR. As a showcase, the thesis demonstrates how to assess the implementation of MAR in terms of suitable sites as well as appropriate scheme using GIS and modeling method in West Coast, South Africa.

1.2 Background to the study

Due to climate change, rapid urbanization and population expansion, water demand and supply show increasing fluctuations (Pachauri et al., 2014). Especially in drought-prone area, not only is the surface water facing depletion, but also groundwater in aquifer is over-exploited because of increased abstraction (Gleeson et al. 2012). The storage of water in surface reservoirs is widespread but it has several disadvantages such as high evaporation losses, large land area requirements, sediment accumulation, the possibility of structural failure and high vulnerability to contamination (Bouwer, 2002; Maliva and Missimer, 2012). An alternative to the surface storage is to store excess water underground during periods of low demand or high availability through MAR (David and Pyne, 2005; Händel et al., 2014).

MAR is the intentional recharge of an aquifer for later recovery or environmental benefits and represents a valuable method for sustainable water resources management (Dillon et al., 2009; Ringleb et al., 2016). Therefore, MAR is able to increase groundwater storage and overcome the temporal imbalance between local water demand and availability thus securing drinking or irrigation water supply at any time of the year. In contrast to other types of recharge such as natural or incidental recharge, the principal benefits of the concept of MAR for water management are twofold: i) it allows storage of large quantity and various sources of water (including surface runoff, stormwater, treated effluent, desalinated seawater, and even groundwater from other aquifers) at those periods of the hydrological year when availability exceeds demand and to restore them when demand exceeds availability; ii) the underground passages (unsaturated and saturated zone) can constitute a complementary treatment step, due to physical, chemical and biological processes that affect water quality.

Currently, Cape Town and its neighboring towns along the West Coast of South Africa are facing water shortage problems. The Western Cape Water Supply System, which provides water to Cape Town and the surrounding towns, is currently stretched past its limit as reviews of water use volumes in the system for both municipal supply and agricultural use showed that water use volumes are greater than the volume of water that can be supplied form the system at the current assurance of supply. Problems associated with water security in the region are further exacerbated by the occurrence of drought, population growth, urbanization and development. Thus under the great pressure from increasing water demand and decreasing water availability, the West Coast District Municipality (WCDM) together with Department of Water Affairs of South Africa (DWA) plan to implement MAR in the West Coast aquifer system with water from Berg River in rainy season and other sources.

A project entitled “Towards the sustainable exploitation of groundwater resources along the West Coast of South Africa” was funded by Water Research Commission of South Africa to get information on the viability of implementing MAR as an adaptive management strategy for augmenting the water supply to the WCDM, as well as to improve the area’s resilience to the impacts of drought. The objectives of this project include: i) to confirm the hydrogeological characteristics and dynamics of the Langebaan Road aquifer system (LRAS) and the Elandsfontein aquifer system (EAS); ii) to determine the natural recharge areas of the aquifer units; iii) to investigate the potential for implementation of a managed aquifer recharge scheme for additional storage of water, as well as the best possible MAR method to be used in this area; iv) to develop a management plan for the LRAS and the EAS; also to design an optimized monitoring network for the aquifer systems. This project is implemented jointly by the Council for scientific and industrial research (CSIR), Department of water and sanitation of Western Cape (WCDWS), and University of the Western Cape (UWC).

The present study is part of the Water Research Commission funded project, and make contributions to the third objective of the project, which is to assess the implementation of managed aquifer recharge in terms of suitable sites and appropriate scheme.

1.3 Problem statement

Given consideration on increasing water demand at the strategic port of Saldana Bay and the rapidly growing holiday and residential status of Langebaan Lagoon area, the plan of implementing MAR at West Coast was first initiated in 2007 (DWAF, 2007a). Subsequently, two borehole injection trials were conducted in the aquifer between September 2008 and March 2009 (Tredoux and Engelbrecht, 2009). However, in order to eliminate the high cost of pipeline construction, the injection boreholes were drilled in the WCDM well field instead of ideal sites. Two weeks after the injection, several boreholes in the downstream area were over flowing (DWA, 2010a), which showed that the injection recharge at the WCDM well field failed to keep water stored underground as initially expected. Therefore, despite of the fact that some attempts on MAR have been made to the aquifers of West Coast, the issues of suitable sites and appropriate scheme which are of utmost importance for the correct functioning of the MAR system are still unknown.

Based on the problem stated, the research questions addressed in the thesis are:

i) Where are the suitable sites for the implementation of MAR?

ii) What is the appropriate implement scheme of MAR?

iii) How to assess the implementation of MAR?

1.4 Study aim and objective

Based on the research questions, the main objective of this study is to assess the implementation of MAR in terms of suitable sites and appropriate scheme using data that is routinely collected together with innovative use of existing analytical tools. In order to achieve this main objective, three specific objectives are considered in this study:

i) To develop the groundwater flow conceptual model of target aquifer system.

ii) To evaluate the suitable sites for implementing MAR.

iii) To assess the appropriate scheme for the implementation of MAR.

1.5 Significance of the study

Knowledge contribution through publication as follows:

i) Paper 1: Site assessment for MAR through GIS and Modeling in West Coast, South Africa.

ii) Paper 2: A modeling approach to improving water security in a drought-prone area, West Coast, South Africa.

iii) Paper 3: A review of the managed aquifer recharge: historical development, current situation and perspectives.

Another contribution of this thesis is made towards the suitable sites, appropriate scheme and further research suggestions for the implementation of MAR at the West Coast, which is helpful for decision makers. Meanwhile, the implications of the research can be applied to guide the implementation of MAR in unconfined or confined aquifers of other drought-prone areas.

The third contribution of this thesis is made towards a reliable assessment approach for the implementation of MAR using GIS based modeling analysis.

The fourth contribution of this thesis is made towards to the application of MAR for the improvement of water security in drought-prone areas thus has beneficial impacts on society.

1.6 Conceptualization of the study

The primary objective of the thesis is to assess the implementation of MAR using GIS and modeling as analytical tools. GIS has the virtue of strong spatial data analysis ability, which is suitable for MAR analysis. Recharge through MAR and abstraction for use are able to be taken as source and sink items of water balance calculation, such consideration lays the foundation of assessment of MAR using groundwater flow modeling in that several softwares (e.g., MODFLOW) are developed based on source and sink theory. A case study approach was adopted using West Coast of South Africa. Firstly, a comprehensive desktop work was conducted on the hydrogeological setting of study area, which was followed by the field visits to groundtruth the collected data as well as the groundwater flow conceptual model. Then GIS was adopted to screen out the initial suitable sites for the implementation of MAR, as well as to prepare the datasets for the development of modeling. Finally modeling was used to verify the suitable sites mapped by GIS method, and to analyze the implement scheme of MAR based on scenario simulation.

1.7 Outline of the thesis

Chapter 1 provides the general introductory aspects of the research in terms of background, problem statement, research question, research objectives, significance and outline of the study.

Chapter 2 describes the literature review from various readings on managed aquifer recharge, relevance of groundwater flow conceptual model to assess MAR, evaluation of suitable sites for MAR, and assessing appropriate schemes for implementing MAR among other aspects.

Chapter 3 describes hydrogeological conditions of West Coast, which lays the foundation of developing groundwater flow conceptual model in Chapter 5.

Chapter 4 describes the methods that were used to collect and analyze the needed data to answer the research questions thereby fulfilling the objectives for this study. This chapter argues that detailed description on research design, methods for data collection and analysis, quality assurance and research integrity.

Chapter 5 addresses the groundwater flow mechanism of study area, as well as the development of the groundwater flow conceptual model.

Chapter 6 presents the suitable sites of MAR which are mapped by GIS based method. The suitable sites of both unconfined aquifer and confined aquifer are discussed.

Chapter 7 demonstrates the results of applying modeling technique to verify and optimize the suitable sites mapped by GIS based analysis, and then the influence and appropriate scheme of implementing MAR in both unconfined aquifer and confined aquifer are discussed based on the designed scenario analysis.

In Chapter 8, the results of the studies are synthesized and discussed to bring forth specific ideas towards the assessment of implementation of MAR in West Coast and other drought occurring area. Then the detailed procedure of three-step GIS based modeling approach is put forward.

In Chapter 9, conclusions are drawn and recommendations are put forward.

CHAPTER 2: Literature Review

2.1 Introduction

The current chapter describes the review from various readings on managed aquifer recharge. The review focused on previous studies of MAR, relevance of groundwater flow conceptual model to assess MAR, evaluation of suitable sites for MAR, assessing appropriate schemes for implementing MAR among other aspects. A review paper has been produced which has provided detailed historical, development and technologies on MAR. The present chapter provides a brief review on key aspects of MAR in a systematic and analytical perspective to unravel the gap in knowledge and practice about MAR.

2.2 Previous studies on MAR

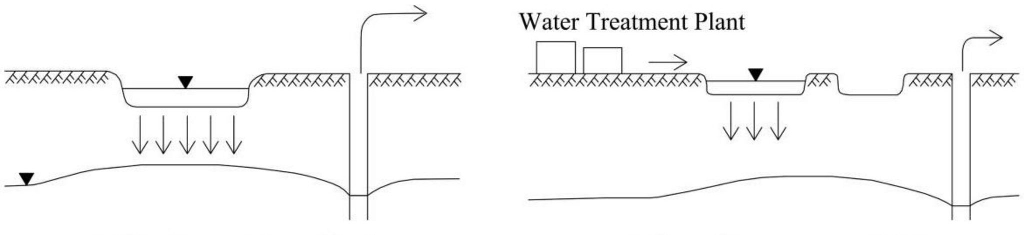
As managed aquifer recharge techniques involve the intentional subsurface recharge and storage of water into an aquifer for subsequent recovery or for environmental benefits, they have the potential to alleviate water crises. Vast researches including hundreds of scientific journal articles, management reports and technical assessments, have been carried out so far to cover the entire scope of MAR.

MAR (including its prototype) and its application experience a long history (Hsieh et al., 2010). The initial prototype of MAR can be dated back to 221 B.C. in China (Wang et al., 2014). Besides the name of managed aquifer recharge, there are several other names for MAR, such as artificial recharge, enhanced recharge and water banking (Dillon, 2005). Previously the term “artificial recharge” was most common, which dated back to the early investigator Richert (1900) who described it as “underground” water recharged by human activities. Some authors suggested that “artificial recharge” falsely implied that a somehow artificial process occurred, which could be misleading because the purification in the subsurface relied on natural processes. Later on, an initial concept of “management aquifer recharge”, which refers to Management of Aquifer Recharge and Subsurface Storage, was proposed by Tuinhof et al. (2003) early this century. The term “managed aquifer recharge” was first coined by Ian Gale in 2005 (Gale and Dillon, 2005). Since “managed aquifer recharge” implies that risks are managed in a quantitative way, MAR becomes gradually prevalent (Pervin, 2015).

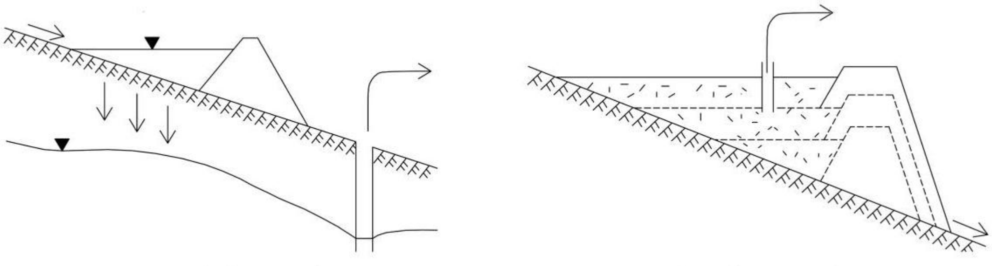
The last several decades has seen unprecedented groundwater extraction and overdraft as well as development of new technologies for water treatment that together drive the advance in intentional groundwater replenishment known as managed aquifer recharge (Dillon et al., 2018). The United Nations Educational, Scientific and Cultural Organization (UNESCO) summarized the experiences of MAR all over the world and extracted the successful examples of different types of MAR (Gale and Dillon, 2005). Several updated overviews of MAR techniques were also described by Grützmacher and Sajil Kumar (2012), by Pervin (2015) and by Sprenger et al. (2017). According to the literature, the MAR technologies are classified based on the recharge and storage technique into five major categories. These are spreading methods, in-channel modifications, recharge by well, shaft and boreholes, induced bank filtration, and runoff harvesting (Table 2-1, Figure 2-1).

Table 2-1 MAR technologies and their applications (after Gale and Dillon, 2005; Pervin, 2015).

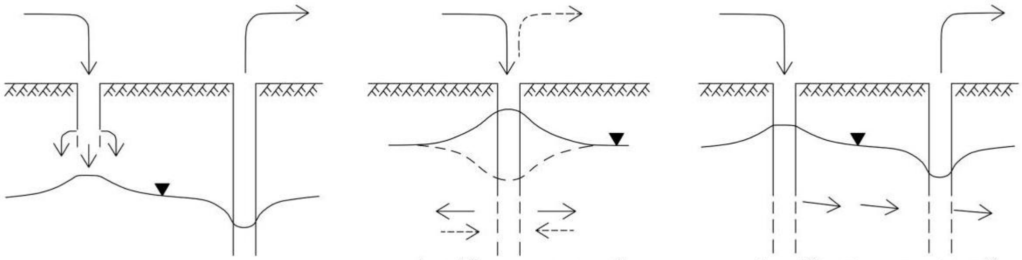
MAR types	MAR sub-types	Applications
Spreading methods	Infiltration ponds and basins; Soil aquifer treatment (SAT); Controlled flooding; Excess irrigation, ditches, trenches, sprinkler irrigation.	Where the unconfined aquifer to be recharged is at or near to the ground surface. Aquifer type: alluvium, sandstone and sometimes carbonate aquifers.
In-channel modifications	Percolation ponds; gabions, among others; Sand storage dams; Subsurface dams; Leaky dams and recharge releases.	Where it runs off in order to have water retention and storage. Especially used for flooding events.
Well, shaft and borehole recharge	Open wells and shafts; Aquifer storage and recovery (ASR); Aquifer storage, transfer and recovery (ASTR).	Where impermeable layer lies above the aquifer. Aquifer type: deep and clay covered aquifers.
Induced bank infiltration	Bank filtration; Dune filtration.	Where close to a surface water body, lowering the water pressure at the lake or river bank, and inducing the water to infiltrate into the aquifer. Aquifer type: Dry rivers with (subsurface) dams/sand dams or at perennial rivers or streams with adjacent permeable sand layers.
Run off / Rainwater harvesting	Rainwater harvesting; Rainwater recharge from open spaces.	Where runoff can be collected for productive use.



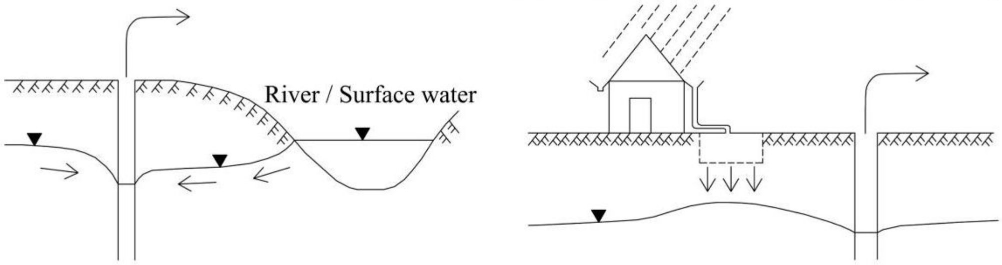
Infiltration ponds and basins Soil aquifer treatment (SAT)



Percolation ponds Sand storage dams



Open wells and shafts Aquifer storage and recovery (ASR) Aquifer storage, transfer and recovery (ASTR)



Bank filtration Rainwater harvesting

Figure 2-1 Schematic of types of the common MAR techniques (after Dillon, 2005; Grützmacher and Sajil Kumar, 2012).

A MAR process can be divided into four stages from an engineering aspect, including planning, investigation, design and construction, as well as operation (ASCE, 2001). And in each stage, several key elements should be taken into account. Elements including sources of recharge water, ultimate uses of recovered water and regulations are best to be taken into account at the planning stage; Hydrogeology is reasonable to be considered at investigation stage; Recharge site, recharge method, water quality control should be taken into account at design and construction stage; While water recovery as well as monitoring and maintenance are elements that should be considered at the operation stage. Once all these stages together with their elements processed correctly, a MAR project would be implemented successfully. Figure 2-2 shows a proposed process for the implementation of MAR.

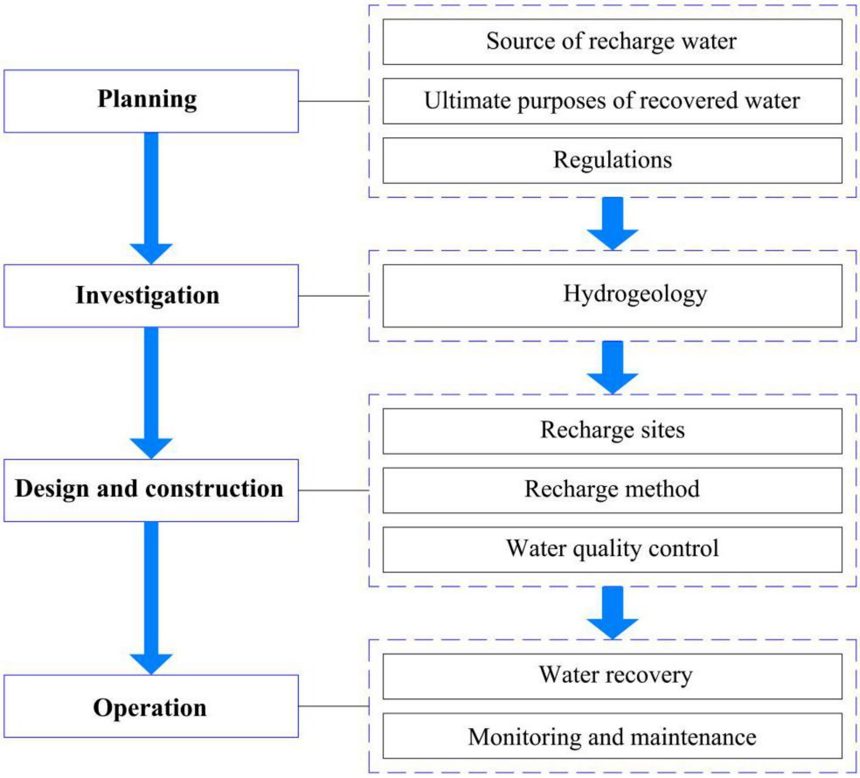


Figure 2-2 A proposed process for MAR implementation, showing varied elements should be taken into account at different stages (modified from Yuan et al., 2019).

According to the database of Global MAR Sites and Regional MAR Suitability Maps (IGRAC, 2016a), there have been 1104 MAR sites registered globally up to now. The most popular application is well, shaft and borehole recharge, with the number of 339, accounting for 30.7% of the total applications; followed by is spreading methods, with the number of 318, accounting for 28.8%; then is in-channel modification and induced bank infiltration, and the least is run off/ rainwater harvesting (Figure 2-3).

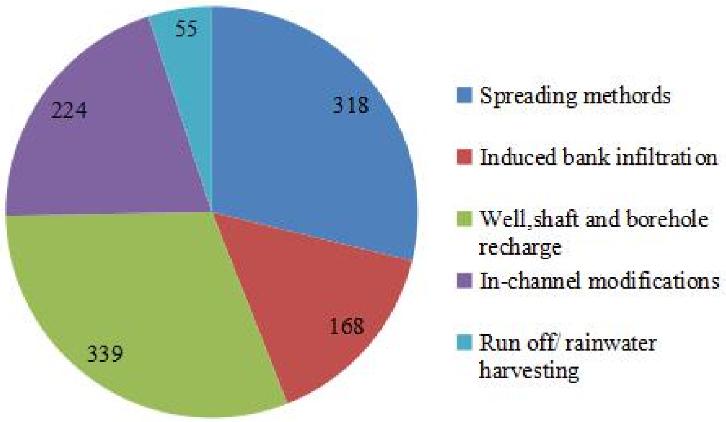


Fig. 2-3 Registered MAR sites in the world, showing the most popular application is well, shaft and borehole recharge, followed by is spreading methods. These two MAR technologies account for 59.5 % of the total applications (data sourced from IGRAC, 2016a).

Among all the sites from IGRAC (2016a) database, 946 sites show their final uses. Domestic use is the most popular application, which is 567, accounting for 59.9%; followed by the agricultural use, which is 235, accounting for 24.8%; then 85 of these applications are for ecological and environmental protection, accounting for 9%; 43 sites are for industrial use, accounting for 3.9% (Figure 2-4).

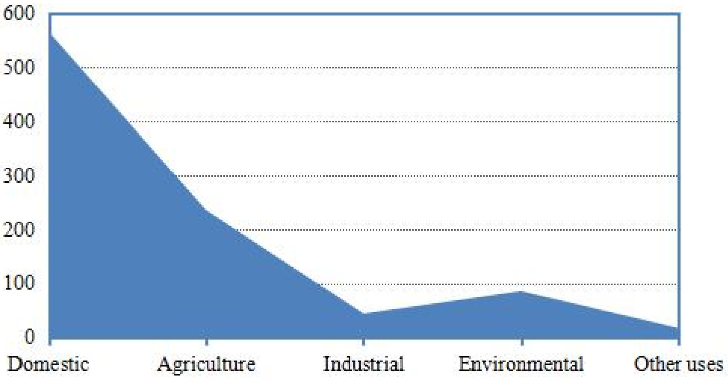


Fig. 2-4 The uses of the MAR applications from IGRAC (2016a), showing domestic water supply is the most important use direction, followed by agriculture and environmental uses.

Although numerous studies have been carried out to cover the entire scope of MAR, still some knowledge gaps are existed for further research. One challenge lies at the theory of description of water flow of MAR. For example, the infiltration theory is mainly concerned with the water flow in vadose zone, while the traditional theory of flow in pumping well is difficult to solve the flow calculation of recharge in vadose zone or pressure injection, and the source and sink theory may lead to distortion problems in some situations (Li et al., 2013). Another challenge is that the current studies lack of systematic research on clogging mechanism, thus make the established theoretical formula or model difficult to promote the application of clogging diagnostic and prevention (Kang et al., 2017).

Apart from the above mentioned knowledge gaps, another challenge to meet is that the complexity of site-specific hydrogeological conditions and the processes occurring at various scales combined with different objectives require a very good understanding of the system's response to the proposed measures (Stefan and Ansems, 2016). From the literature, three main research methods are distinguished: field experiments, laboratory experiments and modeling. The characterization of the hydrogeological conditions including aquifers distribution and their parameters is best investigated by field experiments (Maliva et al., 2015), however, the heterogeneous structure of hydrogeology as well as high expenses limit its application. Laboratory experiments are used to investigate occurring processes in detail but are limited in representing boundary conditions and scale-related issues. Modeling can be used for scenario analysis and future predictions to compare different MAR techniques and operational schemes. Despite adaptive approaches for example using trial and error, modeling is a valuable tool to estimate the feasibility of a MAR method at a given location. However, building up a calibrated model takes up time and requires a detailed data set, furthermore, modeling does not always lead to success and despite that fact, failures are hardly ever published (Ringleb et al., 2016). Since mono analysis method has its advantages and disadvantages, the combination of these methods is hopefully to provide a more reliable assessment approach.

The development history of MAR in South Africa is about 40 years. In the later part of the 1970s, the Atlantis scheme near Cape Town started infiltrating storm runoff and treated waste water for the storage of water in aquifers (DWA, 2010a; 2010b; Bugan et al., 2016; Jovanovic et al., 2017). DWAF (2007a) published a national artificial recharge strategy aimed at promoting the use of subsurface storage of water as part of integrated water resource management, wherever technologically, economically, environmentally and socially feasible in South Africa. The strategy captured existing knowledge on the topic, the applicable legislation, planning and implementation requirements/criteria, and proposed management interventions and areas which require further research. DWA (2010a) published a report which focused on artificial recharge assessments that were undertaken during the roll-out of the artificial recharge strategy, namely Prince Albert and Plettenberg Bay. It also summarized the other studies that were undertaken during the roll-out project, namely those at Sedgefield, Hermanus and in the Vermaaks River Valley near Oudtshoorn, as well as the borehole injection tests carried out at the LRAS of West Coast. Brief summaries have been included on other areas where artificial recharge has been proposed, like the sand dams of the Limpopo and Mpumalanga Provinces, the Lephalale artificial recharge assessment, and the Kenhardt and Kathu proposals.

It can be conclude from the literature that MAR is becoming the emerging-darling of solution to water shortage problems in South Africa. In particular, the Atlantis MAR scheme, which is about 40 kilometers southeast of the Elandsfontein aquifer system, provides a good reference to the implementation of MAR in study area.

2.3 Development of groundwater flow conceptual model

Models are of fundamental importance in most scientific investigations and have become one of the principal tools of modern applied science (Silvert, 2001), which range from physical or imaginary objects to three-dimensional structures, descriptions, equations or combinations of several of these groups. A theory-based description that represents the phenomena being studied founded on a set of variables with logical and quantitative relationships is termed a conceptual model. The procedure whereby hydrogeologists interpret the available information to produce an adequate description of a groundwater system is called developing groundwater flow model or conceptual modeling and applies to all scales of hydrogeological work (e.g., Rushton, 2003).

The development of a conceptual model is the fundamental approach used in all hydrogeological assessments ranging from simple desk studies to complex large-scale investigations. It is an iterative process involving the re-evaluation of the interpretation as new information is obtained until an adequate understanding of the system has been developed to meet the needs of the task in hand. Because a complete reconstruction of field system is not feasible, the conceptual model should be kept as simple as possible while retaining sufficient capacity to adequately represent the physical elements of the hydrological behavior. In the generic sense, the basic components of a conceptual model are the sources of water to the study area and sinks of water from the study area, the physical boundaries of the region, the groundwater flow and solute-transport parameters, and the distribution of hydraulic properties within the study area.

Some forms of structured approaches to system interpretation based on scientific reasoning and an understanding of geology have been used since the earliest days of applied hydrogeology (Mather, 2004). However, formal “conceptual modeling” as such has only begun to be discussed in hydrogeological textbooks in recent decades. Bear and Verruijt (1987) provided definition and list of contents for a conceptual model in 1987. Then a number of textbooks provided some guidance (e.g., Rushton, 2003; Younger, 2007) although none is in sufficient detail to act as an instruction manual. Guidance on conceptual modeling as a precursor to a large-scale mathematical model-based study is provided in Environment Agency of United Kingdom publications (EAUK, 2001), written primarily as a guide for regional-scale investigations and would be difficult to apply to smaller-scale projects. Brassington and Younger (2010) put forward a framework of developing hydrogeological conceptual model for all scales of hydrogeological investigations, which include eight steps for developing the groundwater conceptual model. These steps are: i) defining the objectives; ii) defining the topography and surface water drainage; iii) defining the geology; iv) defining the aquifer framework and boundaries; v) defining groundwater flow directions; vi) defining the aquifer relationships; vii) water balance; viii) describing the conceptual model.

Associated with the knowledge of method of developing conceptual model, large quantity of papers consider the development of conceptual model as an important step before translating it into a numerical model to research the specific hydrogeological topics. Singhal and Goyal (2011) used GIS and Groundwater Modeling System (GMS) to develop conceptual groundwater flow model for tackling groundwater modeling problems of Pali Area, India.

Seleem et al. (2018) adopted remote sensing and GIS technique to develop hydrogeological conceptual model so as to manage groundwater resources in Wade El-Tumult, Egypt.

From the literature, more and more attentions have been paid on the development of groundwater conceptual model. Meanwhile, there is a trend of using muti-disciplinary approach (e.g., remote sensing, GIS, geophysics, modeling) to obtain the data and to develop the groundwater flow conceptual model, thus to serve the assessment of MAR.

With regard to the West Coast of South Africa, the primary aquifers system of it have for a long time been recognized as significant groundwater resources. In 1976 the Saldanha Subterranean Government Water Control Area was established to protect the aquifer units in the region of Saldanha for urban and industrial use. Since then, the aquifer units of West Coast have been the subject of significant hydrogeological investigations including analysis of monitoring data, groundwater isotope studies, assessment of the interaction of the aquifer systems with surface water, several numerical modeling yield assessments, and artificial recharge investigations (Seyler et al., 2016). Detailed relevance studies are shown in Table 2-2.

Table 2-2 List of key previous hydrogeological studies in West Coast area

Reference	**Type of assessment**	**Summary Content**
Timmerman, 1985a; 1985a; 1988	Groundwater resources assessment	1985: Detailed regional assessment including all key elements of a hydrogeological analysis (geology, hydrostratigraphy, delineation of aquifer units, piezometry, water quality). 1988: Numerical modeling carried out to estimate yield.
Woodford, 2002	Groundwater resources assessment	Detailed assessment of water level responses to abstraction, and these are used to build on all aspects of the regional hydrogeology from Timmerman.
Woodford and Fortuin, 2003	Groundwater resources assessment	Builds on Woodford (2002) to assess aquifer potential. Although numerical modeling for aquifer yields was not carried out, detailed assessments of aquifer potential were provided.
Saayman et al, 2004	Groundwater and surface water interaction	Includes appendices with various technical papers, borehole drilling at Langebaan. Use of geophyisics to detect groundwater discharge to lagoon.
WCDM, 2005	Monitoring / data report	Detailed analysis of monitored water level in well field and surrounding boreholes from 1998 to 2005. Also includes a summary and some update of aquifer information from Woodford, 2002 and an update on the conceptual model of the aquifer based on water level responses.

DWAF, 2007b	Groundwater resources assessment	Summarized recommendations from the resources assessment for Elandsfontein aquifer system, Adamboerskraal Aquifer System, and Papkuils Aquifer System.
WCDM, 2008	Monitoring / data report	Monitoring results (abstraction, water level, water quality) between November 2007 and April 2008, for boreholes focused around the Langebaan Well field.
DWAF, 2008	Groundwater resources assessment	Included development of conceptual and numerical model, with the aim to characterize the groundwater resource, and provide a quantitative basis for resource assessment into the future.
WCDM, 2009	Groundwater resources assessment	A critical review and summary of previous hydrogeological reports is provided (excluding DWAF, 2008c: it appears these two studies were carried out in isolation). The hydrogeological information from pre-feasibility study (DWAF, 2007) was incorporated into a numerical model, with the aim of "assessing the long-term yield of the LRAS and EAS".
Tredoux and Engelbrecht, 2009	Artificial recharge & resources assessment	Summaries previous hydrogeological investigations, and contributes to the understanding of hydraulic connectivity between aquifer systems with analyses of water level responses to abstraction. Includes numerical modeling with several aims including defining the sustainable yield of the LAU & UAU. The model appears the same as that of WCDM, 2009, ran for a 9-year time period. Five abstraction scenarios were tested to determine the "sustainability of abstraction and injection". The model scenarios are assessed in terms of the extent of draw-down, and speed of recovery.
DWA, 2010a	Artificial recharge report	Repeats key information from Tredoux & Engelbrecht, and suggests way forward. Also includes a summary of key hydrogeological unknowns for Langebaan (recharge area, recharge rates), and lists required investigations into these unknowns.
WCDM, 2011 and WCDM, 2012	Monitoring / data report	Quarterly and annual monitoring reports from 2010 to June 2013. Reports include all monitoring data (abstraction volumes, water level, water quality, rainfall), and water level trend analysis for Langebaan Road well field, and abstraction at 4 surrounding farms.
Parsons and Associates 2006; 2014	Monitoring / data report	Includes water level and pump test results, hydraulic property estimation, water quality test results, for boreholes drilled in West Coast National Park (Paaikamp borehole and R27 borehole).
Roberts and Siegfried, 2014	Geology report	Include the geology of the Saldanha, Vredenburg and Velddrif environments.
Seyler et al., 2016	Groundwater resources assessment	Summarizes previous hydrogeological investigations, use the Capture Principle approach to analyze the sustainable groundwater use of West Coast aquifers.

These studies discussed the characteristics of hydrogeological setting and groundwater flow mechanism, thus laid good foundation on the development of the groundwater flow conceptual model of West Coast. However, The Elandsfontyn Formation does not outcrop in the region, and is only known from limited deep boreholes (Roberts and Siegfried, 2014), which constrains the understanding of the aquifers system as well as the groundwater flow conceptual model.

2.4 Evaluation of suitable sites for MAR

The assessment of suitable sites, which has been defined as the evaluation of a variety of needs for the prospective location and the suggestion of an area on the basis of a proper assessment of the land, is the main issue and the prime prerequisite for a MAR scheme (Yi et al., 2010). Many factors need to be considered during the site selection process such as complex regional characteristics, heterogeneities in surface and/or subsurface characteristics, variable groundwater qualities, and other factors including political, social, and economic factors, which make the site assessment for MAR a challenge (Anbazhagan et al., 2005; Rahman et al., 2012).

Before 1990, the selection of suitable sites was mainly depending on the knowledge and experience of hydrogeologists. However, assessments are often made on a regional basis, within which there may be limited knowledge on complex surface and subsurface conditions and flows, thus identifying suitable sites for MAR and estimating the influence of these projects on groundwater levels and flows can be difficult only from personal experience.

Since 1990s, computational tools have played an important role in evaluating MAR scenarios and screening potential sites, particularly because they can be applied on regional spatial scales, allow testing of operational scenarios and hydrogeological conditions, and combined with other management options. Plenty of studies have used GIS based integration of spatial data pertinent to groundwater recharge, with data coverages being classified and weighted before combining (Saraf and Choudhury, 1998; Ghayoumian et al., 2005; Anbazhagan et al., 2005; Chowdhury et al., 2010; Sabokbar et al., 2012). In those studies, a varying number of thematic layers were considered, such as geology, geomorphology, drainage density, slope, aquifer transmissivity, water table fluctuations or depth to groundwater level, lineament density, among others. And a set of weights for the different themes and their individual features was decided based on personal judgments considering their relative importance from the artificial recharge viewpoint. Methods used for classification and weighting differ greatly from study to study, due to variations in data availability, local geology, and importance of individual datasets to groundwater recharge. There is no standard set of data coverages or weights that is used in practice. Chowdhury et al. (2010) polled a group of geologists and hydrogeologists to determine a weighting system for their GIS based recharge location assessment, and found that half the group thought equal weighting was appropriate, whereas the other half argued for variable weighting.

GIS based analysis methods are poor in dealing with uncertainty, risks, and potential conflicts; therefore there is a large possibility of losing important information, which in turn may lead to a poor decision (Bailey et al., 2003). Consequently a number of studies developed improved GIS based analysis method based on the theory and method of Fuzzy mathematics or Operational research. Multi-Criteria Decision Analysis (MCDA), which is helpful in identifying priorities and reducing the uncertainties, integrated with GIS (SMCDA) and advanced the traditional map overlay approaches for site suitability analysis (Eastman et al., 1993; Gomes and Lins, 2002). Rahman et al. (2012) developed a spatial multi-criteria decision analysis software tool, which was based on the combination of non-compensatory screening, criteria standardization and weighting, and Analytical Hierarchy Process with Weighted Linear Combination and Ordered Weighted Averaging, and got a reasonable MAR site suitability map when applied to the Querença Silves Aquifer of Portugal. Malekmohammadi et al. (2012) developed a method involving the integration of multi-criteria decision making (MCDM), GIS, and a fuzzy inference system (FIS), which was considered as an effective method in MAR site selection.

Aside from the GIS based methods, numerical modeling can also helpful to identify suitable sites for MAR, and can be used to estimate the potential benefits of MAR projects on regional hydrologic conditions under a range of future climate, water use, and management scenarios (Munevar and Marino, 1999). Russo et al. (2014) adopted GIS and numerical modeling to assess the MAR site suitability for prevention of sea water intrusion at the Pajaro Valley Groundwater Basin, California.

From the literature, GIS based methods are the most popular approaches to the evaluation of suitable sites for MAR, but few studies consider the validation of results. Meanwhile, numerical modeling is also applied to assistant the evaluation of suitable sites for MAR.

2.5 Assessing appropriate schemes for implementing MAR

The appropriate scheme is important to the implementation of a MAR project. Therefore, there is a need to determine how the impacts of MAR could vary with project location, size, and operating conditions. Some of these questions can be resolved through field testing, but small scale pilot field studies could be expensive and may provide limited spatial information. With rapid increases in computation power and the wide availability of computers and model software, groundwater modeling has become a standard tool for professional hydrogeologists to effectively perform most tasks. Groundwater flow models have been used: i) as interpretative tools for investigating groundwater system dynamics and understanding the flow patterns; ii) as simulation tools for analyzing responses of the groundwater system to stresses; iii) as assessment tools for evaluating recharge, discharge and aquifer storage processes, and for quantifying sustainable yield; iv) as predictive tools for predicting future conditions or impacts of human activities; v) as supporting tools for planning field data collection and designing practical solutions; vi) as screening tools for evaluating groundwater development scenarios; vii) as management tools for assessing alternative polices; and viii) as visualization tools for communicating key messages to public and decision-makers. Consequently, groundwater modeling is widely used to serve the analysis on MAR.

Groundwater flow and transport models have been applied to plan and optimize MAR facilities, to quantify the impact on the local groundwater, and to determine geochemical processes and the resulting recovery efficiency, as well as to assess the MAR schemes (Ringleb et al. 2016). Valley (2006) and Jha et al. (2007) applied modeling to compare different proposed recharge methods as well as sites and help to select a MAR method and evaluate its advantages and disadvantages at a proposed location. Clark et al. (2015) adopted scenario analysis to incorporate climate change and effects of urbanization into MAR scheme design to assess the reliability of urban stormwater harvesting in Salisbury, South Australia.

Kloppmann et al. (2012) published a summary of the application of groundwater models to the estimation and optimization of the performance of MAR schemes.

It can be seen from the literature that groundwater flow models have been applied to the assessment of MAR schemes, and the most popular assessment tool is MODFLOW (Ringleb et al. 2016). However, building up a calibrated model takes up time and requires a detailed dataset. Meanwhile, modeling does not always lead to success and despite that fact, failures are hardly ever published. Given the advantages and disadvantages of modeling, a model-based preliminary assessment is often recommended prior to pilot field experiments. Some countries including Australia and the USA implemented guidelines that specifically regulate the requirements for risk assessment of new MAR facilities and advise the application of modeling during the planning phase.

2.6 Understanding theoretical relevance of MAR

There are generally two theories which are related to MAR. One is the infiltration theory represented by Horton model, Kostiakov model and Philip's model, which is mainly studying the infiltration rates and infiltration potentials during the process of water flow through the soil's pores in unsaturated zone. Another is groundwater seepage theory which is mainly concerned about the groundwater flow in the saturated zone. Since the movement of recharged water in unsaturated soils is only happened during the infiltration process in terms of some types of MAR technique such as infiltration ponds and basins, it has little meaning to the principal intention of MAR which is to store water in aquifer for later recovery. Therefore, the groundwater seepage theory is more realistic to the practice of MAR.

For the description of water flow of MAR, the popular way is considering the recharge process as the reverse process of pumping represented by Dupuit formula (Eq. 2-1), Thiem formula and Theis formula, among others.

$$Q = \pi k \frac{h_w^2 - h_1^2}{\ln(r_1 / r_w)} \qquad (2\text{-}1)$$

Where: Q is the recharge rate (L^3/T); k is the hydraulic conductivity of aquifer (L/T); h_w is the water head in the recharge well (L); h_1 is water head in the piezometer (L); r_1 is the distance from piezometer to the recharge well (L); r_w is the radius of recharge well (L).

Another way to express the water flow of MAR is taking recharge and pumping as the source and sink items during water balance calculation, known as the source and sink theory. The essence of groundwater movement is the transfer process from potential energy to groundwater flow. Thus it conforms to the law of mass conservation and the law of energy conservation. The basic concept of increasing groundwater storage by MAR can be represented by the theory of water balance: The amount of water entering a control volume during a defined time period (inflow, I), minus the amount leaving the volume during the time period (discharge, Q), equals the change in the amount of water stored ($\triangle S$) in the volume during that time period.

$$\underbrace{(P+G_{in}+R_i+I_r+W_{MAR})}_{Inflow,I}-\underbrace{(R_e+G_{out}+E_l+G_{ex})}_{Outflow,O}=\Delta S \qquad (2\text{-}2)$$

Where: Inflow (I) consists of precipitation (P), lateral groundwater inflow (G_{in}), influent seepage from rivers (R_i), infiltration from other sources (I_r), managed aquifer recharge (W_{MAR}); Outflow (O) consists of effluent seepage to rivers or ocean (R_e), groundwater lateral outflow (G_{out}), evaporation losses (E_l), and groundwater extraction (G_{ex}). $\triangle S$ is the change of water storage in ground water.

The movement of recharged water can be represented by Darcy's law :

$$Q=-KA\frac{dh}{dl} \qquad (2\text{-}3)$$

Where: Q is rate of water flow (L^3/T); K is hydraulic conductivity (L/T); A is column cross sectional area (L^2); dh/dl is hydraulic gradient.

Based on the principle of water balance and Darcy's law, the groundwater flow of MAR can be represented by a finite differential equation 2-4.

$$\frac{\partial}{\partial x}(K_{xx}\frac{\partial h}{\partial x})+\frac{\partial}{\partial y}(K_{yy}\frac{\partial h}{\partial y})+\frac{\partial}{\partial z}(K_{zz}\frac{\partial h}{\partial z})-W=S_s\frac{\partial h}{\partial t} \qquad (2\text{-}4)$$

Where: K_{xx}, K_{yy} and K_{zz} are values of hydraulic conductivity along the x, y, and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity (L/T); h is the potentiometric head (L); W is a volumetric flux per unit volume and represents inflow and/or outflow of water (1/T); S_s is the specific storage of the porous material (1/L); t is time (T).

Equation 2-4 has been incorporated into the famous MODFLOW, which lays the foundation of applying MODFLOW to simulate the groundwater flow of MAR.

2.7 Critiquing the current conceptual understanding of MAR

From the literature, there are a lot of studies on natural recharge, consequently these research results of natural recharge are applied to understand the process of MAR. Figure 2-5 shows a sketch map of water flow in natural recharge and MAR, within which natural recharge from precipitation and stream as well as artificial recharge through infiltration pond and injection well are included. It can be seen that the flow mechanism of natural recharge and managed aquifer recharge is different. The flow mechanism of recharge through infiltration pond is similar with natural recharge from precipitation for the recharged water would flow through the unsaturated zone to saturated zone, but they are different in that recharge through infiltration pond is a continuous percolation process and the recharge process is always under pressure while natural recharge is always discontinous with no pressure. Due to the difference in the flow mechanism, there is imperfection in the infiltration theory of describing the groundwater flow in aquifers. In addition, the traditional theory of flow in pumping well (e.g., Dupuit formula, Theis formula) is neither to solve the flow calculation of recharge through wells in vadose zone, nor the pressure recharge; while the source and sink theory may lead to distortion problems when the diameter of recharge well is large enough or under a mixed well recharge condition (Li et al., 2013). Therefore, more research on the groundwater flow theory of MAR is needed in order to have a better understanding on the recharge process.

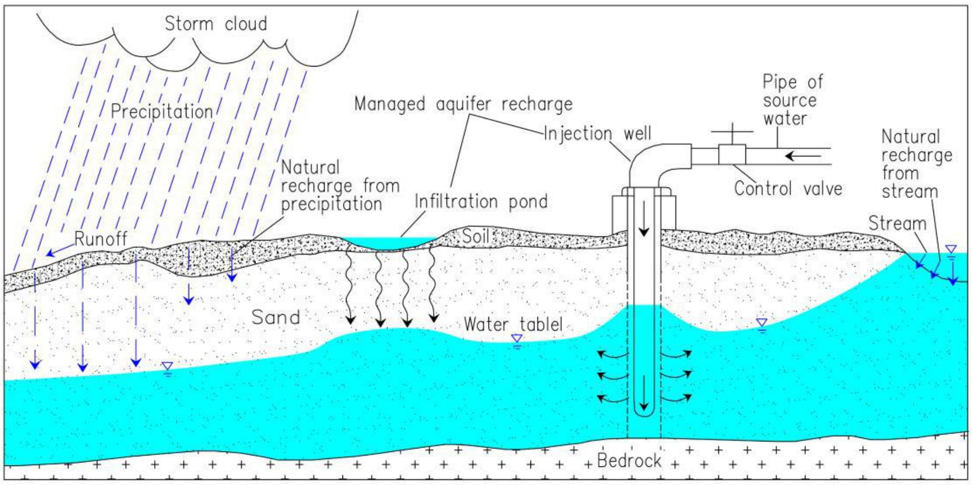


Figure 2-5 A conceptual sketch map of natural recharge and managed aquifer recharge of groundwater. Two kinds of natural recharge including recharge from precipitation and stream as well as two kinds of artificial recharge including recharge through infiltration pond and injection well are shown in this map.

For the evaluation of MAR, GIS based methods are the most popular approaches for suitable sites assessment due to its powerful spatial analysis ability, but few studies consider the validation of results; modeling is popular to the assessment of implement schemes, however, modeling is not as powerful as GIS in spatial analysis, furthermore, building up model takes up time and requires detailed dataset. Mono analysis method has its advantages and disadvantages.

2.8 Chapter summary

In this Chapter, previous studies of MAR, relevance of groundwater flow conceptual model, evaluation of suitable sites for MAR, and assessing appropriate schemes for implementing MAR are reviewed. Vast of studies have been carried out to cover the entire scope of assessment of MAR. There are varied methods to cope with the study objectives, however, computational tools play an important role in assessing MAR in terms of suitable sites as well as implement scheme. GIS is usually used to screen out the suitable sites for the implementation of MAR, while modeling is always adopted to analyze the recharge process and influence of implementing MAR thus to assess the scheme of MAR. These researches and applications lay a good foundation on the assessment of MAR.

Although a lot of researches have been carried out on MAR, there are still knowledge gaps existed. From the relevant theoretical aspect, the groundwater flow mechanism of MAR is different from either the infiltration of precipitation or the reverse process of pumping. From the perspective of practice, few studies consider the validation of GIS based analysis in the assessment of site suitability. Modeling is useful to analyze MAR, but it is not as powerful as GIS in spatial analysis, furthermore, building up model takes up time and requires detailed dataset.

CHAPTER 3: Hydrogeological background of the West Coat, South Africa

3.1 Introduction

The current chapter describes the hydrogeological condition of the West Coat, South Africa, which provides a brief view on the study area.

The study area is located between 17.8413°E and 18.7981°E, 33.5871°S and 32.6981°S along the West Coast of South Africa, which is about 100 km northwest of Cape Town city. There are mainly three catchments in study area including G10M, G10L and G21A, with the area of 4670 km^2. The area is bounded to the northwest and west by the Atlantic Ocean. Berg River is the dominant perennial river in the region, which drains northwestwards into the Atlantic Ocean at Saint Helena Bay (Figure 3-1).

3.2 Topography, drainage and land use

The topography is dominated by the underlying geology (Seyler et al., 2016); with sand dunes along coastal areas reaching up to 100 m above mean sea level (a.m.s.l), relatively flat-lying sandy plains across most of the inland area especially in the flood plain of the Berg River, and intrusive granite plutons generating koppies reaching up to 500 m amsl in the area (Figure 3-1).

The Atlantic ocean encircles the study area to the north and west side. The Berg River is the dominant perennial river in the region, lying in a broad flat plain with elevation less than 20 m amsl. The Berg River drains northwestwards into the Atlantic Ocean at St Helena Bay. The Sout and Groën Rivers (and their tributaries) drain northwards into the Berg River, with their sources in the higher relief Malmesbury Group outcrop areas of the G10L catchment.

According to the national land use mapping classification (NLC 2000, cited in DWAF, 2008), the land use is dominated by shrub land, low fynbos, and commercial cultivated land (large commercial farms). Built-up and industrial areas occur in the small towns of the area, which include Saldanha, Langebaan, Velddrif and Hopefield.

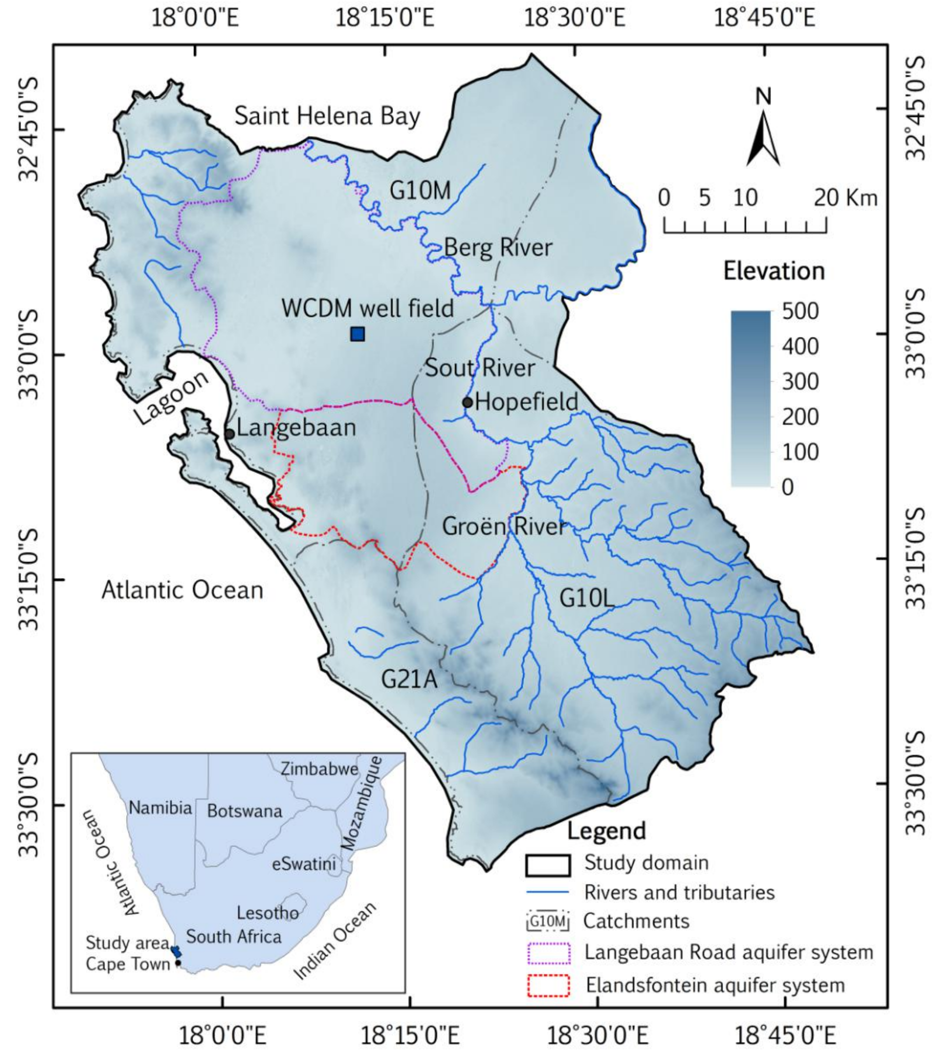


Figure 3-1 Location and topographic elevation of the study area

3.3 Hydrological setting

The climate in the region is considered as Mediterranean (DWAF, 2008). The daily temperature varies from 2.4°C to 36.8°C, with an average value of 17°C. According to the data collected from 9 rainfall stations which are distributed in the study area, the average annual rainfall varies from 200 mm in the northwest to 450 mm in the south (Figure 3-2). The rainy season is from May to August, during this time period rainfall accounts for over 60 percent of the annual amount (Figure 3-3).

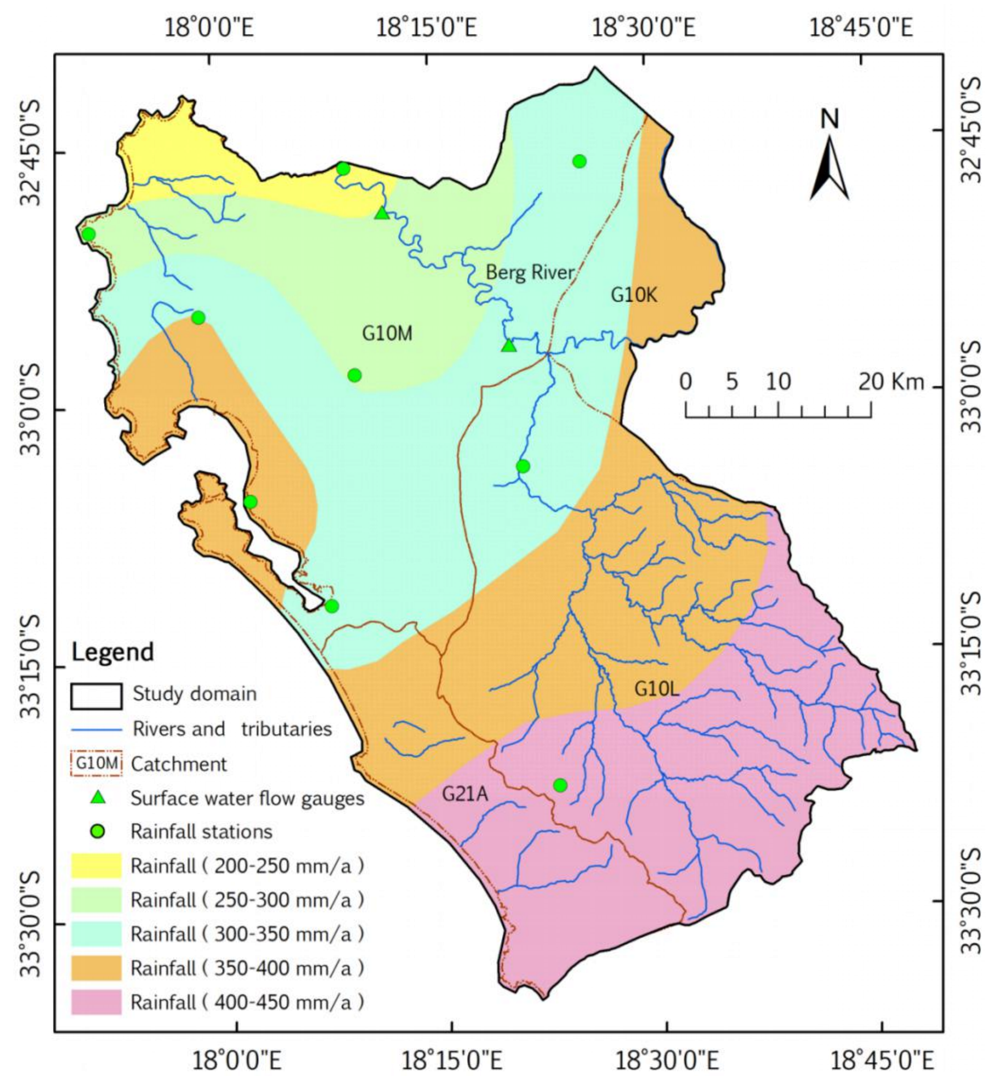


Figure 3-2 Average annual rainfall distribution of the study area from 1974 to 2017, showing average annual rainfall ranges from 200 mm/a in the north to 450 mm/a in the south.

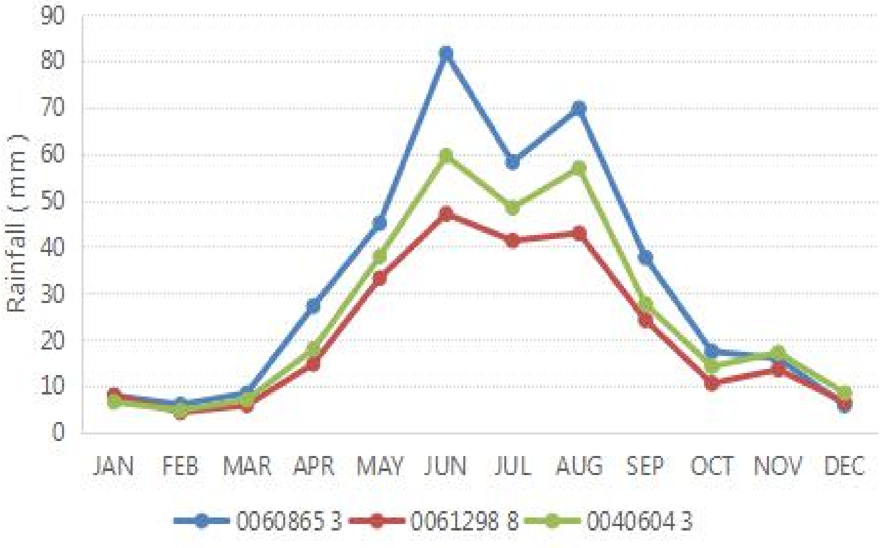


Figure 3-3 Monthly average rainfall of three rainfall stations in the study area from 1974 to 2017.

The Berg River is the dominant perennial river in the region, lying in a broad flat plain with elevation less than 20 m amsl, which drains northwestwards into the Atlantic Ocean at St Helena Bay. The Sout and Groën Rivers (and their tributaries) drain northwards into the Berg River. The monitoring data of water flow gauge G1H023, which is located about 4.3 km northwest of the junction between Berg River and Sout River, shows that the hourly water level of Berg River fluctuates from 0.46 m to 4.35 m (Figure 3-4). The water level of gauge G1H023 usually peaks during the rainy season shortly after rainfall and then falls back to less than 1 m amsl in dry season.

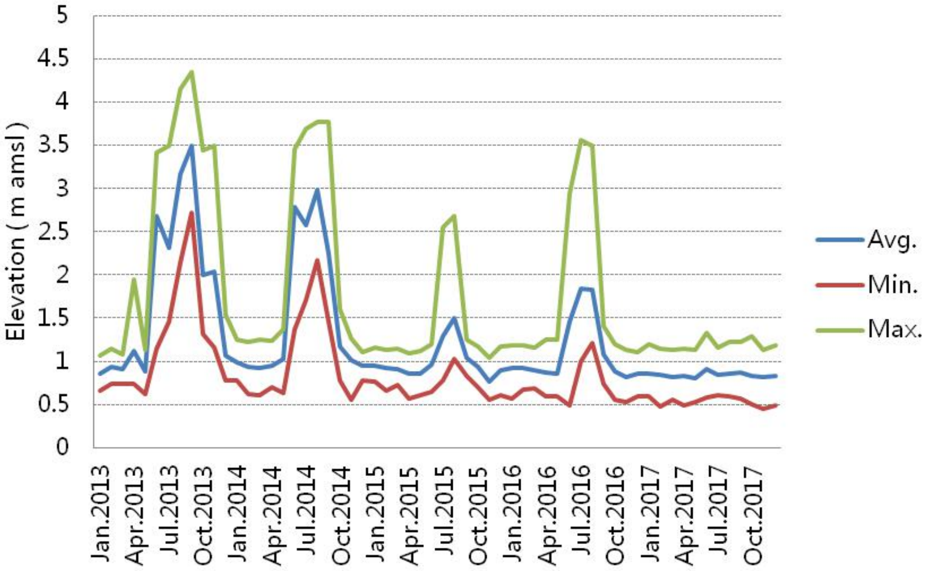


Figure 3-4 Water level of Berg River (Data from G1H023 during 2013 and 2017)

3.4 Geologic and hydrogeological setting

The predominant geology of the region is the unconsolidated Cenozoic sediments of the Sandveld Group. The underlying bedrocks are the Malmesbury Group Shale in the east and the Vredenburg and Darling Plutons of the Cape Granite Suite in the west. The inferred contact between the granite and shale of study area coincides with the Colenso Fault (Timmerman, 1985a; 1985b). The Cenozoic Sandveld Group unconformably overlies the bedrock (Figure 3-5, Table 3-1).

Palaeochannels are founded based on the geophysical and borehole investigation, which represent the palaeo-courses of previous rivers. Due to the limitation of data availability, there are divergent opinions on certain key features of the palaeo-topography. Woodford and Fortuin (2003) defined a southern Palaeochannel (the Elandsfontein palaeochannel) that was continuous towards the Langebaan Lagoon, and a northern palaeochannel (the Langebaan palaeochannel) beneath the WCDM well field, which was not continuous towards the Saldanha Bay. However, DWAF (2008) motivated that if the palaeochannels were palaeo-courses of previous rivers, they would be continuous rather than isolated depressions, and the southern and northern palaeochannels both extended to the south-west coastline (Figure 3-5). The area of the palaeochannels coincides with thick water-bearing sedimentary sequences of Elandsfontyn Formation of Sandveld Group, which is composed of poorly-sorted, angular, fine to coarse-grained quartzose sand and gravel, with variable proportions of sandy clay, clay carbonaceous clay and lignite.

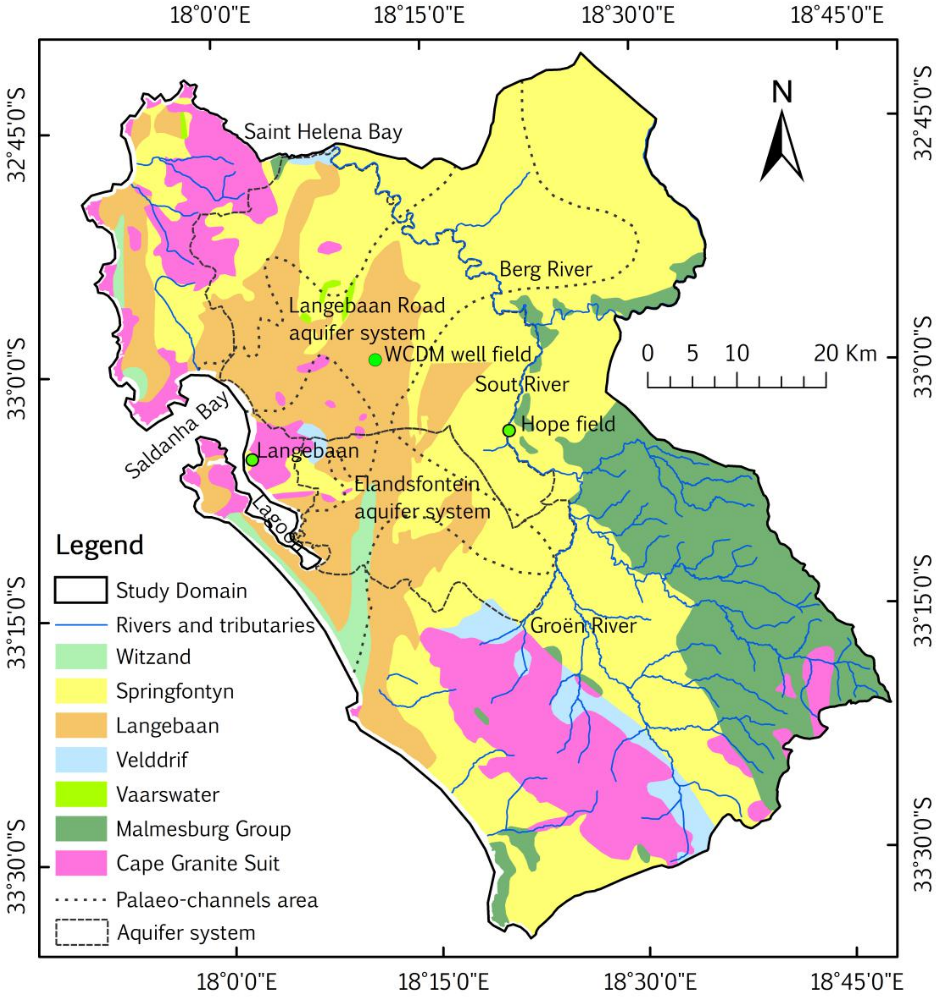


Figure 3-5 Geological map and aquifer distribution of the study area (after DWAF, 2008; Seyler et al., 2016)

Table 3-1 Stratigraphy and hydrogeological characteristics of study area (after Roberts and Siegfried, 2014; Seyler et al., 2016)

Group	Formation	Origin	Lithology	Function in aquifer system	Thickness (m)	Hydraulic conductivity Kx (m/d)
Sandveld	Witzand	Aeolian	Semi-consolidated calcareous dune sand.	Upper unconfined aquifer (UAU)	0~121.0	0.09 ~86.4
	Springfontyn	Aeolian	Clean quartzitic sands, a decalcified dune sand. Dominates in the coastal zone.			
	Langebaan	Aeolian	Consolidated calcareous dune sand. The Aeolian deposit accumulated during the last glacial lowering of sea level when vast tracks of unvegetated sand lay exposed on the emerging sea floor.			
	Velddrif	Marine	Beach sand. Associated with the last interglacial sea level rise with 6-7 m above present level.			
	Vaarswater	shallow marine, esturine, marsh and fluvial.	Deposits include a coarse basal beach gravel member, peat layers, clay beds, rounded fine to medium quartzes sand member and palatal phosphate rich deposits.			
	Elandsfontyn	Fluvia	Clays and peat in the upper sections.	Aquitard	0~84.0	4.3×10^{-5} ~2.0
			Coarse fluvial sands and gravels, deposited in a number of palaeo-channels filling depressions.	Lower (semi) confined aquifer (LAU)	0~64.5	0.1 ~70.0
Cape Granite Suite			Granites	Aquitard	/	4.3×10^{-3} ~0.26
Malmesbury Group			Metamorphosed shales			

3.5 Aquifer systems

The area of the Langebaan palaeochannel and the area of the Elandsfontein palaeochannel coincide with thick water-bearing sedimentary sequences, which have been named the Langebaan Road aquifer system (LRAS) and the Elandsfontein aquifer system (EAS), respectively (Woodford and Fortuin, 2003). The detailed distribution of these two aquifers is shown in Figure 3-6.

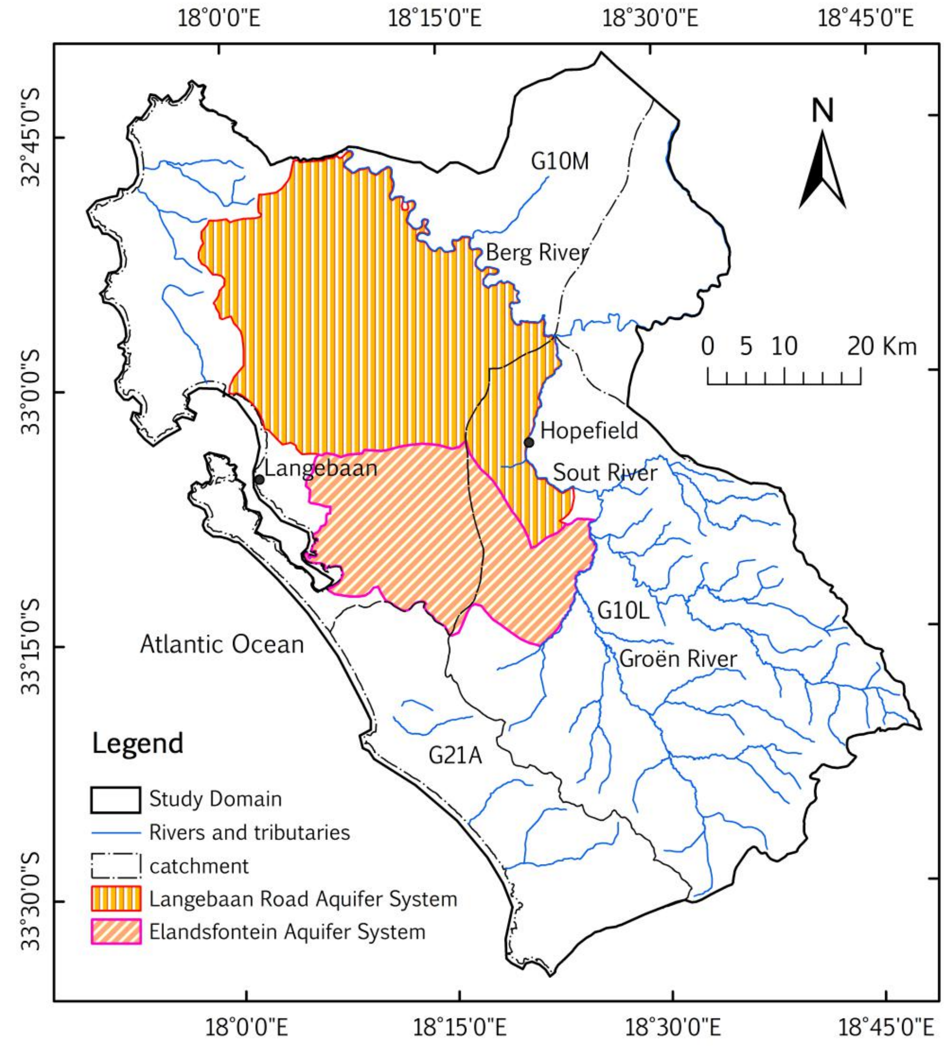


Figure 3-6 Distribution of Langebaan Road aquifer system and Elandsfontein aquifer system

The Elandsfontyn Formation of Sandveld Group is a marker layer with fluvial origin, which distributes only in bedrock depressions of palaeochannels (Roberts and Siegfried, 2014). The upper layer of the Elandsfontyn Formation include significant thickness of clay, which forms the layer of aquitard between the upper aquifer and lower aquifer (Figure 3-7).

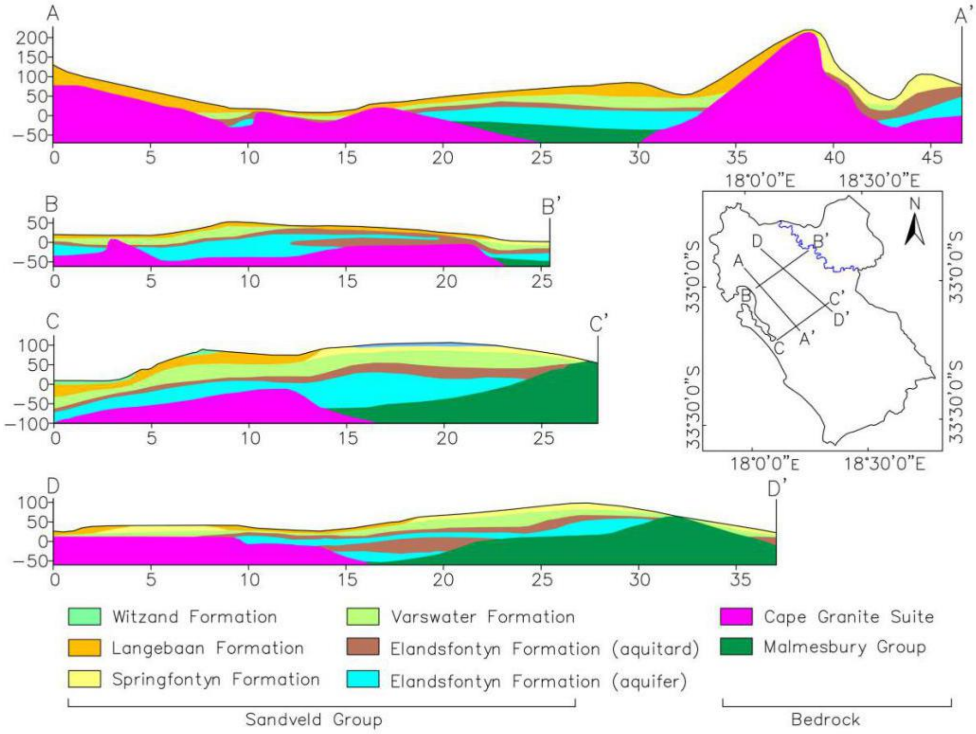


Figure 3-7 Geological cross section of Langebaan Road and Elandsfontein aquifer system (after DWAF, 2008)

The complex hydrostratigraphy of study area can be represented on the regional scale by four aquifer key units according to the vertical distribution of lithology (Timmerman, 1988; DWAF, 2008; WCDM, 2009; Seyler, 2016):

(1)The upper unconfined aquifer unit (UAU)

The variably consolidated sands and calcretes together with interbedded peat and clay of the Witzand, Springfontyn, Langebaan, Velddrif and Vaarswater Formations can be considered as a single unconfined aquifer, which form the UAU. However, Timmerman (1985b) cautioned that UAU especially in the Elandsfontein aquifer system is a very complex succession of up to four aquifer-aquitard layers at the local scale.

(2)The aquitard clay

Clay of the upper Elandsfontyn Formation acts as aquitard to (semi) confine the lower basal aquifer. DWAF (2008) considered that this clay layer distributes in a wide area over the centre of the Langebaan road aquifer system, Elandsfontein aquifer system and north of the Berg River, so that it can cover all areas of the basal gravel sediments. However, WCDM (2005) cautioned that the clay layer is not always present, and leads to indistinguishable identification of the LAU and UAU in some places. A total of 212 boreholes with logsheets from National Groundwater Archive of South Africa (NGA) were processed to piece together a map of clay distribution, which is discontinuous (Figure 3-8), and an obvious clay-missing window existed between Langebaan Road Aquifer System and the Elandsfontein aquifer system in the west of Hopefield (Figure 3-8, Figure 3-9).

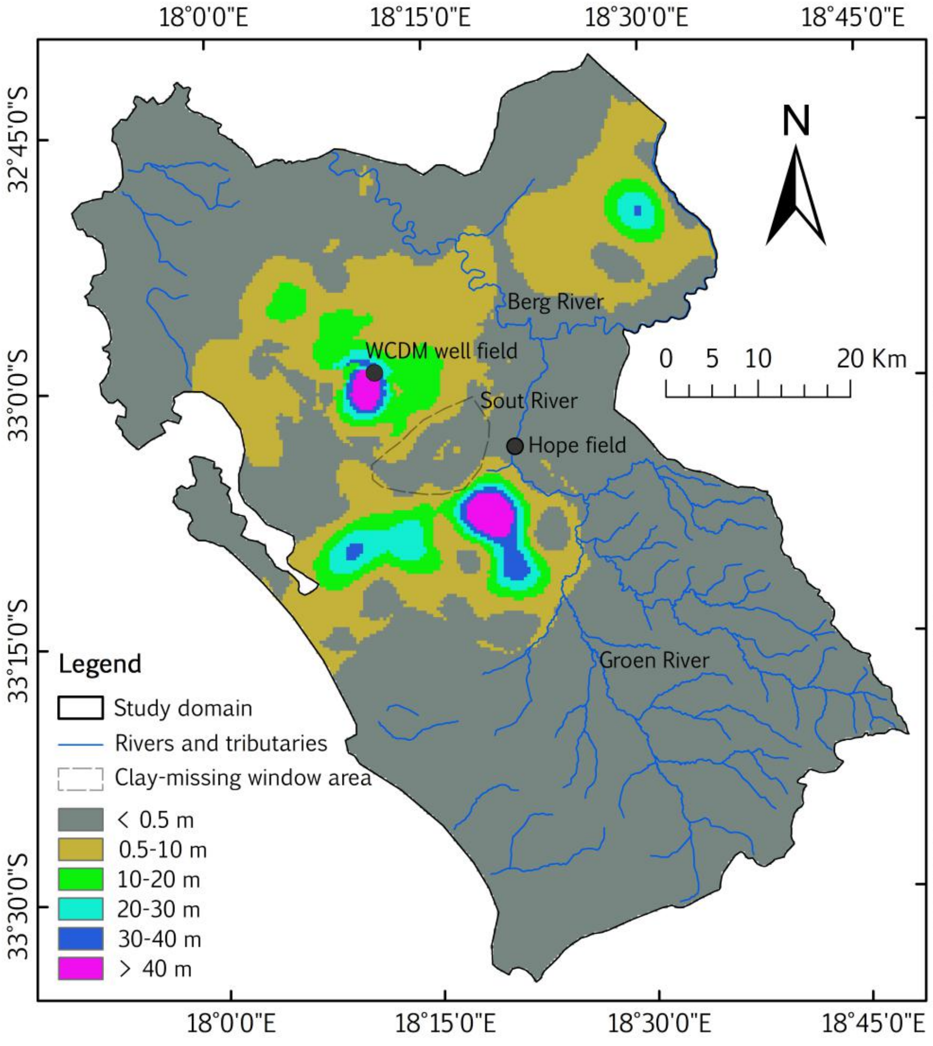


Figure 3-8 Distribution of clay from upper Elandsfontyn Formation shows the aquitard clay is discontinuous (data sourced from NGA boreholes)

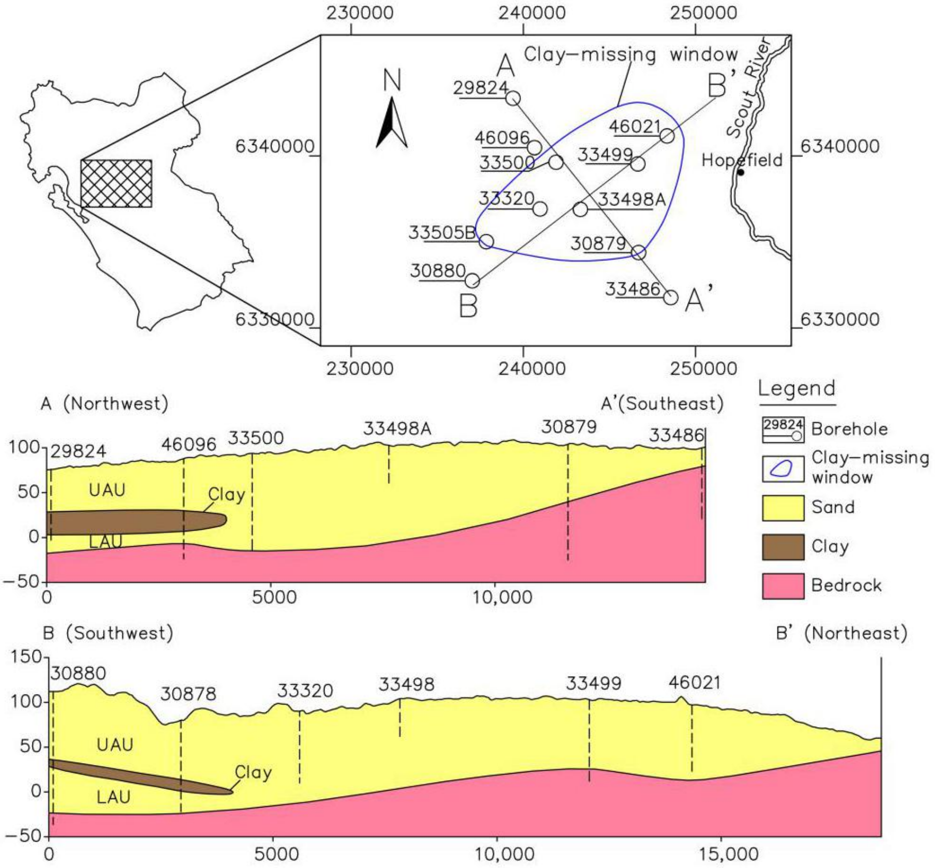


Figure 3-9 Geological cross section showing clay-missing window exited at the west of Hopefield (data sourced from NGA boreholes)

(3) The (semi) confined lower aquifer unit (LAU): LAU is composed of the basal gravels of the Elandsfontyn Formation. Due to the thickness (up to 60 m in some area) and larger spatial extent of this aquifer unit, it is considered as the most important aquifer of West Coast. However, this aquifer is restricted to palaeochannels based on its depositional environment.

(4) The bedrock: Compared with the Cenozoic sediments aquifers, the bedrock is considered as insignificant regionally although some limited areas are of potential higher permeabilities.

3.6 Groundwater level

Groundwater level data from 102 boreholes in the study area, which were monitored by the project partner WCDWS, were collected and then verified by the joint project working group through field investigation in August 2017. The monitored data showed that the depth to groundwater table in UAU varied from 0.4 m to 49.3 m below ground level (b.g.l), with the average value of 11.3 m bgl; and the depth to groundwater table in LAU varied from 1.4 m to

51.4 m bgl, with an average value of 16.8 m bgl. There is a piezometric head difference between LAU and UAU, and the piezometric head in LAU is lower than in UAU. Further analysis showed that the depth to groundwater table is shallower in Langebaan Road aquifer system than in Elandsfontein aquifer system.

Map of groundwater table was drawn based on these monitored water level data in August 2017 , which indicated a strong correlation with surface topography (Figure 3-10).

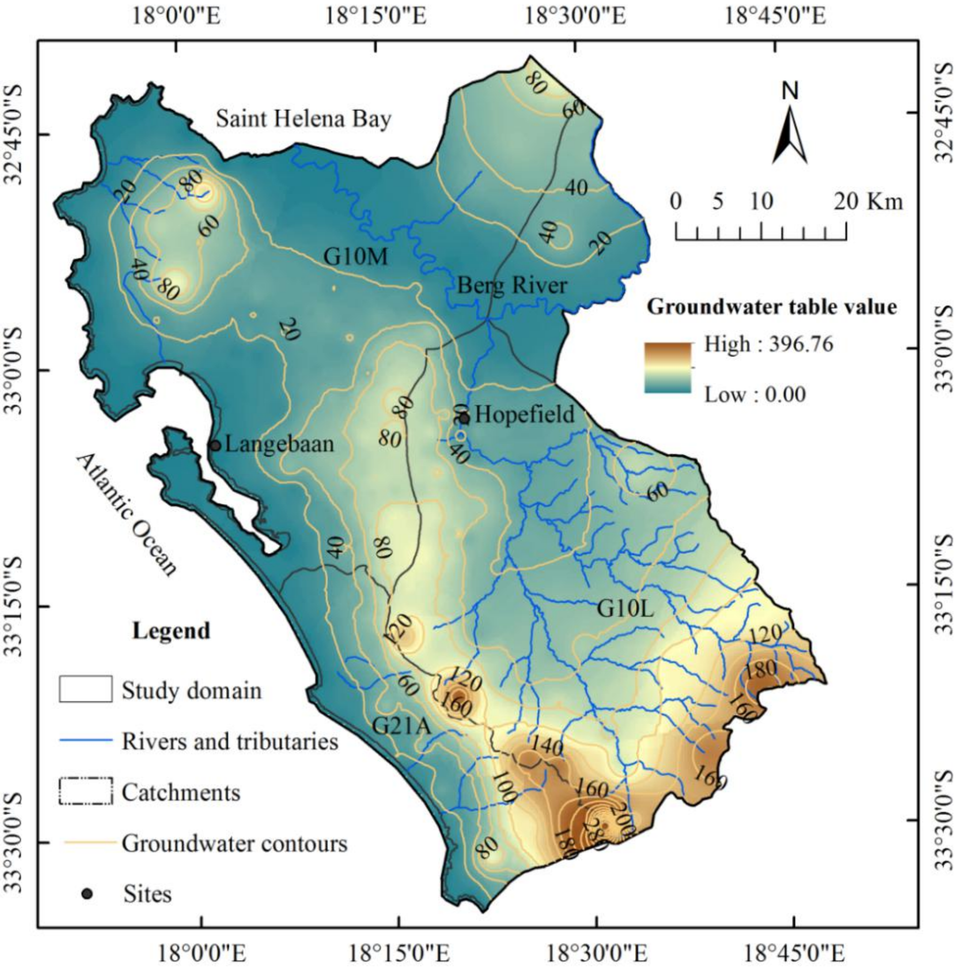


Figure 3-10 Map of groundwater table (Data source from WCDWS in August 2017)

Groundwater (at least in the UAU) flows from the water level high located in the south (around the junction of G10M, G10L, and G21A) in a semi-radial direction towards Langebaan Road aquifer system in the northwest, towards the surface water drainage systems in the northeast, and towards the Langebaan lagoon in the southwest. The flow to the north crosses from the area of Elandsfontein aquifer system to the Langebaan Road aquifer system, hence the two systems are in hydraulic connection at least in the UAU. Groundwater of north of the Berg River flows south and southwest, towards the Berg River and the coastline.

As uncertainties remain with regard to assigning an aquifer per borehole due to the fact that there is inadquate information on the borehole construction, the monitored data is not sufficient to develop piezometric maps in LAU. However, piezometric head difference is found between the aquifers of UAU and LAU based on the water head monitoring, which reveals that piezometric head in LAU is usually lower than water level in UAU. DWAF (2008) developed a piezometric map, which suggested that the flow in the LAU is "controlled by the bedrock topography", with flow concentrating along the axis of the Langebaan and Elandsfontein palaeochannels towards their mouths on the southwest coastline.

3.7 Sources and sinks

3.7.1 Areal recharge

The recharge to the aquifers system is mainly derived from rainfall. Estimates including GRID-based GIS modelling technique, chloride mass balance approach (CMB), and Water Balance Model showed that the recharge rates vary from 3% to 10% mean annual precipitation (Timmerman, 1988; Woodford and Fortuin, 2003; DWAF, 2008).

3.7.2 Lateral recharge

The possibility and extent of leakage from the bedrock into the sand aquifers was raised as an unknown by DWAF (2010), however this is unlikely to have the good water quality signal of the LAU. Isotope and Geo-chemical studies however concluded that recharge is a local phenomenon, rather than occurring via deep-seated flow through the bedrock from distant mountain ranges (Weaver and Talma, 2000, cited in WCDM 2009).

The area has a significant number of boreholes, and the casing details of these boreholes are generally unknown. It is plausible that uncased boreholes may allow a hydraulic connection between aquifers (hydraulic shortcut), allowing local downwards or upwards leakage depending on the local degree of confinement.

3.7.3 Interaction with surface water

The groundwater level map (Figure 3-10), along with the monitored piezometric head showing flow (at least in the UAU) towards the Berg, Sout and Groën Rivers, and Atlantic ocean indicates that groundwater discharge to surface water is expected.

Coastal discharge is the main mechanism of discharge for LAU, if the LAU is considered continuous along the palaeochannel. Whether the LAU has (direct) interaction with surface water, also discharging to the Berg River is dependent on whether the LRAS palaeochannel (and associated Elandsfontyn Formation) extends beneath the Berg River, and if it does extend, whether the clay confining layer is present. It also depends on the depth of incision of the riverbed. Given that the basement data from DWAF (2008) is likely to be the base data for this assessment, a direct connection between the LAU and the Berg River may be precluded.

DWAF (2008) pointed out that in times when the river is in flood, the groundwater gradient in the UAU will be reversed, and surface water will recharge the aquifer, at least locally to the river. Flow gauging data from G1H023 and G1H024 showed that annual river stage fluctuations and the peak river flows are up to 2 m above the annual average stage. The pressure effects of the fluctuations in river stage are detectable in water levels in the UAU. WCDM (2009) documented that water levels in holes near to the Berg River show yearly cyclical fluctuations of up to 0.8 m, which are not related to rainfall, but are the result of pressure variations caused by fluctuating water levels in the Berg River. The effects of this pressure wave in the aquifer are “damped” further away from the river.

3.7.4 Groundwater abstraction

(1) Municipal abstraction

The West Coast District Municipality operated a well field abstracting from the LAU within the Langebaan palaeochannel (WCDM well field), including the abstraction boreholes 46032, 46033, 46034, 45635A, 46036 and 176/1B. The abstracted groundwater augmented the surface water dominated Withoogte Water Supply Scheme, supplying a broad region slightly beyond the boundaries of Langebaan Local Municipality. The well field was licensed to abstract groundwater 4000 m^3/day or 1.46 million m^3/a. And between commissioning in December 1999 and January 2005, the WCDM utilized 80% of this allocation. Over this 5-year period of abstraction, the piezometric level in the LAU reduced by around 10 m, while the UAU water table remained stable (Seyler et al., 2017). Concern was raised over the 10 m reduction in piezometric level in the LAU during 2005, leading to a reduction in the abstraction rates by 10%. With the reduction of 10 m the LAU remains confined in the area of the well field. Abstraction during April 2006 and March 2007 totaled just over 1 million m^3/a (76% of revised allocation). From 2007 to 2010, annual abstraction values however remained around 1 million m^3/a (WCDM, 2012). Abstraction has significantly reduced after July 2009 due to well field pump and infrastructure vandalism. Groundwater is also abstracted from a well field at Hopefield and no detailed information could be sought on this. The All Towns Strategy (DWS, 2016) stated that the town has 7 boreholes which are in poor condition, with yield of 0.16 million m^3/a, but that these are not currently in use.

(2) Private abstraction

There are 78 registrations in the Water Authorization Registration Management System (WARMS) database in the study area, with a total registered abstraction of 6.9 million m^3/a. The sum of registered abstractions per water use sector is shown in Figure 3-11. The majority of groundwater use is for irrigation.

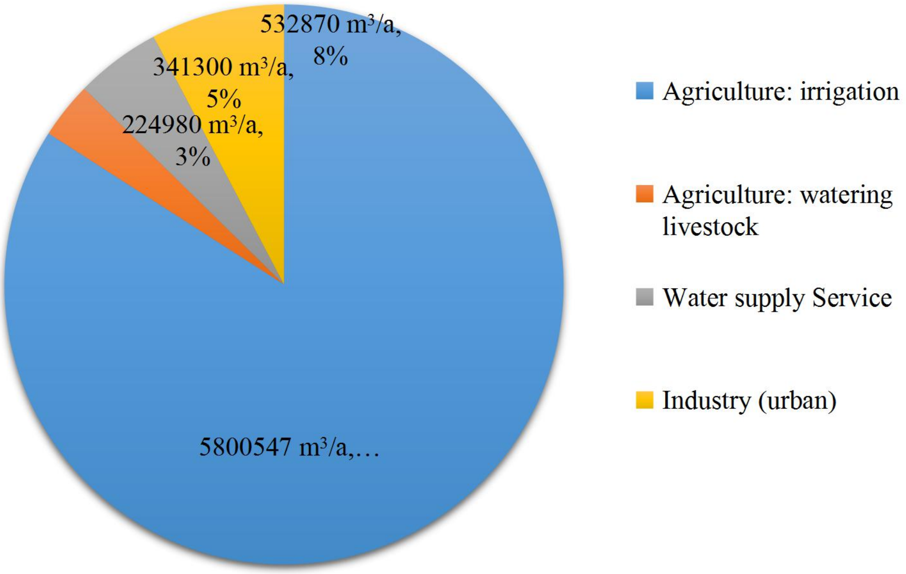


Figure 3-11 Registered groundwater abstraction in WARMS (data sourced from Seyler et al., 2016)

Comparing the distribution and sum total of WARMS abstraction along with the distribution and sum total of abstractions from WCDM monitoring reports (WCDM, 2005, 2009, 2011, 2012), it is clear that a number of private abstractions are not captured in the WARMS database. An additional challenge with the WARMS database is that there is no information on which aquifer is targeted (LAU or UAU). The majority of private groundwater use is assumed to be from the UAU, however some private groundwater users do access the LAU (DWAF, 2010).

Raw data (location or borehole name, and abstraction) from the original DWAF hydrocensus is not available. Figure 3-12 shows the available information regarding borehole locations, and Appendix 2 of Woodford and Fortuin (2003) contains a list of the total abstraction per cadastral unit rather than per borehole. The abstraction data are recreated by using the table of total abstraction per cadastral unit and digitizing the points shown in Figure 3-13, then distributing the total abstraction per cadastral unit across the boreholes indicated. This method is not ideal but it is the only available method to recreate the hydrocensus information. However, the uncertainty of groundwater abstraction dataset would affect the analysis to some extent, which should be highlighted.

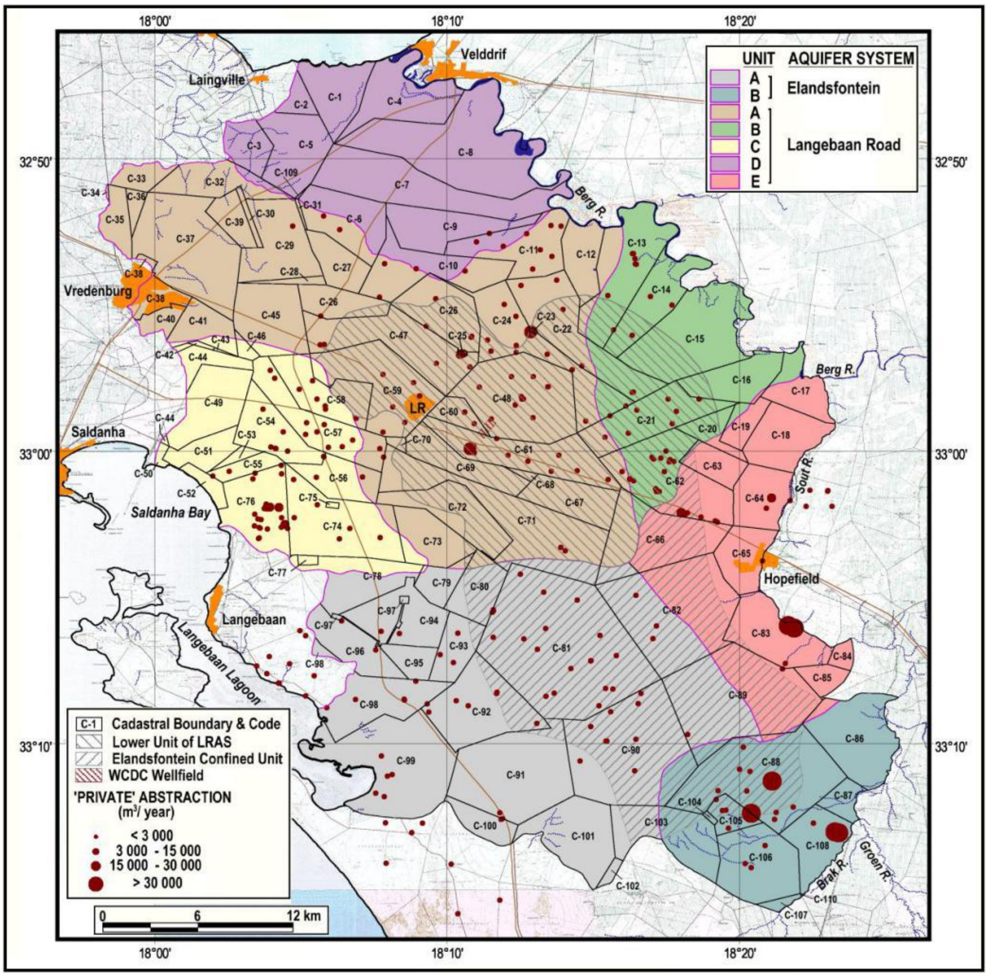


Figure 3-12 Private groundwater abstraction hydrocensus (WCDM, 2009)

3.8 Groundwater quality

According to chemistry analysis of water samples, the pH value of groundwater of UAU and LAU is ranging from 7.4 to 8.2, with an average value of 7.8 in the region, and the dominant water types are Na-Cl and Ca-HCO_3 (Figure 3-13).

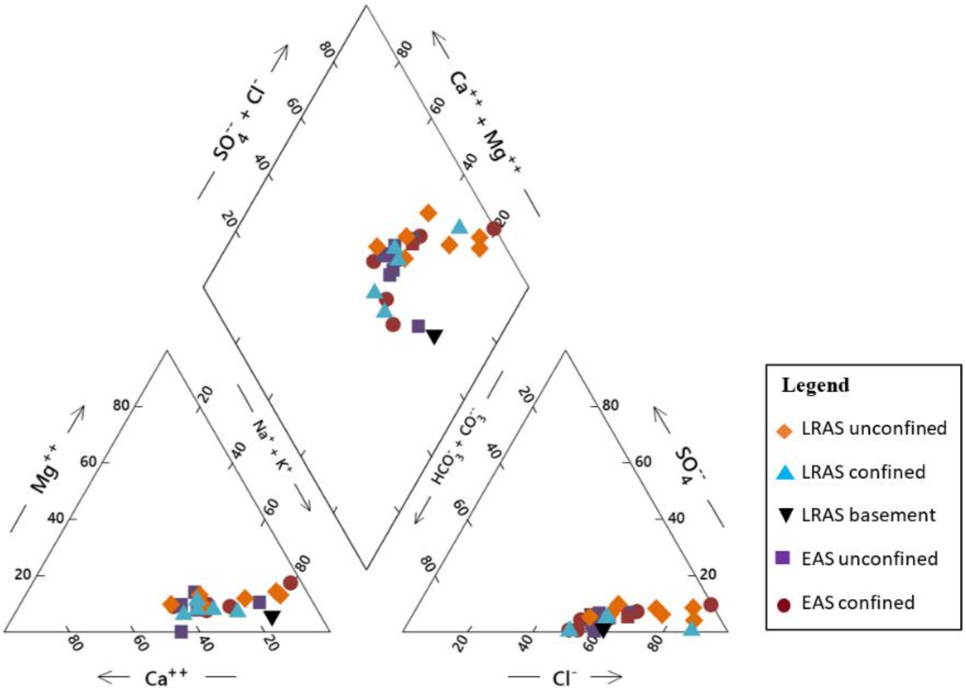


Figure 3-13 Piper map of the groundwater samples

From the chemical analysis of water samples, there is a marked difference in salinity between the UAU and LAU. WCDM (2005) presented a map of EC in groundwater of study area, which is shown in Figure 3-14. EC's are commonly less than 120 mS/m in the LAU; while EC's in the UAU are often over 250 mS/m, and often exceed 500 mS/m where close to the Berg River, and close to Saldanha Bay. Meanwhile, the groundwater quality of UAU in Elandsfontein aquifer system is better than in Langebaan Road aquifer system, the possible reason of which maybe owing to the pristine conditions of Elandsfontein aquifer system.

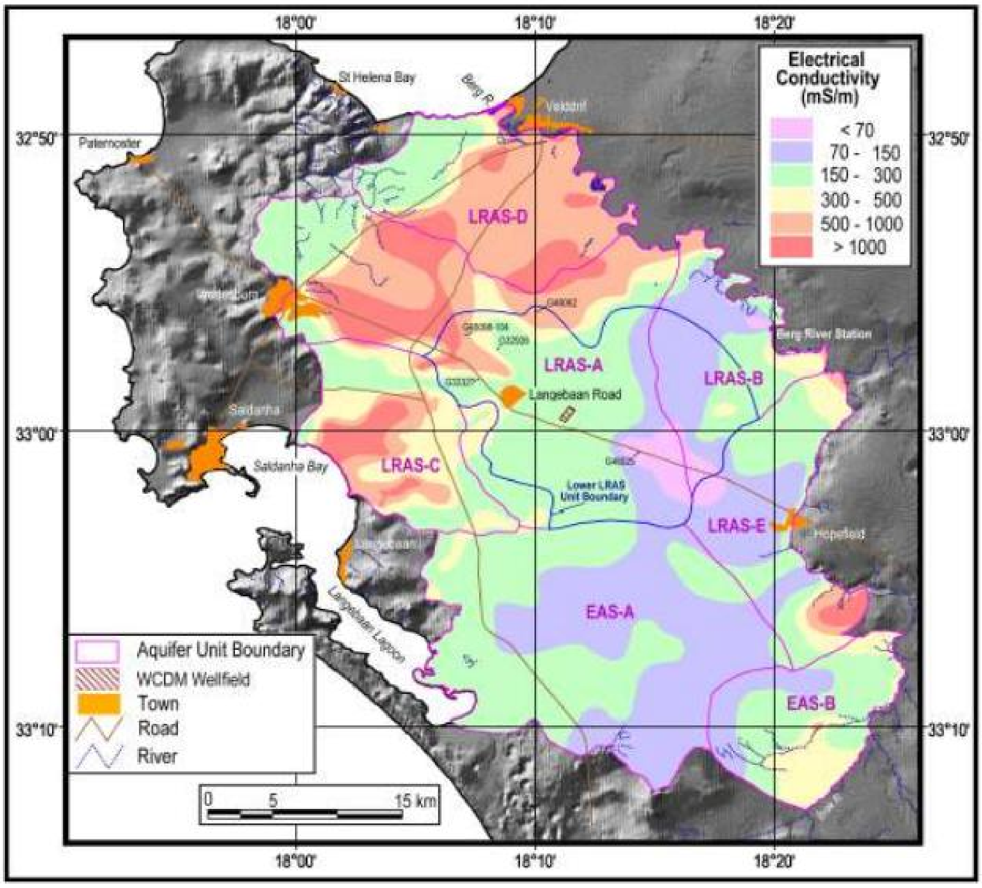


Figure 3-14 EC map of the groundwater in Langebaan Road aquifer system and Elandsfontein aquifer system (from WCDM, 2005)

3.9 Chapter summary

Since 1980, the aquifer units of West Coast have been the subject of significant hydrogeological investigation. There are mainly two aquifer systems in West Coast of South Africa, namely the Langebaan Road aquifer system and the Elandsfontein aquifer system. According to the vertical distribution of lithology, the complex hydrostratigraphy of study area can be represented on the regional scale by four aquifer key units: the upper unconfined aquifer unit (UAU), the aquitard clay, the (semi) confined lower aquifer unit (LAU) and the bedrock. The groundwater flow, interaction between the aquifer systems, interaction of the aquifer systems with surface water are also discussed by various researches. These researches lay a good foundation on the development of groundwater flow conceptual model.

Uncertainties are also existed due to the complexity of the aquifers system. The information of Elandsfontyn Formation and palaeochannels are mainly from the limited deep boreholes and geophysics because of lacking outcrop, thus make the understanding on the spatial distribution of clay aquitard as well as LAU not enough. Meanwhile, the existed boreholes are constructed by different people with different purposes. Owing to the absence of construction borehole logs, it is difficult to correspond the monitoring data with the right aquifer, especially for the LAU.

Chapter 4: Research design and methodology

4.1 Introduction

The current chapter describes the methods that were used to analyze the needed data to answer the research questions set in chapter one thereby fulfilling the objectives for this study. This chapter focuses on i) research design; ii) methods for data collection and analysis; and iii) other factors including quality assurance and research integrity.

4.2 Research design

4.2.1 Study design

The general approach to this study was a case study approach whereby West Coast of South Africa was used. A comprehensive approach was adopted to understand the hydrogeological setting as well as to assess MAR in terms of suitable sites and implement scheme.

Firstly, a broadly literature review was conducted to capture the extensive knowledge pertinent to MAR and West Coast aquifers system. And the researches of MAR in terms of suitable sites and implement scheme were reviewed as a key.

Secondly, a groundwater flow conceptual model of West Coast aquifers system was conceptualized based on the analysis of the data that were obtained from collection and field investigation.

Thirdly, GIS and modeling were combined to assess the suitable sites and implement scheme in West Coast.

4.2.2 Research design methods

This study incorporated the following main steps in the research design: Desk study, Data collection and collation, Field investigation, GIS analysis and Modeling.

The desk study involved a review of all relevant available information, including: A literature review on MAR, focusing on the researches pertinent to suitable sites assessment and scheme planning; A literature review of previous studies on the West Coast aquifers system, such as geological and hydrogeological maps and reports, groundwater monitoring data, groundwater isotope studies, assessment of the interaction of the aquifer systems with surface water, and artificial recharge investigations, among others.

Data collection and collation: A lot of secondary data were collected and sorted out. These data included landform, land use, climatology, water level and piezometric head, water quality, water utilization, as well as geology and hydrogeology data.

Field investigation: Field investigation was carried out to check those secondary data with uncertainty, such as questionable locations of boreholes, questionable water levels.

GIS analysis: GIS analysis was adopted to screen out the suitable sites for the implementation of MAR, as well as to preprocess the data sets including hydrological, hydrogeological and geological for developing modeling.

Modelling: Modeling was adopted to verify and optimize the suitable sites selected by GIS method, as well as to analyze the scheme of implementing MAR.

4.2.3 Data types and their sources

This study is part of the Water Research Commission funding project “Towards the sustainable exploitation of groundwater resources along the West Coast of South Africa” which is fulfilled by a joint group of Council for scientific and industrial research (CSIR), Department of water and sanitation of Western Cape (WCDWS), and University of the Western Cape (UWC).

The data type in this study is mainly secondary data from the official channel. However, a proportion of primary data would be get through field investigation when the data was found to be questionable. The following three major methods for data collection were used:

(1) Ground surface was sourced from 30 m space-grid DEM data from USGS website.

(2) The geological data were mainly obtained from the Geology maps (Cape Town and Clanwilliam, 1:250000), and the boreholes lithology logs from National Groundwater

Archive of south Africa (NGA). And a fraction of data references the related research reports from Department of Water Affairs and Forestry, South Africa (DWAF). The geological layers were mainly deprived through kriging interpolation from 341 NGA boreholes lithology logs.

(3) The water heads and climatology data were sourced from the partner WCDWS. And the groundwater level was deprived from kriging interpolation of the monitored water level dataset. Water utilization was sourced from Water Authorization Registration Management System database of Department of Water Affairs (WARMS database), as well as reports and hydrocensus from West Coast District Municipality of South Africa .

4.3 Research methodology

From the literature, computational tools play an important role in assessing MAR in terms of suitable sites as well as implementing scheme. GIS is usually used to screen out the suitable sites for the implementation of MAR, while modeling is always adopted to analyze the recharge process and influence of implementing MAR thus to assess the scheme of MAR. The application of GIS based analysis method and modeling separately is well known but few study (to author's knowledge) has been performed together to assess the MAR. The GIS based method has strong spatial data analysis ability and overlay function but poor in dealing with uncertainty, risks, and potential conflict. Modeling is not as strong as GIS in spatial analysis, however, it is good at evaluating the advantages and disadvantages of implementing MAR at a proposed location when combined with specific scenarios. Combining GIS based analysis with numerical modeling can allow a more detailed and quantitative assessment of MAR opportunities and impacts. Figure 4-1 shows the general framework of research methodology. Three steps are included in the process of assessment of MAR.

Step 1: Based on the hydrogeological setting, the groundwater flow conceptual model was proposed, which laid the foundation of modeling analysis of MAR.

Step 2: GIS based analysis was adopted to screen out the suitable sites for MAR. Meanwhile, datasets such as hydrological, hydrogeological and geological data were also prepared to develop the groundwater flow model .

Step 3: Modeling was adopted to verify and optimize the suitable sites which were selected by GIS based analysis. Then scenario analysis was employed to assess the scheme of implementing MAR.

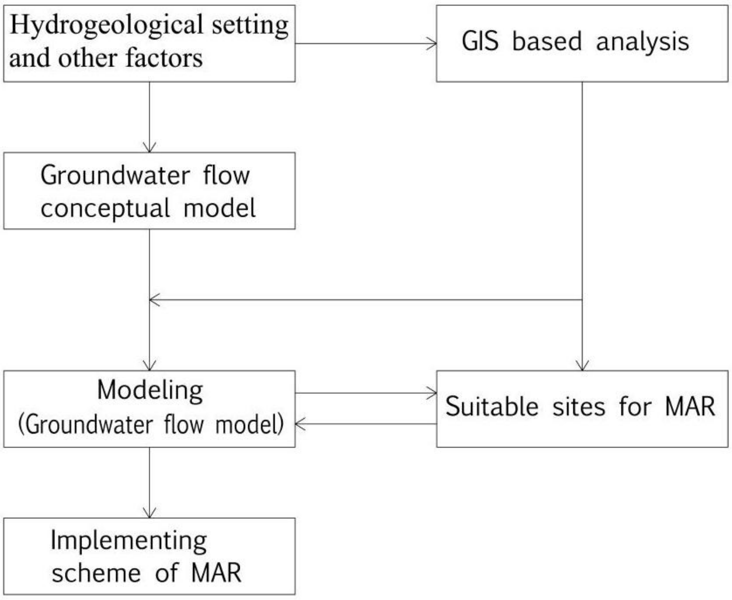


Figure 4-1 Framework of research methodology. Three steps are included: i) The groundwater flow conceptual model is proposed based on the hydrogeological setting; ii) GIS based analysis is adopted to screen out the suitable sites for MAR as well as to prepare the datasets for modeling; iii) Groundwater flow model is developed to verify and optimize the suitable sites, as well as to assess the scheme of implementing MAR.

4.4 Research methods

4.4.1 Methods of developing groundwater flow conceptual model

A large quantity of data and reports were available to take as references in West Coast. The first step was to review the available documentation, and understand the distribution of aquifer units based on the geological data. Then the data including groundwater level, groundwater chemistry were collected to get the information of groundwater flow, groundwater quality and the interaction of the aquifer systems with surface water. Field investigation as well as groundwater monitoring and sampling were conducted as a supplementary way to verify or correct the questionable data. Through comprehensive analysis on the data available, the groundwater recharge, flow and discharge was understandable, and the groundwater flow conceptual model was able to be developed.

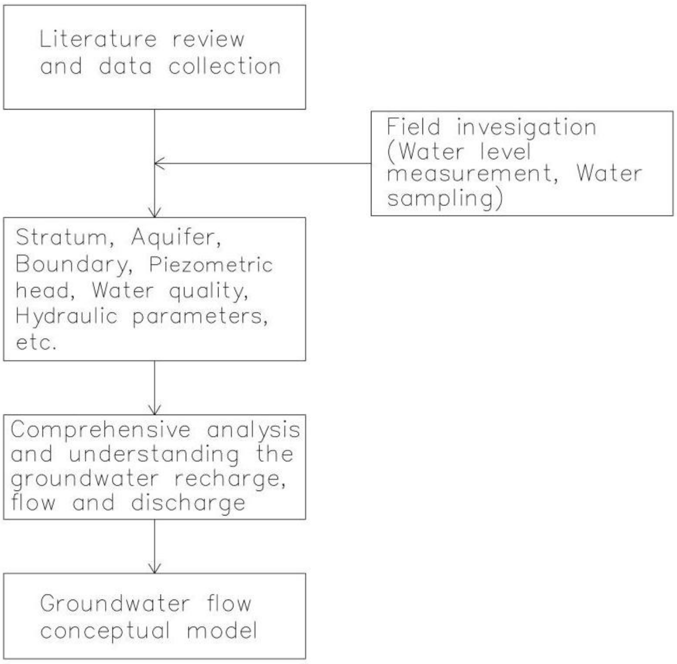


Figure 4-2 The research method of developing groundwater flow conceptual model

4.4.2 Methods for evaluating suitable sites for the implementation of MAR

In the site selection process, due to the fact that the volume of geographical data is huge and the analysis is very complex and time-consuming, the application of GIS will be inevitable (Malekmohammadi et al. 2012). Since the AHP has been the most commonly used technique to overcome the subjectivity of weight definition, AHP was introduced to assist the choice criteria and weight determination (Kazakis, 2018). Five sub-steps were included to serve as a reference for the basic method of GIS based analysis for the site suitability assessment of MAR. This assessment procedure is shown in Figure 4-3.

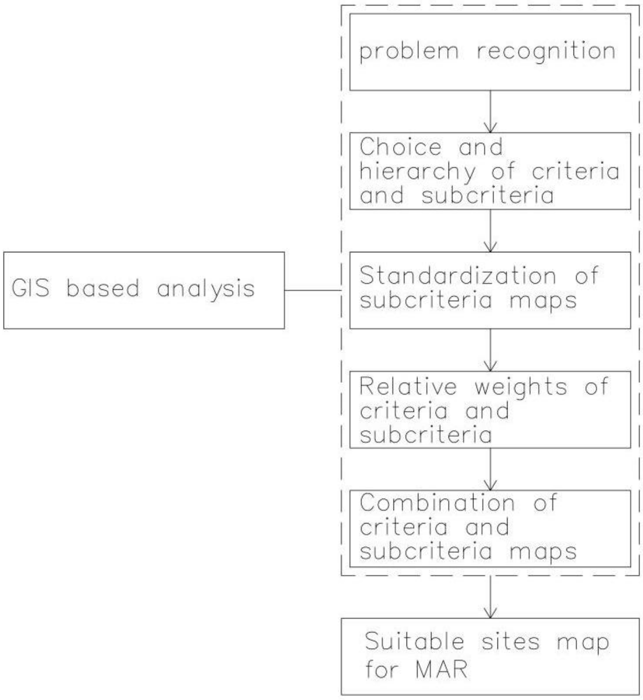


Figure 4-3 The GIS based analysis procedure of suitable sites for MAR.

i) Problem recognition

In a range of water resource management interventions, MAR has been proven to be an effective option. MAR is helpful for the recovery of groundwater levels, the improvement of groundwater quality, and for the storage of water and as a barrier against the intrusion of salinity. As problems differ from place to place, so do the techniques. Even if they are used for the same problems, the techniques required would vary from one case to another. A successful MAR scheme depends largely on the recognition of specific problems associated with a project. The main purpose of this study is to select the suitable sites and scheme for the implementation of MAR in terms of water storage for later recovery.

ii) Choice and hierarchy of criteria and subcriteria

For any MAR site selection, different types of data are required. Considerations must be given to data availability and the objective of the analysis during the selection data of the type. The choice of datasets is divergent from case to case (Saraf and Choudhury 1998; Piscopo 2001; Murray and Mcdaniel 2003; Shankar and Mohan 2005; Jasrotia et al. 2007; Chitsazan and Akhtari 2009; Yeh et al. 2009; Adham et al. 2010; Chenini et al. 2010; Rahman et al.

2012; Russo et al. 2015), however, the primary data adopted include surficial geology, soil infiltration capacity, land use, elevation (topographic slope), verified (measured) infiltration and recharge rates from observational studies, aquifer thickness, aquifer hydraulic conductivity, aquifer storativity, residence time, vadose zone thickness, historical changes in water table elevation, and groundwater quality (Figure 4-4).

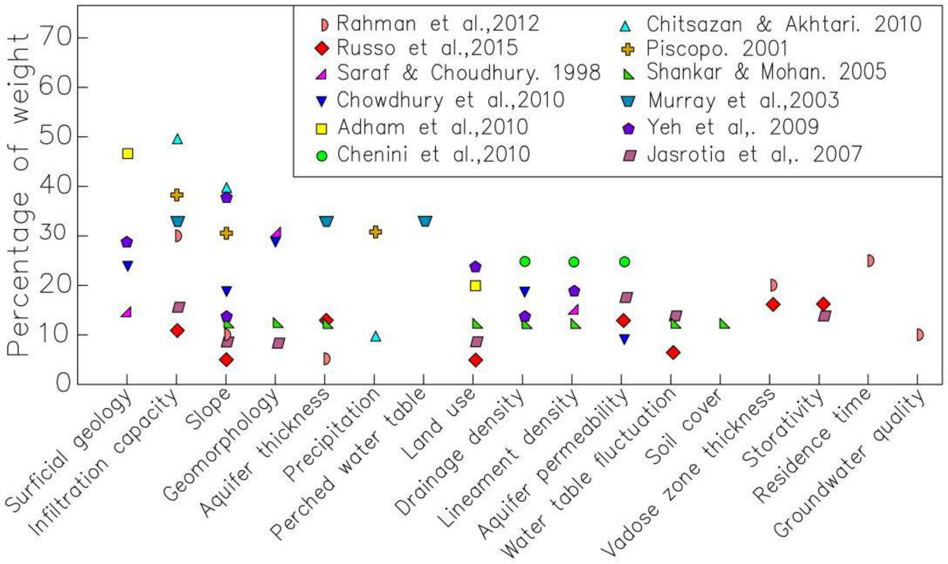


Figure 4-4 Comparison of the criteria and weights used in other similar studies (after Russo et al. 2015).

These datasets have proven to be functional in previous studies. However, due to the internal relationship between themselves, a good result cannot be expected by simply combining them together. The analytical hierarchy process (AHP), introduced by Saaty (1980), has proven to be useful for spatial decision problems with a large number of criteria (Eastman et al. 1993). It can be used to combine all the representative criteria into a “criteria tree”, with different levels of priorities accordingly (Sharifi et al., 2006; Chowdhury et al., 2010). Therefore, AHP was introduced to assist the choice criteria and weight determination to improve the accuracy of GIS based analysis. The application of AHP involves the decomposition of the ultimate goal into a three-level hierarchy consisting of subcriteria of the goal. The top of the hierarchy is the goal of the analysis, relating to the ”suitable sites map”. The middle level contains more specific criteria with regard to the objective, and the bottom level refers to the most specific criteria, which are related to the main criteria in the middle level.

High MAR suitability means that if a water supply of sufficient quantity and quality is available, the surface and subsurface conditions are likely to be favorable for developing a MAR project (Russo et al. 2015). Accordingly, criteria including source water availability, infiltration capacity, and storage capacity were taken into account as the middle level. For the most specific subcriteria level, source water quantity, water quality, and distance to source water were chosen to support the source water availability analysis; land use, slope, and soil hydraulic conductivity were adopted to support the infiltration capacity analysis; the aquifer thickness, vadose zone thickness, residence time, ground water quality and the influence of pumping wells were taken into account to support the storage capacity analysis based on the assumption that the storativity of aquifer is constant. Other factors (e.g., existing infrastructure, socioeconomic variables, social acceptance and among others) were not taken into account as these factors can change with time.

iii) Standardization of subcriteria maps

Each subcriterion in the criteria tree is represented by a map of different types such as a classified map (e.g., land use) or a value map (e.g., slope, aquifer thickness). For decision analysis, the values and classes of all of the maps should be converted to the same scale to reduce the dimensionality. Such conversions are known as standardization (Sharifi and Retsios, 2004). Different standardization methods were applied to different maps, and linear, piece-wise linear, and step functions for standardization were adopted. The outcome of the function is always a value between 0 and 1. The function is chosen in such a way that cells in a map that are highly suitable for achieving the goal obtain high standardized values and less suitable grids obtain low values.

iv) Relative weights of criteria and subcriteria

The next step in the site selection procedure is to assign values of importance for all criteria and subcriteria, which is planned by assigning a weight to each specific criterion. Different weighting methods are available, however, pair-wise comparison and direct weighting were used here. The subcriteria under each main criterion were compared amongst themselves and an initial weight was assigned to each one. Next, a sensitivity analysis of the weight for the subcriteria was conducted by using the perturbation method to obtain the reasonable value range of weight of each subcriterion. The weight of each subcriterion was finally obtained by the correction of the initial weight based on the sensitivity analysis, as were the main criteria evaluated.

v) Combination of criteria and subcriteria maps

After standardization and weighting, the next step is to obtain the overall suitability index of each alternative. The index value was given to the cells of the map. For each grid cell in the analysis, an index was calculated by summing the products of value and weight for each subcriterion:

$$Index(x,y) = \sum_{i=1}^{n} v_i(x,y)w_i \,. \qquad (4\text{-}1)$$

Where n is the total number of subcriteria; v_i is the standardized value for subcriterion i at location (x,y); and w_i is the weight assigned to subcriterion i.

This process is called the weighted linear combination (WLC), which is available by using “raster calculation” function in ArcGis. Then, the map of suitable sites for implementing the MAR was produced.

4.4.3 Methods for assessing the scheme for implementing MAR

In order to assess the scheme for implementing MAR, modeling is adopted to verify and optimize the suitable sites developed by GIS based method, as well as to assess the appropriate MAR scheme based on the designed scenarios. ModelMuse, together with the MODFLOW and MODPATH packages, were used in this work (Winston, 2009). During the entire process, the consistency of data used in the GIS and modeling must be maintained. GIS is used extensively for preprocessing of hydrological, hydrogeological and geological data, and make sure the data sets including topography, geology, groundwater and other data used in the modeling must be those that were used or generated in the GIS based analysis. Once the process of development, calibration, and validation of the groundwater flow model is performed, several scenarios can be applied to verify the suitable sites map produced by GIS based analysis, as well as to assess the appropriate MAR scheme.

The procedure of this modeling analysis of MAR, which is shown in Figure 4-5, include five steps: i) choosing the appropriate software; ii) preparing the data needed in the groundwater flow model; iii) developing the numerical model using the chosen software; iv) calibrating the groundwater flow model; and v) running the groundwater flow model with the designed scenarios to analyze the implementation of MAR.

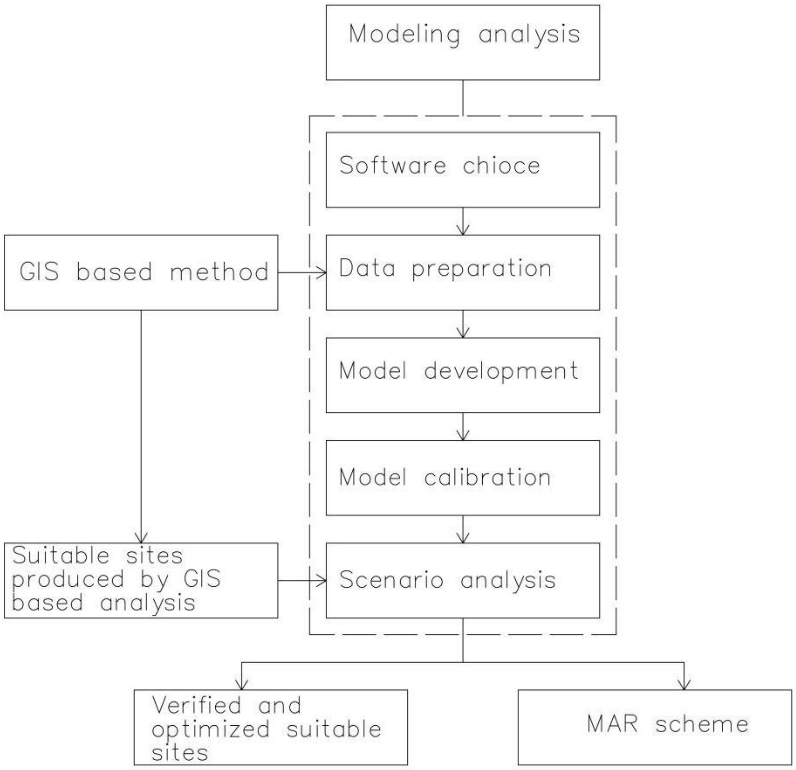


Figure 4-5 The procedure of modeling analysis of MAR.

4.5 Quality assurance or quality control

Firstly, this study is part of the Water Research Commission funding project “Towards the sustainable exploitation of groundwater resources along the West Coast of South Africa” which is fulfilled by a joint group of CSIR, WCDWS and UWC. The members of this research group are trustworthy. All the data were collected from the official channel, meanwhile, a field investigation was carried out to check those questionable data.

Secondly, this study incorporates GIS based analysis and modeling to assess the suitable sites as well as implementing scheme. GIS worked as a tool to screen out the initial suitable sites, then modeling is adopted to verify and optimize the suitable sites mapped by GIS as well as to analyze the implement scheme. With the advantages of both spatial analysis in GIS and the seepage simulation in modeling, this analysis approach provides a more reliable solution to the assessment of MAR.

4.6 Research integrity

The field work including groundwater level measurements and water sampling was guided by the consultants of Department of water and sanitation (Western Cape), who set a very good example on the informed consent to the stakeholders from ethical consideration aspect, as well as respect from legal consideration. From the technical consideration aspect, Winston Richard of USGS who developed the software ModelMuse is acknowledged for his technical support during the process of modeling.

4.7 Study limitation

Although great efforts have been paid to this study, still exists study limitations.

Firstly, The data available is limited which constrains the study. There are more than two thousand of boreholes in the study area, but most of these boreholes are too shallow to uncover the distribution of aquitard clay and LAU. The stratum layers are developed by Kriging interpolation based on the limited available borehole logs, thus may result in inaccuracy of groundwater flow model as well as the GIS analysis. Meanwhile, owing to lacking of construction logs of the boreholes, sometimes it is difficult to correspond the monitoring data with the right aquifer, which makes a separate calibration on groundwater model impossible. Furthermore, there is inadquate data to support the boundary condition of groundwater model. For example, constant head boundary is applied along the coastline of Atlantic, however, the water level of coastline fluctuates acturally. In addition, the uncertainty of groundwater abstraction dataset would also affect the analysis.

Secondly, based on the theoretical framework, this study has not taken the water flow in the vadoze zone into account because this simplification has little influence on the assessment of suitable sites as well as the implementing scheme. However, from the theoretical aspect, there is a limitation for the assessment of MAR.

Thirdly, Although measures were taken to keep the data consistent between the elevation of boreholes and DEM, the accuracy of DEM data may also cause some errors during the process of modeling analysis.

Based on the above mentioned study limitations, although measures are taken to control the research quality, the results deduced from this research is still suggested to be verified by the field test or application.

Chapter 5: Developing groundwater flow conceptual model of West Coast: Results and discussion

5.1 Results

5.1.1 Groundwater flow mechanism of study area

The UAU is recharged directly from precipitation. Rainfall is greater in the higher lying areas in the south of the study area, and thus a recharge mound for Langebaan Road aquifer system and Elandsfontein aquifer system has been postulated in the southwest of Hopefield among G10M, G10L and G21A. Groundwater flow in UAU is topographically controlled and occurs from the recharge mound to the Berg River or the coastline. On average the Berg River together with its tributaries gains from the aquifer as there is a strong hydraulic gradient towards it. However, it is possible that the Berg River recharges the UAU during rainy season.

The "clay-missing window" in the vicinity of the recharge mound would facilitate the downward percolation of the water into the LAU, then groundwater flows along the palaeochannels, and finally drains toward the Berg River or the coastline or the abstraction boreholes.

Based on the hydrogeological characteristics of study area, the groundwater flow mechanism of Langebaan Road aquifer system and Elandsfontein aquifer system is conceptualized in Figures 5-1, 5-2, and 5-3.

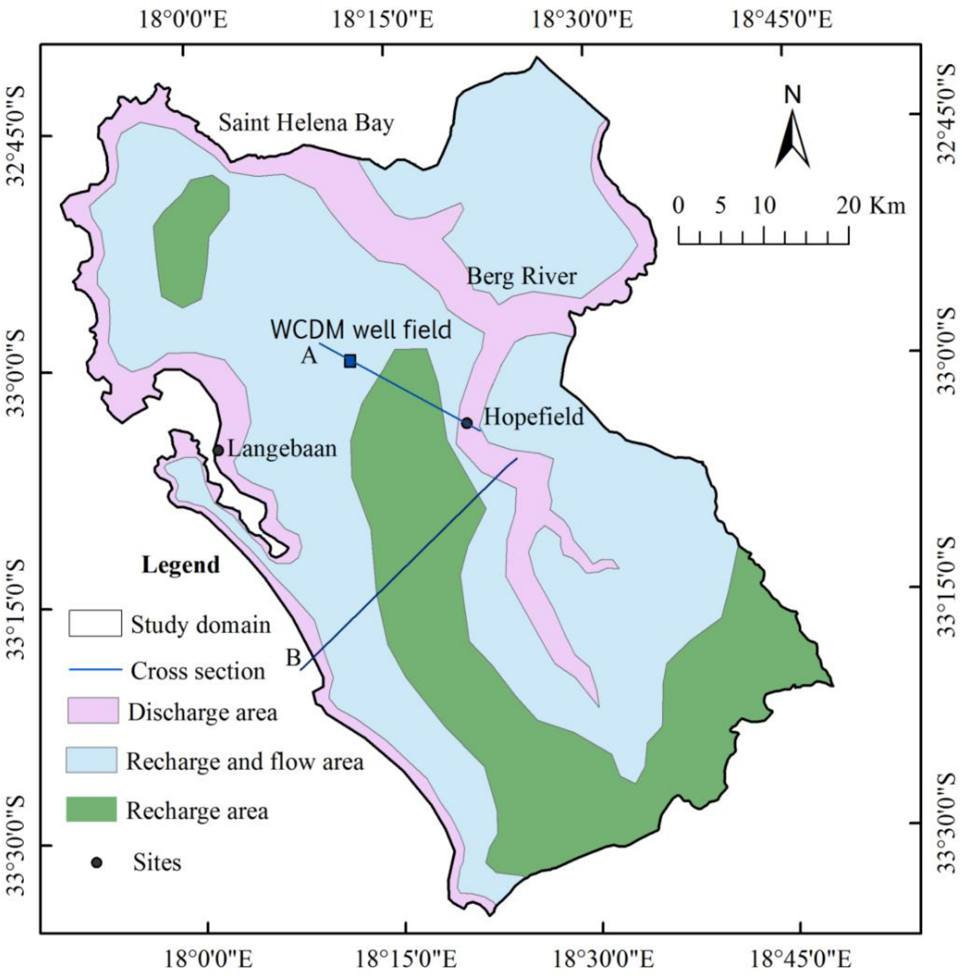


Figure 5-1 Groundwater flow zoning map of study area

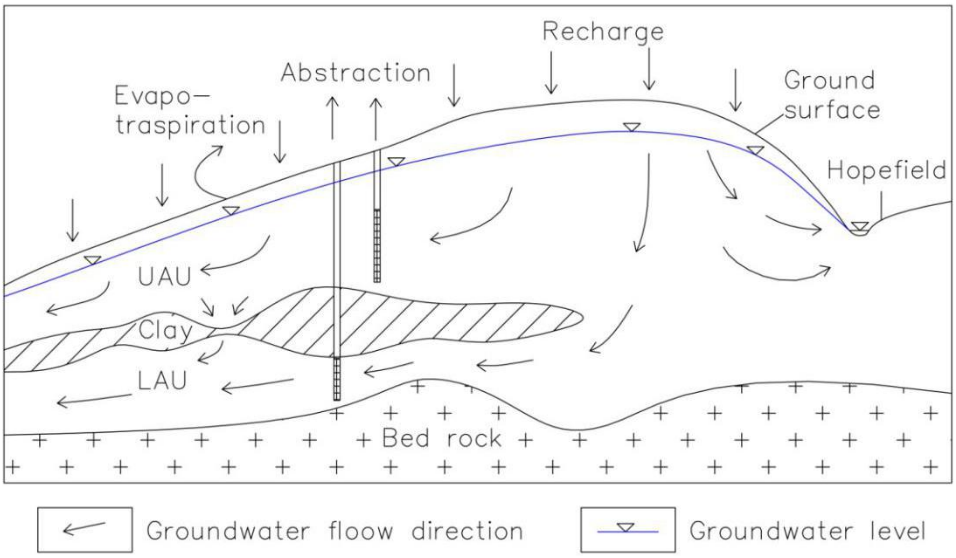


Figure 5-2 Diagrammatic cross section summarizing the key features of the groundwater flow of UAU and LAU in Langebaan Road aquifer system (not to scale, after DWA, 2010a)

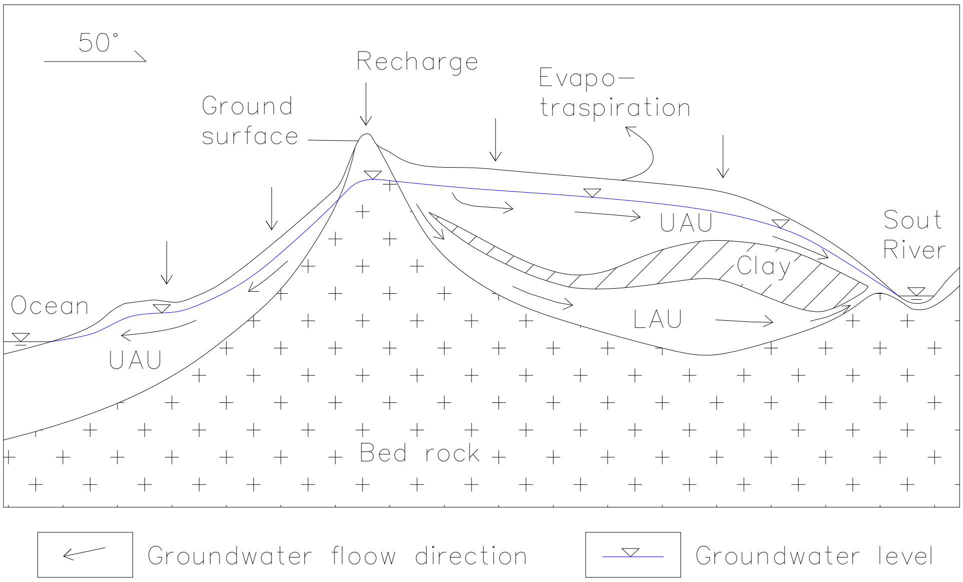


Figure 5-3 Diagrammatic cross section summarizing the key features of the groundwater flow in Elandsfontein aquifer system (not to scale)

5.1.2 Groundwater flow conceptual model of West Coast

(1) Domain and layers of the model

The groundwater flow conceptual model was developed using ModelMuse where MODFLOW and MODPATH packages were selected. The grid of model comprises four layers with varying thickness, together with 77059 (Rows 293, columns 263) cells within each layer that covers an area of 4670 km^2. The mesh size at area of Langebaan Road aquifer system and the Elandsfontein aquifer system is 250 m, while the mesh size of other areas is 500 m (Figure 5-4). Four layers are included in the conceptual model, details are shown in Table 5-1 and Figure 5-5. All the data representing aquifer layers as well as boundaries were prepared through GIS, and then be converted into ASCⅡ raster file or shapefile before they were imported into ModelMuse to develop the numerical model.

Table 5-1 Layer arrangement for the numerical model (Timmerman, 1988; WCDM, 2009; Seyler et al., 2016)

Layer	**Represe-ting**	**Thickness (m)**	**Hydraulic conductivity Kx (m/d)**	**Data source**	**Data preparation**
1	UAU	2.0~119.0	0.1 ~ 86.4	Layer top: Ground surface. Layer bottom: UAU bottom as defined through NGA lithology data (The thickness this layer is	Ground surface is sourced from 30 m space-grid DEM data from

				assumed to be equal to or greater than 2.0m).	USGS, and the data of layers are
2	Clay layer	0~84.0	4.3×10^{-5} ~ 2.0	Layer top: UAU bottom as defined through NGA lithology data. Layer bottom: clay bottom as defined through NGA lithology data.	defined from 341 NGA boreholes lithology logs. All the data
3	LAU	0.1~64.5	0.1 ~ 34.6	Layer top: clay bottom as defined through NGA lithology data. Layer bottom: bedrock elevation defined through NGA lithology data.	representing layers are prepared using ArcGIS and then be converted
4	Bedrock	20.0	4.3×10^{-3} ~ 0.26	Layer top: bedrock elevation defined through NGA lithology data. Layer bottom: bedrock elevation minus 20m	into ASC II Raster file.

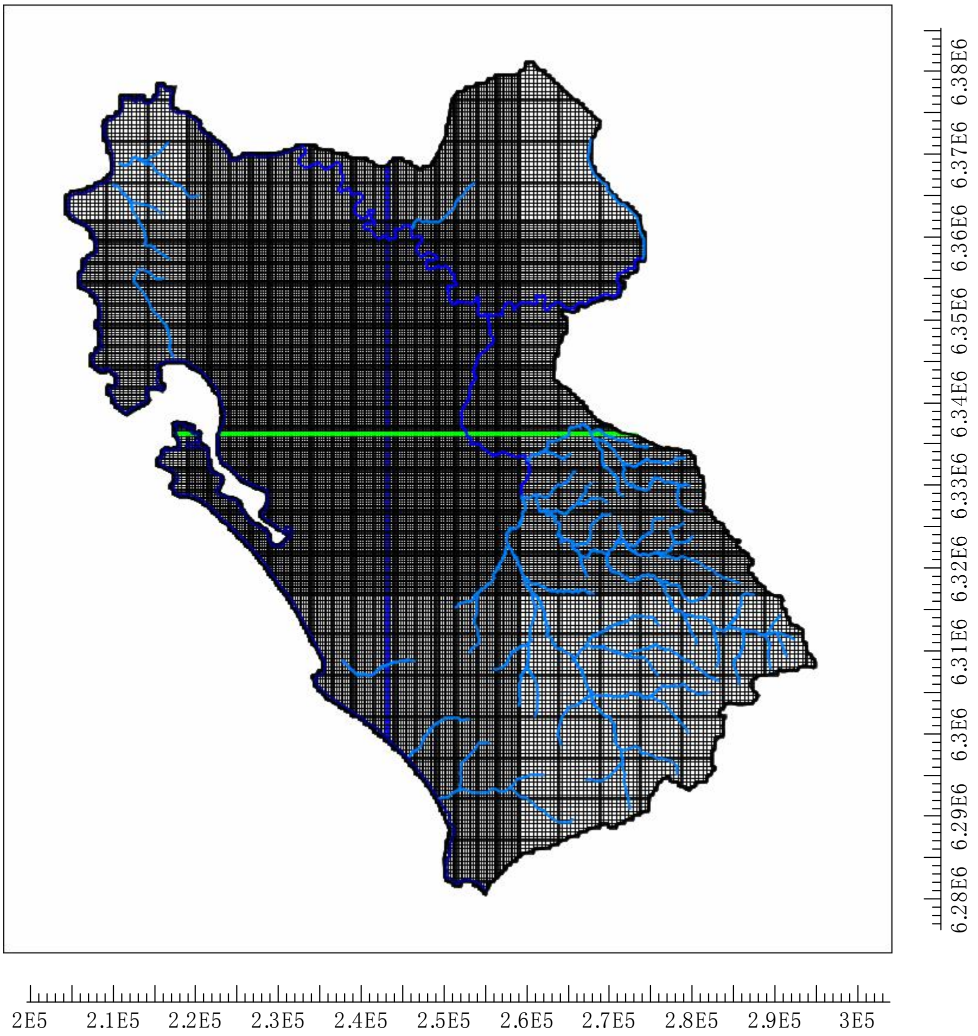


Figure 5-4 The groundwater flow model domain and its finite-difference grid

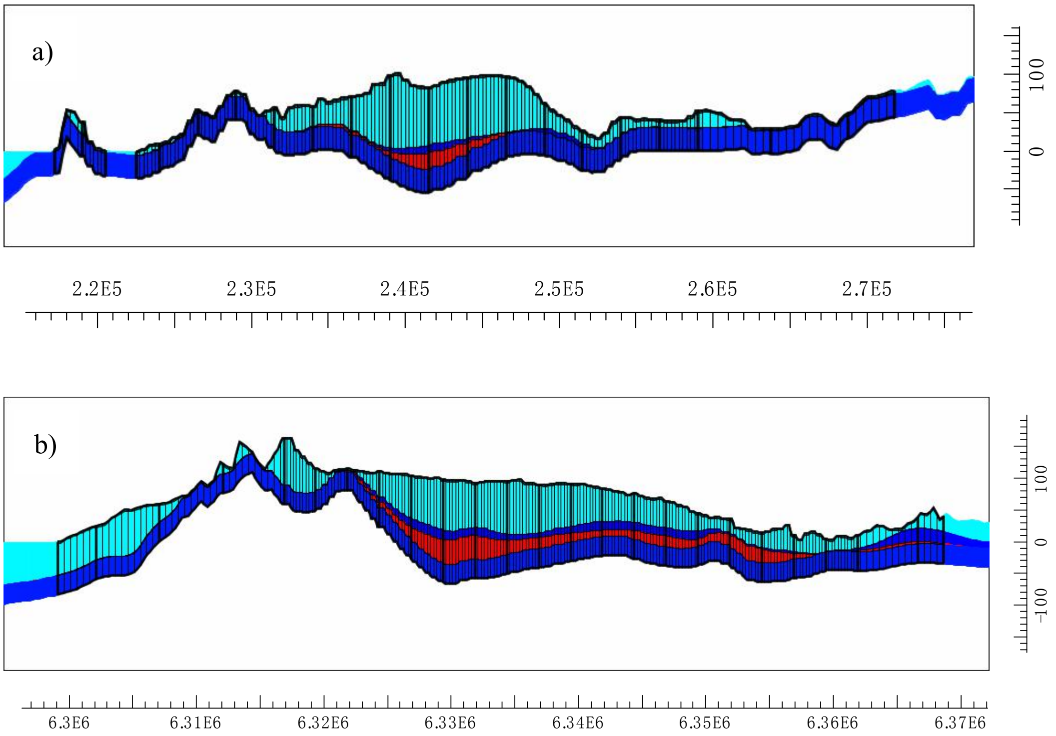


Figure 5-5 Profile of the groundwater flow model. a) is drawn from west to east, b) is drawn from south to north, and the colors only indicate layers in model.

(2) Boundaries of the model

Boundaries of the model are defined at positions where a known hydraulic head, known flux of groundwater, and known loss of groundwater from the groundwater system. Details of this groundwater flow model are described in Table 5-2.

Table 5-2 Description of model boundaries

Location	**Conceptual Description and assumptions**	**Numerical Translation**
Atlantic coastline (Northwest and west border of the model)	Atlantic ocean works as a regional drainage datum plane and accept the discharge from aquifers.	Constant head boundary is applied along the coastline.
Berg River and Sout River	The Berg River and Sout River are assumed to be in contact with the UAU, without deeply incised.	River boundary is applied.
Ephemeral Rivers (Groën River together with the tributaries and gullies)	Work as water drainage channel of the model.	Drain boundary is applied.
Watershed of northeast, south and southeast mountain area	It is assumed that there is no flux across the boundary of the catchment .	No-flow boundary is applied.
Model domain	Recharge from precipitation	Recharge boundary is applied.
Model domain	Recharge or abstraction from aquifers	Well boundary is applied.

(3) Sinks and sources of the model

The recharge distribution developed by DWAF (2006) which suggests a recharge rate between 6% and 7% of the multi-year average precipitation was adopted in the model. Recharge was set according to four zones with the recharge rate varies from 5 mm/a to 35 mm/a (Figure 5-6).

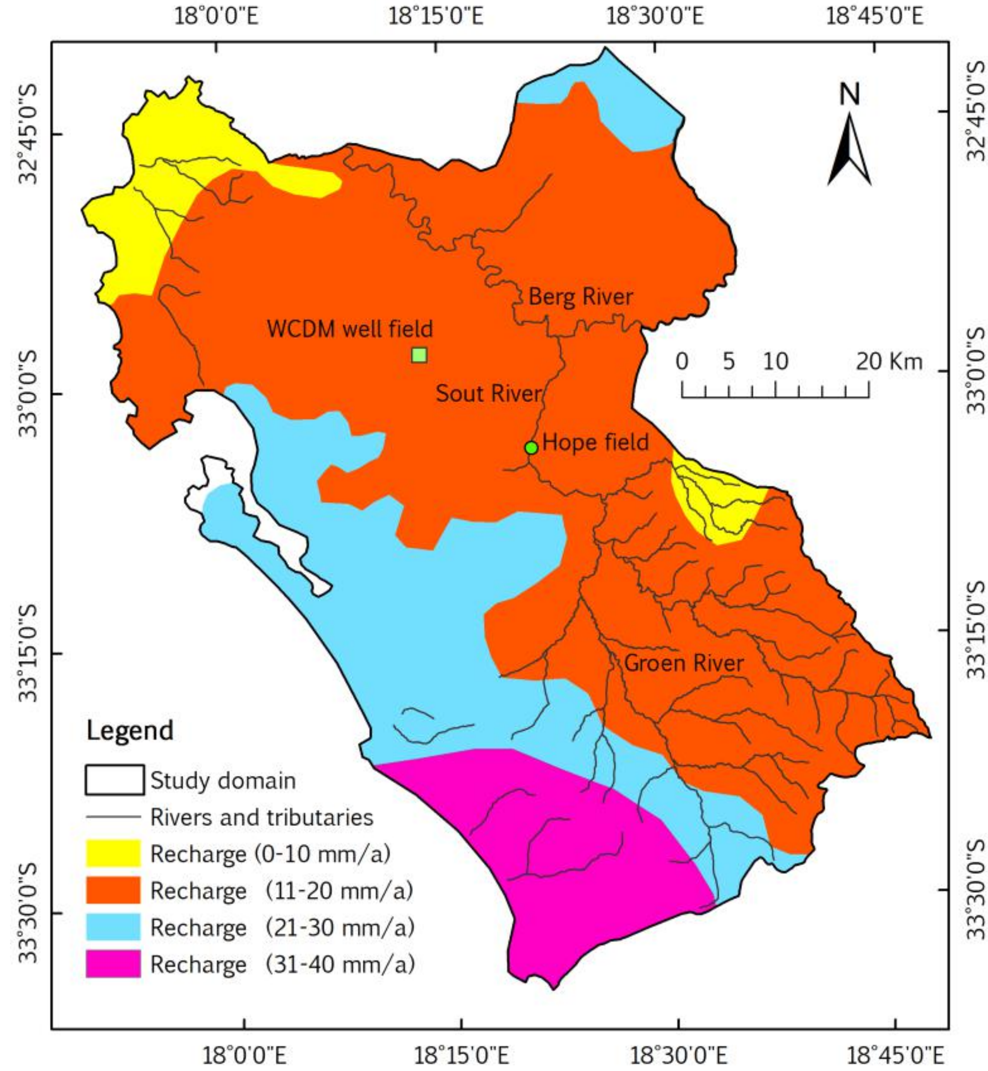


Figure 5-6 Recharge adopted in the model (from DWAF, 2006)

The abstraction from WCDM well field for municipal water supply reduced significantly after July 2009 due to the vandalism of well field pump and infrastructure, thus the main groundwater abstraction are the 78 private users with a total registered abstraction of 6.9 million m^3/a. And the majority of these private users are assumed to take water from the UAU. The abstraction dataset available for modeling contained the Woodford and Fortuin (2003) hydrocensus (Figure 3-12) and the WARMS data used in the modeling of DWAF (2008). Borehole abstraction from the model domain was simulated using the pumping well boundary condition. Outflow rates were assigned to single nodes (at the appropriate elevation) within the model mesh.

(4) Initial conditions of the model

The initial conditions of model were specified as follows:

Initial water level for the model are water heads dataset which were monitored by WCDWS in 2010 and interpolated using Kriging interpolation in ArcGis. When applied to the model, the elevation of water level was corrected if it is above the ground surface.

Hydraulic conductivities were given based on the existing estimates for the area (Table 3-1). Horizontal hydraulic conductivities were set to the same value in both X and Y direction, while vertical hydraulic conductivities were set at 10% of the horizontal conductivities, and not varied.

The water level of Atlantic ocean was set as Time-Variant Specified-Head package with the value of 0 m asml based on the assumption that water level of the ocean won’t change during modeling or the fluctuation has little impact on the groundwater flow system.

The water level of Berg River was assigned through River package by two segments, with its value interpolated from 0 m asml at its ocean entrance in the north, then to 5 m asml at the conjunction of Sout River, and then to 10 m asml in the southeast of the model domain. The water level of the perennial segment of Sout River was assigned through River package with the value to be “Ground surface + 1” m asml. And water level of the other ephemeral streams in the model domain were assigned through Drain package with their values to be “Ground surface”.

(5) Calibration of model

The groundwater flow model started to run after input the data representing initial and boundary condition. Then the model was calibrated by using groundwater monitoring data from 61 boreholes found in the area of Langebaan Road aquifer system and Elandsfontein aquifer system. Among these boreholes, 33 of them represented groundwater table of UAU, and the other 28 boreholes represented the piezometric head of LAU (Figure 5-7). Due to the fact that the dataset is insufficient to form conclusions over the degree of hydraulic separation (difference in piezometric head) between the UAU and LAU, and insufficient for a separate calibration of UAU and LAU. All water level calibration data was therefore grouped together. The model was calibrated for a steady-state condition representing the flow regime before 2014 when there was no significant decrease in rainfall.

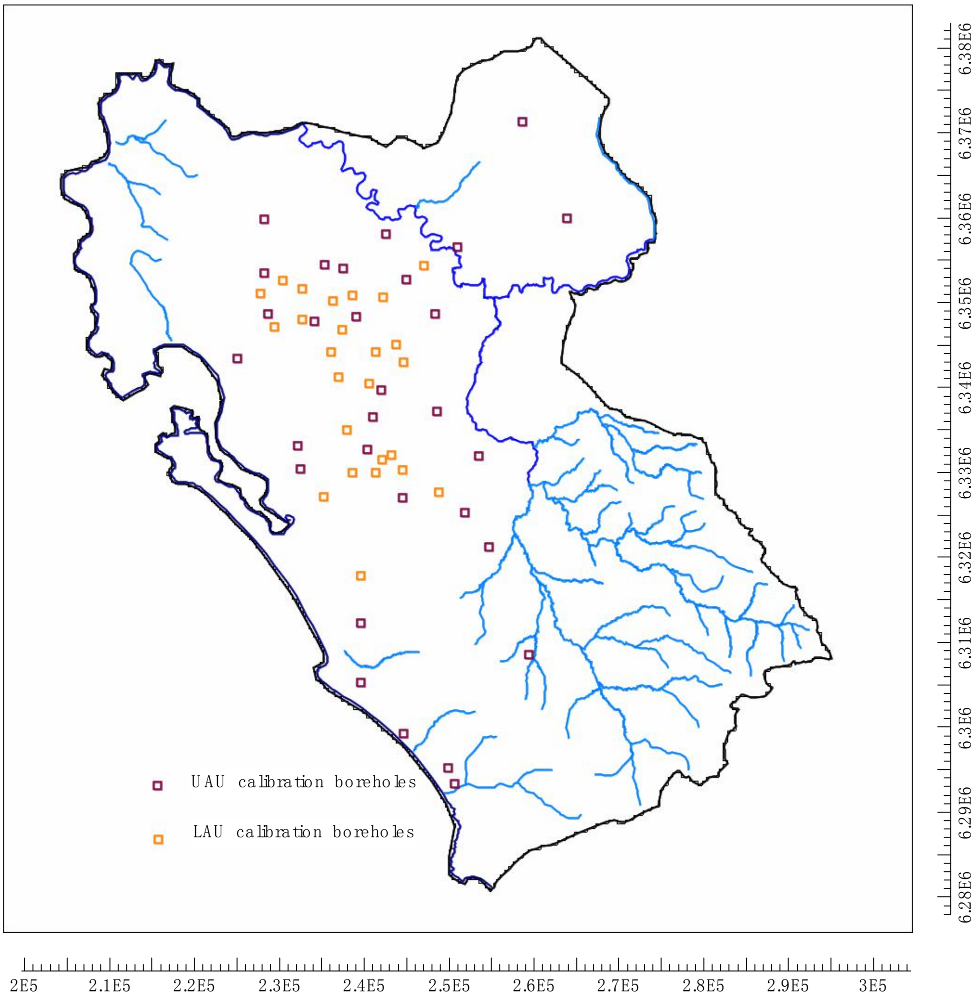


Figure 5-7 Distribution of calibration boreholes

After a period of debugging and improvement, the resulting correlation between observed and simulated piezometric heads is shown in Figure 5-8, which indicates that most of the data distribute closely to the 1:1 line, and the correlation coefficient value is 0.943.

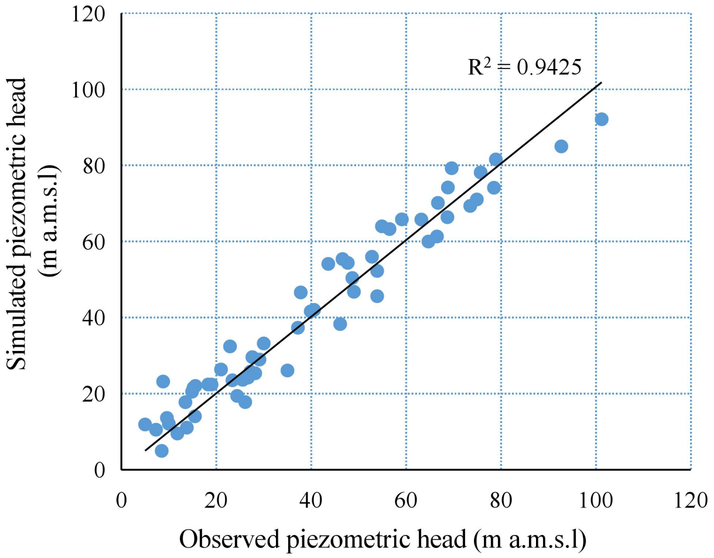


Figure 5-8 Simulated and observed piezometric heads of calibration boreholes, showing most of the simulated and observed data distribute close to the 1:1 line with the correlation coefficient value of 0.943.

Usually, the root mean square error (RMSE) and normalized root mean square error (RMSE) are used as quantitative indicators for the adequacy of the fit between the observed (h_{obs}) and simulated (h_{sim}) water heads:

$$RMSE = \sqrt{\frac{\sum (h_{obs} - h_{sim})^2}{n}} \qquad (5\text{-}1)$$

$$NRMSE = \frac{RMSE}{h_{\max} - h_{\min}} \qquad (5\text{-}2)$$

The result of RMSE of 5.4 m and NRMSE of 5.3% was achieved, with a mean error of 1.04 m. Normally, the value of RMSE and NRMSE less than 10 is generally considered acceptable (Seyler et al., 2016), thus the calibration is considered to be acceptable for the intended modelling purpose.

The calibrated groundwater level in UAU is shown in Figure 5-9, and the groundwater piezometric head of LAU is shown in Figure 5-10.

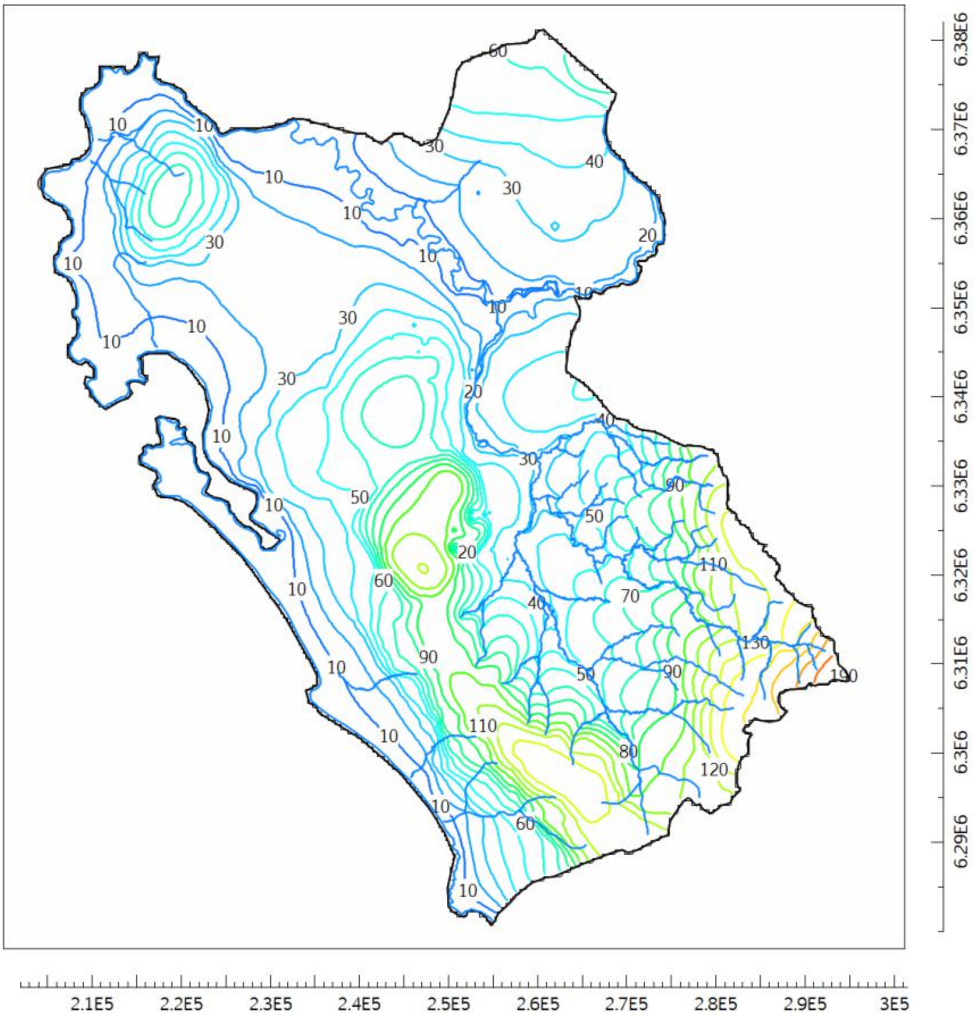


Figure 5-9 Simulated groundwater contours of UAU

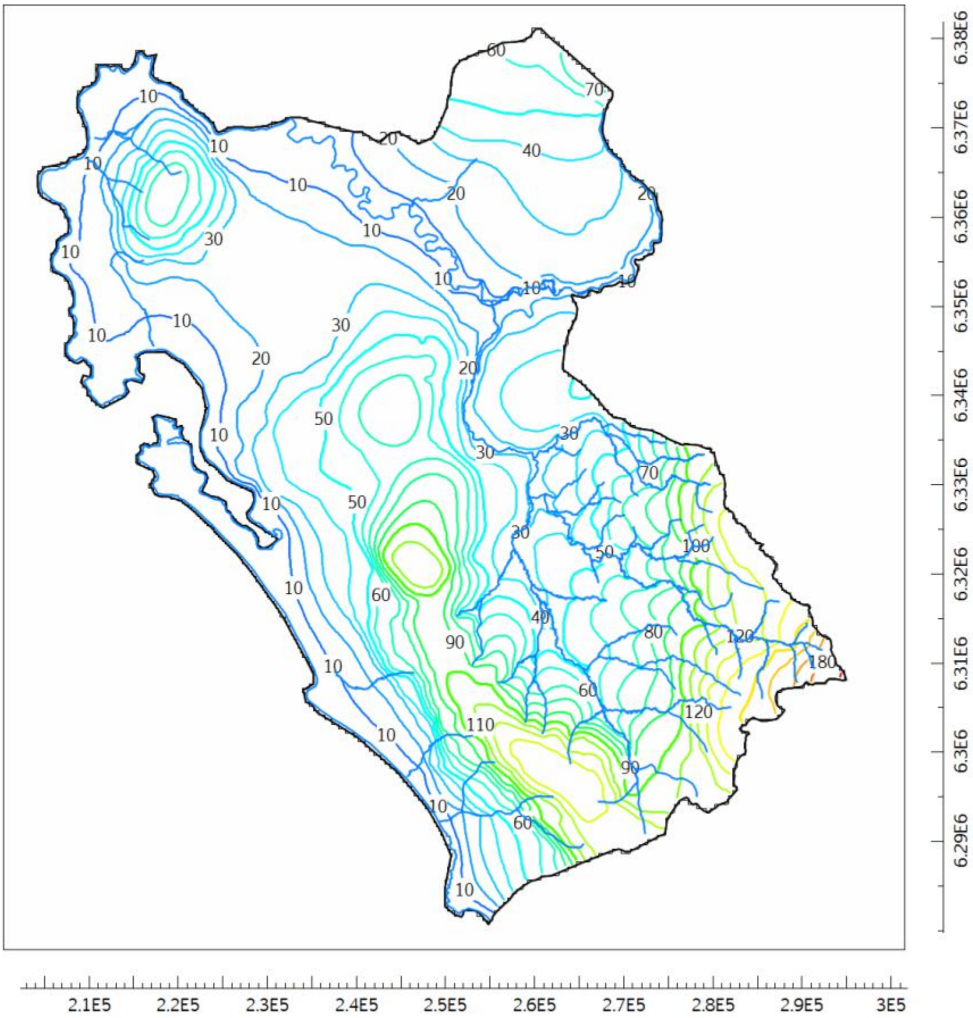


Figure 5-10 Simulated groundwater piezometric head of LAU

5.2 Discussion

The understanding of groundwater flow mechanism is the foundation of the development of groundwater conceptual model. Groundwater flow in UAU is dominated by the topography, which gets recharge form the high elevation areas in southeast of Hopefield then flows and discharges to the low elevation area such as Berg River or the coastline. The groundwater flow mechanism of UAU is consistent with the studies of Timmerman (1985; 1988), DWAF (2010), and Seyler et al. (2016).

Due to lack of outcrop of the Elandsfontyn Formation and its separation from the UAU by the clay layer across most of the interior, the recharge mechanism of LAU is more complex, and more open to interpretation. Timmerman (1985b) suggests that the low permeability UAU sediments around the recharge mound (southwest of Hopefield), would facilitate the downward percolation of the recharged water into the LAU, and then the lateral movement of this water, under increasing confining pressures to the north and northeast, in a north-westernly direction towards the Langebaan Road aquifer system via a ”piston-flow” mechanism. This suggestion is broadly supported by the mapped Elandsfontyn clay thickness for there are several clay-missing windows existed in the southwest of Hopefield which would assist the downward percolation of the recharged water into the LAU. The calibrated groundwater flow model here also achieved a result on the difference of water heads between UAU and LAU, which corresponds with the available dataset that the water levels in the UAU are greater than those piezometric heads in the LAU. This difference in water head would drive the water in UAU moves downwards to recharge LAU, thus supports the “piston-flow” mechanism. According to the distribution of Elandsfontyn clay and the groundwater piezometric heads, the groundwater flow mechanism of LAU in Elandsfontein aquifer system is similar to Langebaan Road aquifer system.

During the calibration process, it is found that there is a highly heterogeneous hydraulic conductivity in each layer to represent the water level variability. Large differences in model errors occurred in close proximity to each other, suggesting a high heterogeneity that is not replicated in the model. To replicate the observed water levels, the hydraulic conductivity of UAU is lower in the Elandsfontein aquifer system than other regions (Table 5-3). This maybe caused by the special stratum structure. According to Timmerman (1985b), up to four aquifer-aquitard layers may be present within the UAU in the Elandsfontein aquifer system. In comparison to the Elandsfontein aquifer system, the hydraulic conductivity of UAU in the Langebaan Road aquifer system region is larger than other regions in order to replicate the observed water levels. Due to the complexity of the aquifer, the calibrated conductivities are not well in good match with the geology map.

Table 5-3 Calibrated hydraulic conductivities of modeling

Model layer	Hydraulic conductivity (m/d)			Remarks
	Kx	Ky	Kz	
1	0.05-9	Kx	Kx /10	The low values are usually concerned with stratigraphy of Langebaan Formation, which is mainly distributed at the area of Elandsfontein aquifer system together with the connection area between Langebaan Road aquifer system and Elandsfontein aquifer system; High values are usually concerned with stratigraphy of Springfontyn Formation, which is mainly distributed at Langebaan Road aquifer system area.
2	0.001-0.008	Kx	Kx /10	/
3	0.2-50	Kx	Kx /10	The low values are mainly distributed at the area of EAS together with the connection area between Langebaan Road aquifer system and Elandsfontein aquifer system; High values are usually distributed at Langebaan Road aquifer system area.
4	0.02-0.2	Kx	Kx /10	/

The water budget of calibrated model is shown in Table 5-4. From the calculated water balance, the recharge in the modeling is 229897.27 m^3/d. The biggest contribution to discharge is drainage from tributaries, accounting for 40.82% of the total discharge amount; followed by the drainage to the ocean, accounting for 34.13%; and then river leakage, with the value of 17.27%. This water budget is similar to the research of Seyler et al. (2016).

Table 5-4 Water budget of the calibrated model (inflows to the aquifer as positive, outflows as negative)

Item	Fluxes (m^3/d)	percentage
Recharge	229897.27	100
Ocean net	-78463.32	-34.13
River leakage (Berg River and Sout River)	-39698.8	-17.27
Drains (Groën River & Tributaries)	-93838.05	-40.82
Abstraction	-17232.47	-7.5
Difference	664.63	0.28

Although uncertainty exists due to the complexity of aquifers system as well as the availability of limited data, the groundwater flow model is match with water flow mechanism, the model is considered to be acceptable for the following modeling assessment of MAR.

Chapter 6: Evaluation of suitable sites for MAR: Results and discussion

6.1 Results

6.1.1 Suitable sites for MAR of UAU in West Coast, South Africa

(1) Criteria and the AHP structure

The hydrogeological characteristics and all of the other available data of the study area were analyzed, and the main hierarchical structure with the criteria and subcriteria is shown in Figure 6-1. In terms of the criterion of source water availability, the source water is assumed to be the runoff of the Berg River in the rainy season, thus both the water quantity and quality are supposed to satisfy for the purpose of artificial recharge; subsequently, the source water availability mainly depends on the distance between the source and the recharge sites.

The subcriteria, or thematic layers were standardized, and results areshown in Figure 6-2.

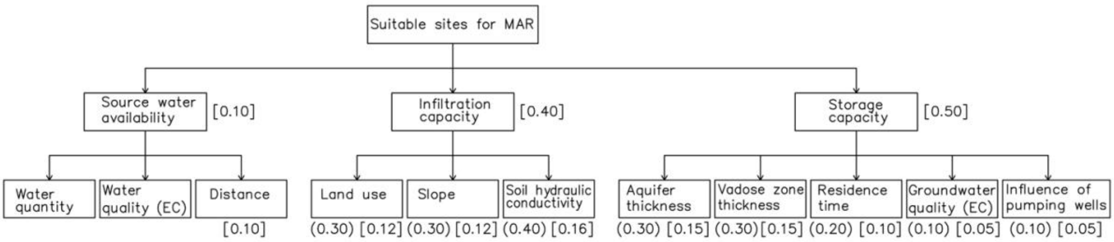


Figure 6-1 Criteria for the suitability mapping and hierarchical structure with local weights given in "( )"and global weights given in "[ ]".

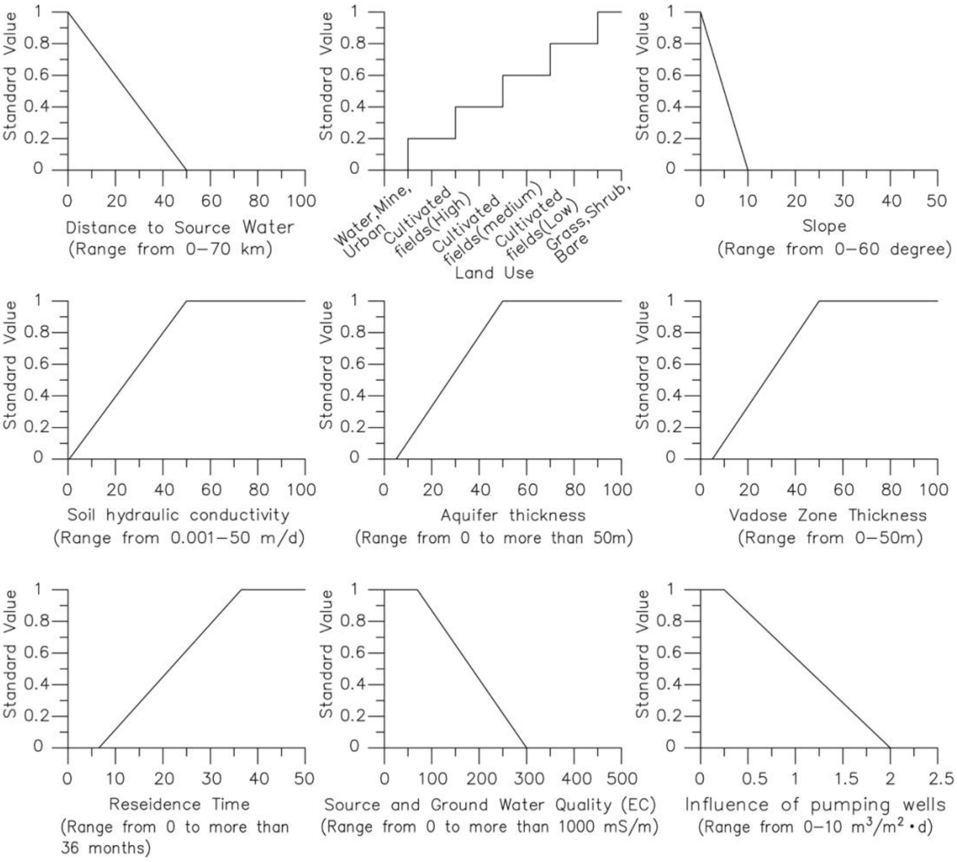


Figure 6-2 Procedure for the subcriteria standardization used in this study (range indicates the limit of the criteria value present in the study area).

(2) Distribution of suitable sites for MAR in UAU in West Coast

Thematic maps including distance to source water, land use, slope, soil hydraulic conductivity, aquifer thickness, vadose zone thickness, residence time, ground water quality and the influence of pumping wells, together with the site suitability index are shown in Figure 6-3.

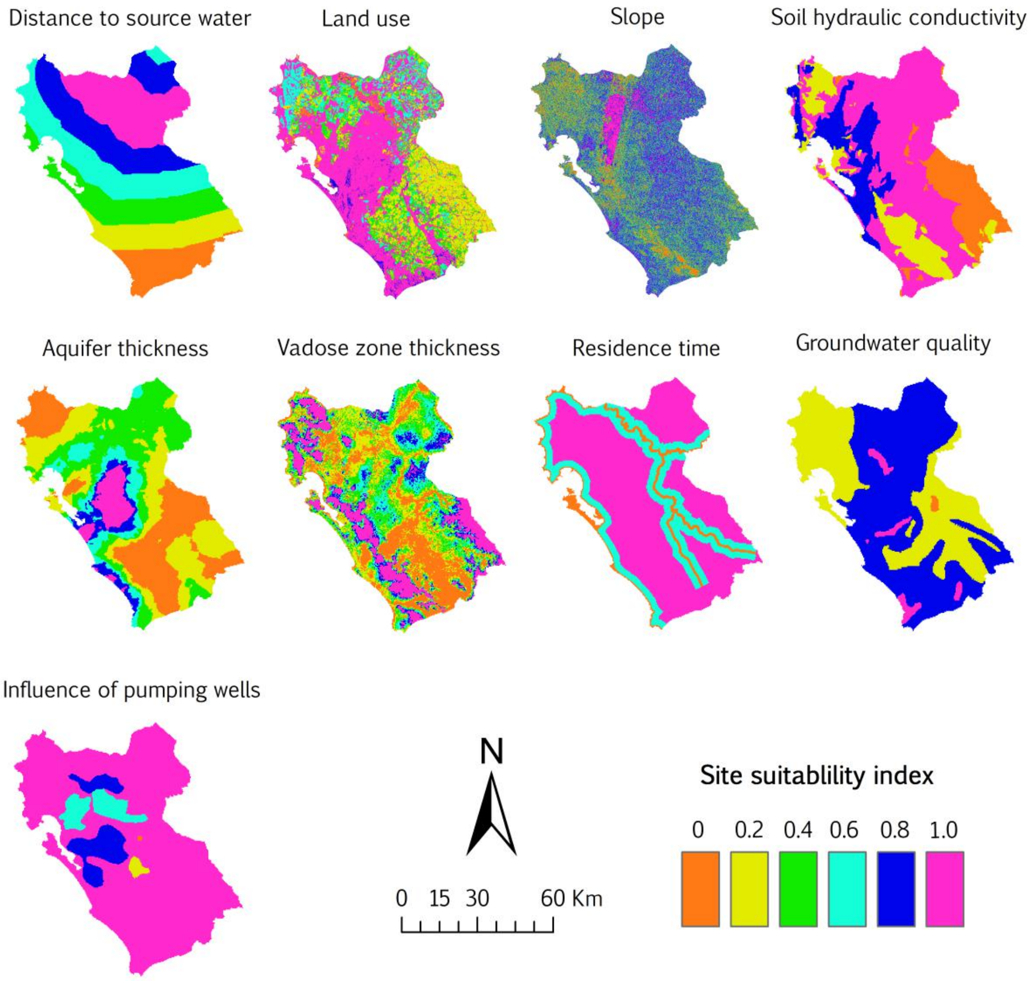


Figure 6-3 Thematic maps of the site suitability index to apply MAR in UAU of study area

Maps of source water availability, infiltration capacity, storage capacity were classified, and results are shown accordingly in Figures 6-4, 6-5 and 6-6. Since the water availability is mainly dependent on the distance to the Berg River, the greater the proximity, the more suitable the site (Figure 6-4). For the criterion of infiltration capability, the area distributed with Cenozoic sediments was more suitable than the area with an outcrop of bedrocks, which indicates the significant influence of lithology (Figure 6-5). The suitability map of the storage capacity criterion showes that the high suitability sites are located west of Hopefield, where the aquifer thickness and the depth to groundwater table are greater than at any other place, while the low suitability sites are located in areas close to the discharge area including the Berg River and coastline (Figure 6-6).

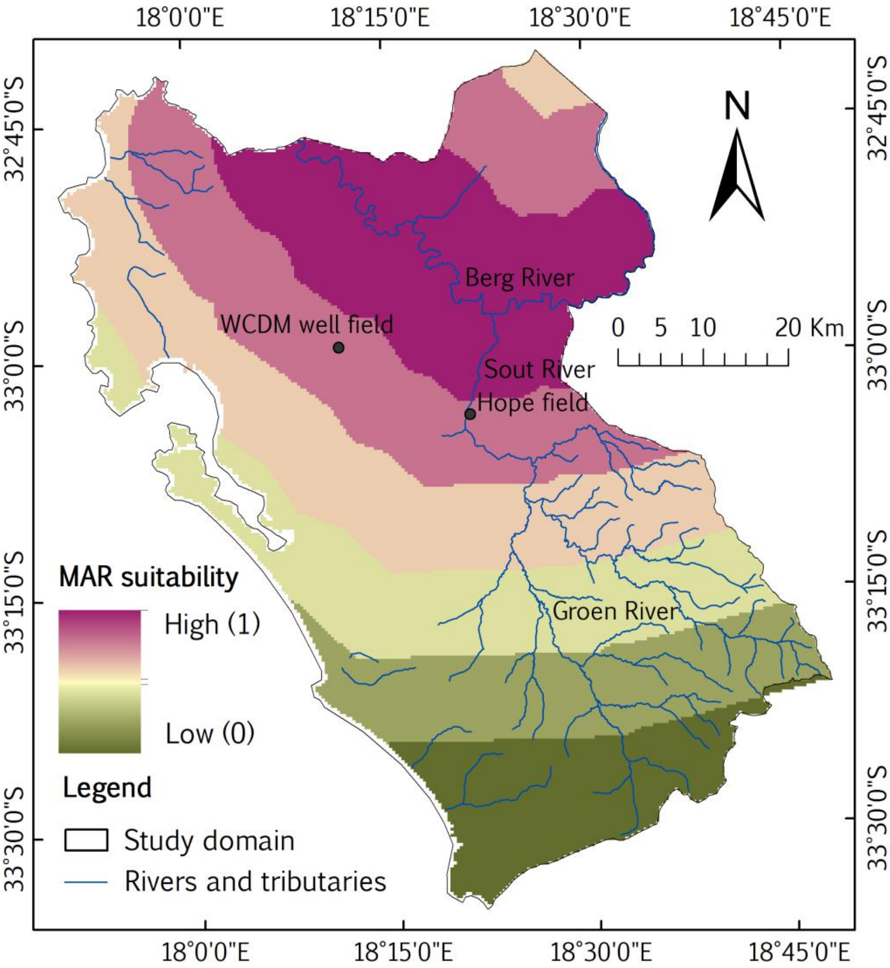


Figure 6-4 Criterion source water availability and its relative MAR suitability

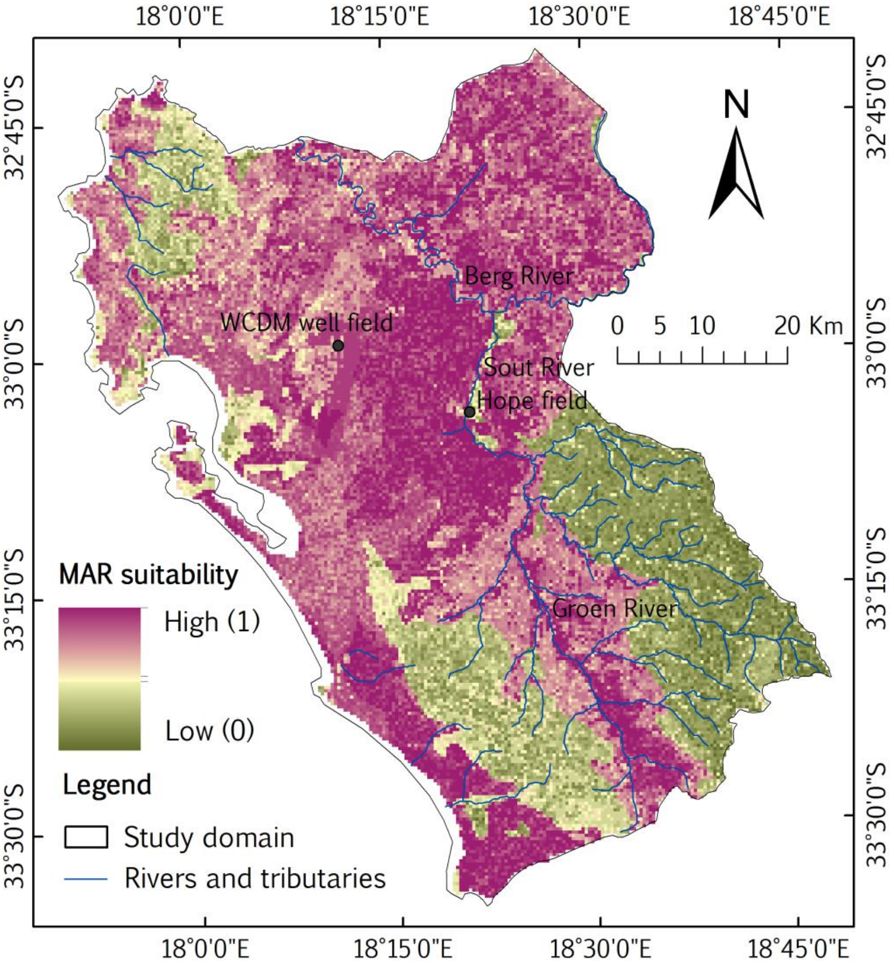


Figure 6-5 Criterion infiltration capability and its relative MAR suitability

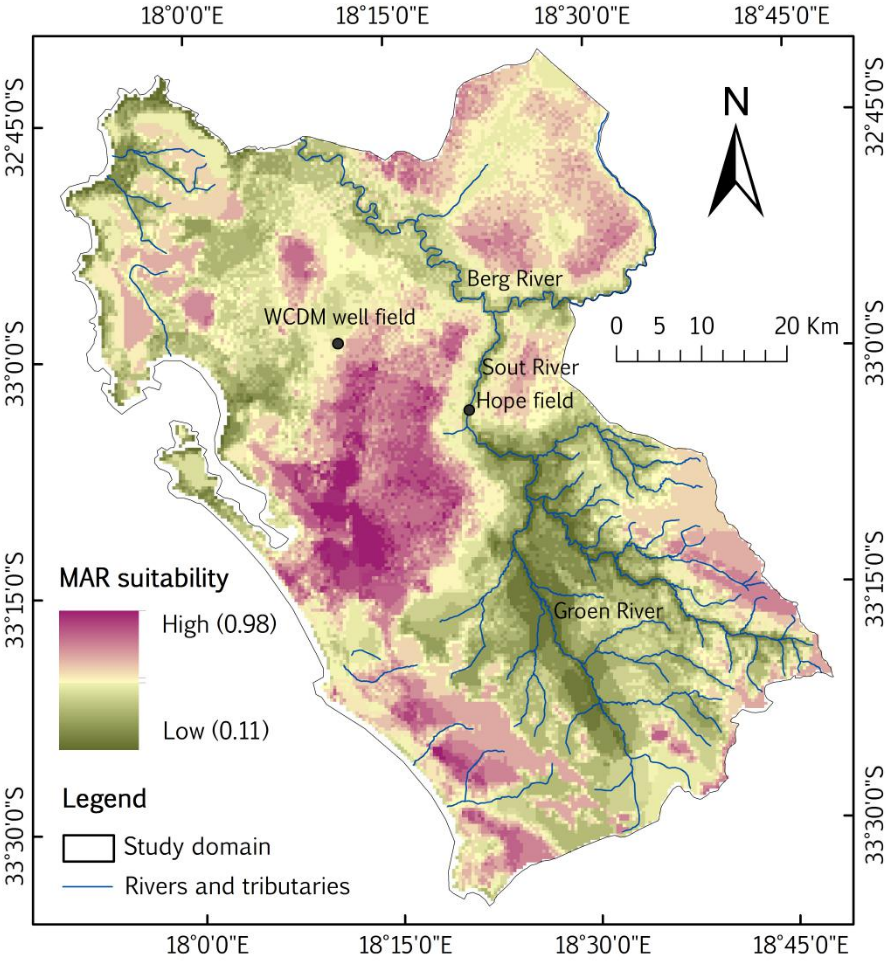


Figure 6-6 Criterion storage capability and its relative MAR suitability

The datasets of the criteria for the classified maps were combined to generate an integrated site map across the study area (Figure 6-7). The calculated MAR suitability indices range from 0.17 to 0.93 in the order of increasing suitability, with a mean value of 0.57 and a standard deviation of 0.16. The area of low suitability sites (Index < 0.60) is 2327.6 km^2, accounting for 52.2% of the total assessed area, which is mainly located in the southeast and northwest part of the study area. The area of suitable sites (Index > 0.60) is 2135.3 km^2, accounting for 47.8% of the total assessed area, covering most of the Cenozoic sediments distribution area. The area of sites with a high suitability (Index > 0.80) is 231.3 km^2, which is located southwest of Hopefield, and commonly regarded as the natural recharge area of the Langebaan Road aquifer system and Elandsfontein aquifer system, followed by of the area north of the Berg River.

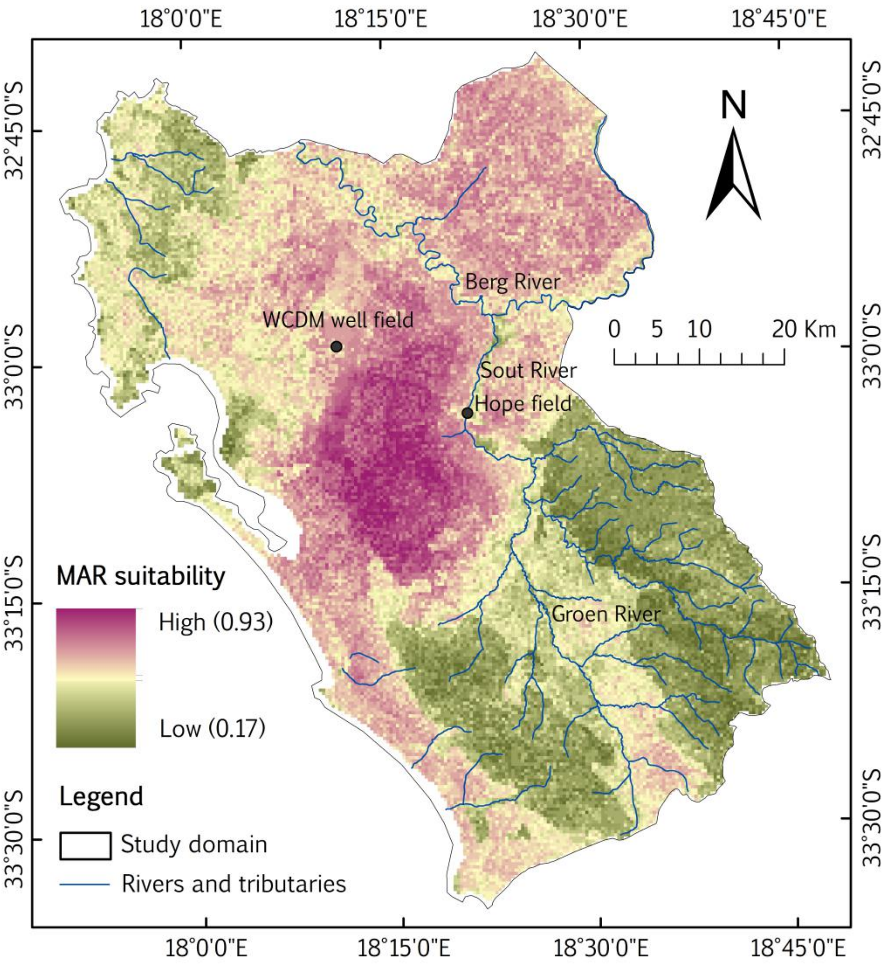


Figure 6-7 Suitable sites map for UAU integrated by the GIS based analysis.

6.1.2 Suitable sites for MAR in LAU in West Coast, South Africa

Compared with the UAU, the recharge mechanism of LAU is more complex. The confined aquifer is usually divided into recharge area, confined area and discharge area, and the recharge area is always considered as the most suitable site for the implementation of MAR (Figure 6-8). Since the recharge mechanism of recharge area is similar to the unconfined aquifer, the criteria and hierarchical structure used in UAU in Figure 6-1 is also feasible to map the suitable sites of LAU, but the thickness of confined aquifer is used to replace the data of unconfined aquifer. Meanwhile, the aquitard clay was added as a subcriterion to support the criterion of Infiltration capacity. The criteria and hierarchical structure for the suitability mapping is shown in Figure 6-9.

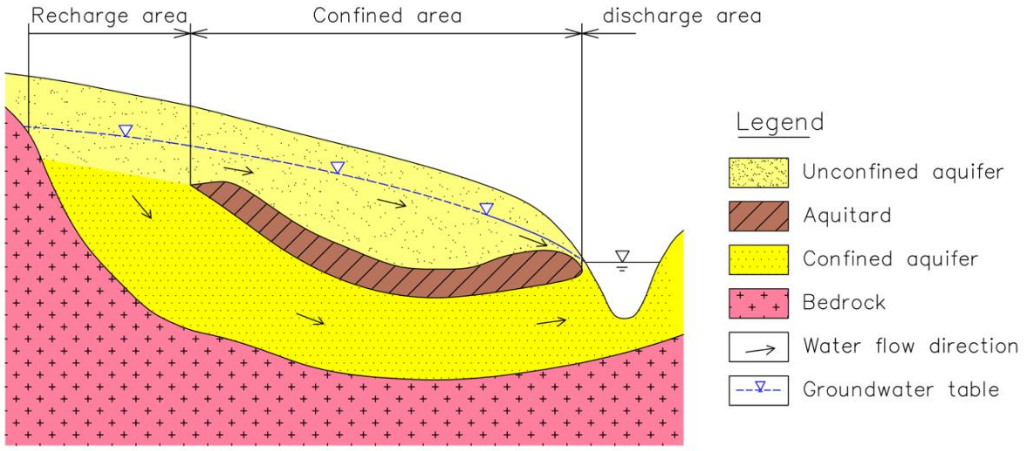


Figure 6-8 Sketch map of confined aquifer system

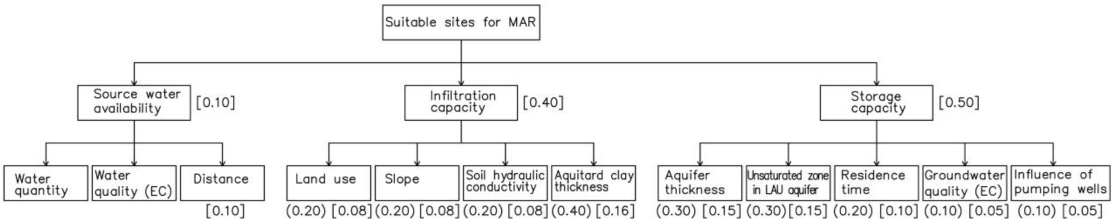


Figure 6-9 Criteria of the suitability mapping for LAU and hierarchical structure, local weights given in “( )”and global weights given in “[ ]”.

Thematic maps including distance to source water, land use, slope, soil hydraulic conductivity, aquifer thickness, aquitard clay thickness, vadose zone thickness, residence time, ground water quality and the influence of pumping wells, together with the site suitability index are shown in Figure 6-10.

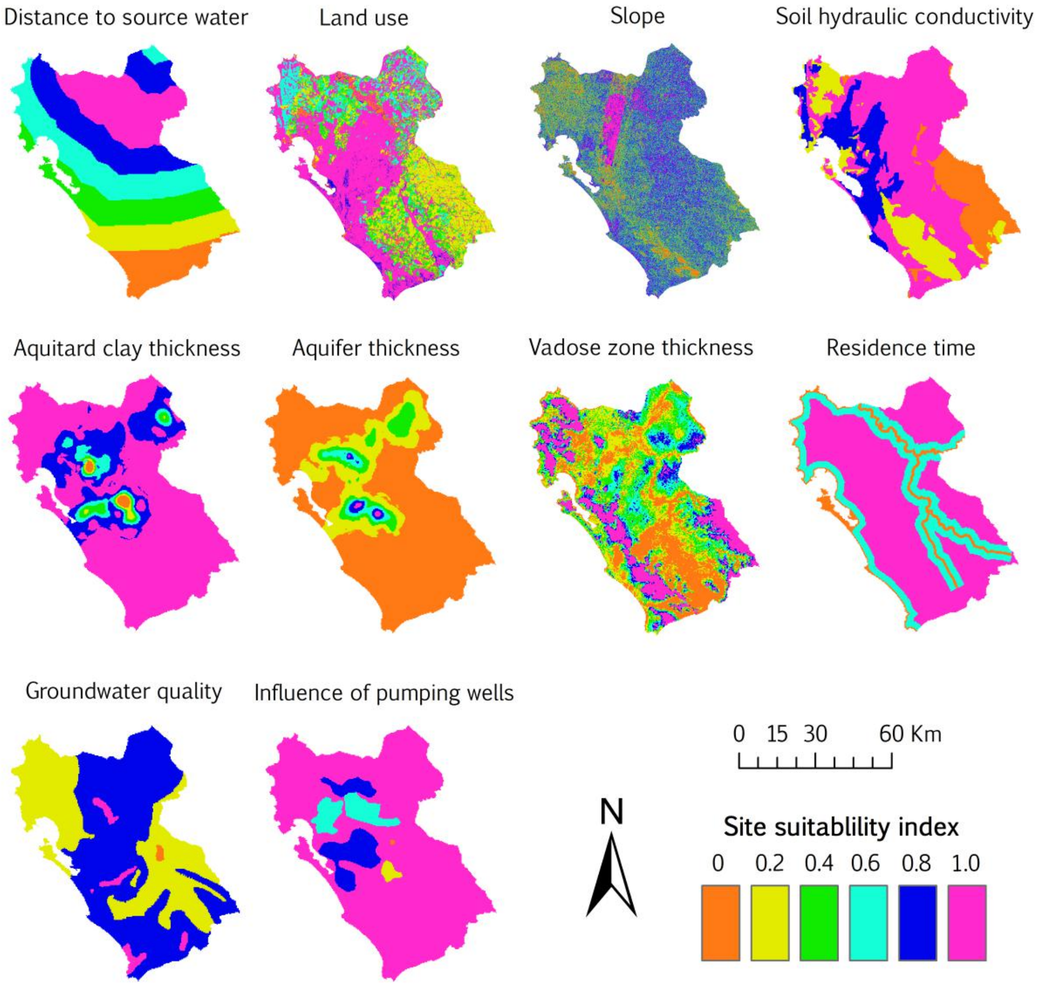


Figure 6-10 Thematic maps of the site suitability index to apply MAR in LAU of study area

The suitable sites map for LAU is shown in Figure 6-11. The calculated MAR suitability indices range from 0.31 to 0.85 in the order of increasing suitability, with a mean value of 0.57 and a standard deviation of 0.08. The area of low suitability sites (Index < 0.60) is 2788.8 km^2, accounting for 62.5% of the total assessed area, which is mainly located in the southeast parts of the study area. The area of suitable sites (Index > 0.60) is 1675.9 km^2, accounting for 37.5% of the total assessed area, which is mainly located in the Cenozoic sediments distribution area of Langebaan Road aquifer system, the Elandsfontein aquifer system and north of Berg River. The area of sites with a high suitability (Index > 0.80) is 4.9 km^2, which is mainly located southwest of Hopefield, where it is commonly regarded as the natural recharge area.

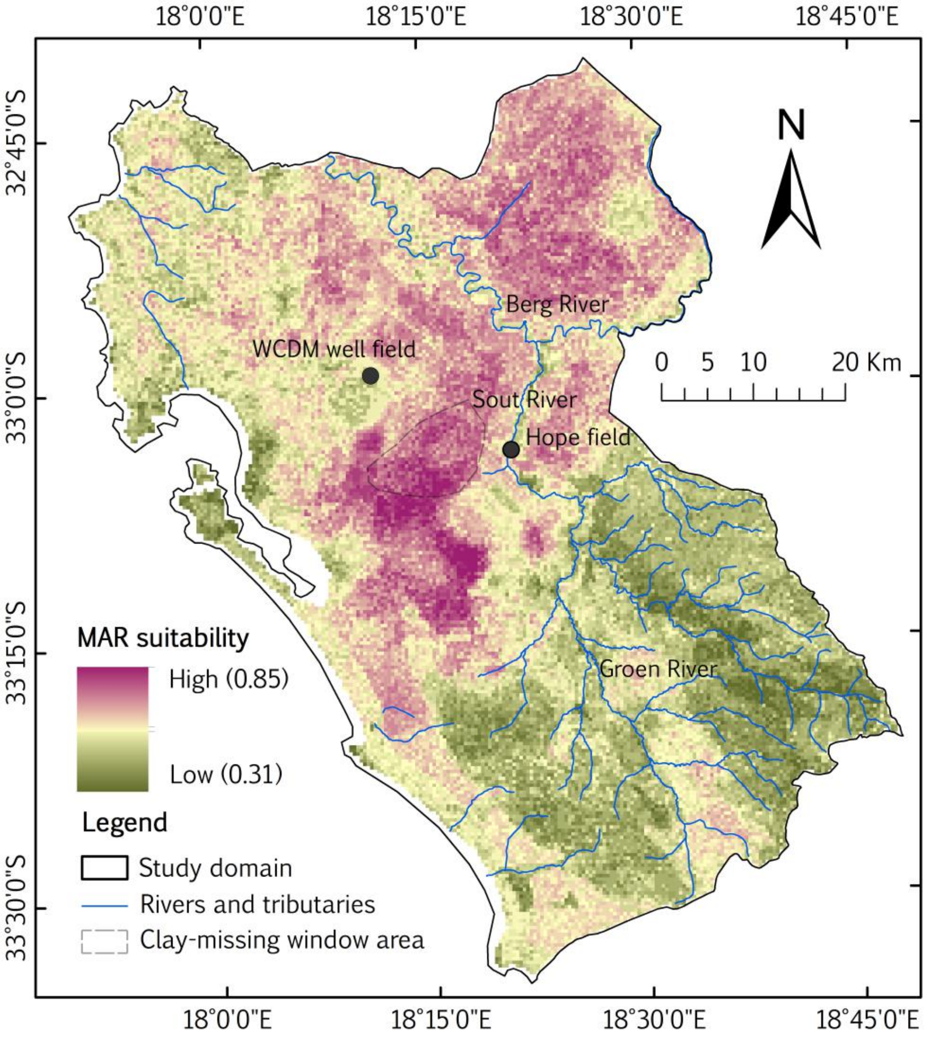


Figure 6-11 Suitable sites map for LAU integrated by the GIS based analysis.

6.2 Discussion

Due to the powerful spatial analysis ability of GIS, the GIS based method has been widely applied to suitability analysis, and has been proven to be a useful technique. The most popular method from the literature has been to integrate the criteria with different weights, despite the adopted criteria and weighting methods being divergent from different cases. In this thesis, the AHP was incorporated into the criteria choice and weights determination. The AHP method was adopted to develop a three-level criteria tree based on the fact that the MAR project is largely dependent on the factors of source water availability, infiltration capacity, and storage capacity. Then, subcriteria including source water quantity, water quality, distance, land use, slope, soil hydraulic conductivity, aquitard clay thickness, aquifer thickness, vadose zone thickness, residence time, ground water quality, and influence of pumping wells were chosen to support these three criteria. The combination of AHP with WLC was assumed to provide a more effective way for spatial decision problems. When this method was applied to the case study of the West Coast of South Africa, a reasonable result was achieved. The area of suitable sites (Index > 0.60) for implementing MAR in UAU is 2135.3 km^2, which are mainly located west of Hopefield as well as parts of north Berg River and coast area of G21A where were characterized by Cenozoic sediments distribution area, thick aquifer and larger depth to groundwater table. It seems that the GIS based analysis is useful and correct to select the suitable sites in UAU.

The area of suitable sites for implementing MAR in LAU is 1675.9 km^2, which are also mainly located west of Hopefield and north of Berg River. The mapped suitable sites coincide with the clay-missing area described in Figure 3-8 and Figure 3-9 in Chapter 3. Meanwhile, Figure 6-11 also shows that the area of WCDM well field is unsuitable sites for the implementation of MAR, which was verified by the two borehole injection trials targeting at LAU at WCDM well field carried out by Tredoux and Engelbrecht (2009). Therefore, this GIS method is proved to be functioning in LAU. However, the mapped area of suitable sites is larger than the clay-missing areas in Figure 3-8, especially at the areas where are characterized as thick aquifer and large thickness of vadoze zone. The possible reason of which maybe the suitability index was enlarged by the weighted linear combination method of GIS analysis. Meanwhile, the groundwater flow was not taking into account, which may also result in uncertainty.

As is mentioned above, the suitable sites which are screened out for implementing MAR in West Coast by the GIS based method are generally reasonable. And it seems that the GIS based analysis performs better in UAU than in LAU. Based on the mapped suitable sites , the areas of west of Hopefield and north of Berg River are the suitable sites with most possibility for the implementation of MAR in both UAU and LAU, which need to be focused on.

Chapter 7: Assessing appropriate schemes for implementing MAR: Results and discussion

7.1 Results

7.1.1 Simulation scenarios

In order to simulate the suitable sites and proper scheme of MAR implementation, five predictive scenarios were designed to model the impacts of implementing MAR in UAU and LAU (Table 7-1). The aim of scenario one was to model the implementation of MAR in UAU through infiltration pools based on the suitable sites mapped through GIS method (Figure 7-1), while scenario two intented to simulate the groundwater flow of implementing MAR in LAU at the suggested sites by GIS analysis (Figure 7-2). Scenarios three, four and five were designed to simulate the influence of implementing MAR in LAU under varied situation. As is described in Chapter 3, there is a clay-missing window at west of Hopefild, which is considered as the most suitable site for LAU of Langebaan Road aquifer system and Elandsfontein aquifer system, therefore, injection wells and infiltration ponds were assigned mainly in this clay-missing window in the modeling.

Table 7-1 Details of predictive scenarios in simulation

No.	Aim	Scenario description
Scenario one	To verify suitable sites mapped by GIS analysis, and to simulate the influence of implementing MAR at different sites in UAU.	Six infiltration ponds (Length × Width × Depth: 250 m × 250 m × 3 m) with the recharge rate of 200 m^3/d respectively were placed at the different sites (Figure 4.3-6). A and B representing locations with high suitability; C and F representing locations with medium suitability; D and E representing locations with low suitability. MODPATH was used to trace the recharged water.
Scenario two	To verify the result of GIS mapping, and to optimize the suitable sites for implementing MAR in LAU.	Four injection wells including G, H, M and N with the recharge rate of 200 m^3/d each were placed at four different sites (Figure 4.3-7). The depth of the injection wells was from model top to LAU bottom. MODPATH was used to trace the recharged water.
Scenario three	Simulating the influence of implementing MAR in LAU at clay-missing window	Step 1: Three injection wells with the recharge rate of 200 m^3/d each were placed at three different sites in the clay-missing window area, which is also considered as the natural recharge area of LAU. The depth of the

		injection wells was from model top to LAU bottom. Step 2: Same as step 1, three injection wells with the recharge rate of 200 m^3/d each were placed at three different sites in the clay-missing window area. At the same time, four abstraction boreholes at the WCDM well field (including 46032, 46033, 46034, 46036) were pumping groundwater from LAU with the rate of 500 m^3/d each. Modpath package was used to trace the recharged water.
Scenario four	Simulating the influence of implementing MAR in LAU at clay-missing window under varied abstraction rate in WCDM well field	One injection well with the recharge rate of 200 m^3/d was placed at the north of clay-missing window, and the abstraction boreholes 46036 at WCDM well field was assigned with the pumping rate varied at 500 m^3/d, 1000 m^3/d, 2000 m^3/d and 5000 m^3/d. Modpath package was used to trace the recharged water.
Scenario five	Simulating the implementation of MAR in LAU in clay-missing window and outside clay-missing window under varied abstraction quantity in WCDM well field	One injection well with the recharge rate of 200 m^3/d was assigned in the west of clay-missing window area, and another infiltration pond (Length: 250 m, Width: 250 m, Depth: 3 m) with the recharge rate of 200m^3/d was placed outside of the clay-missing window but closer to the WCDM well field. Simulation was performed based on the varied number of abstraction boreholes at the WCDM well field with the rate of 500 m^3/d each.

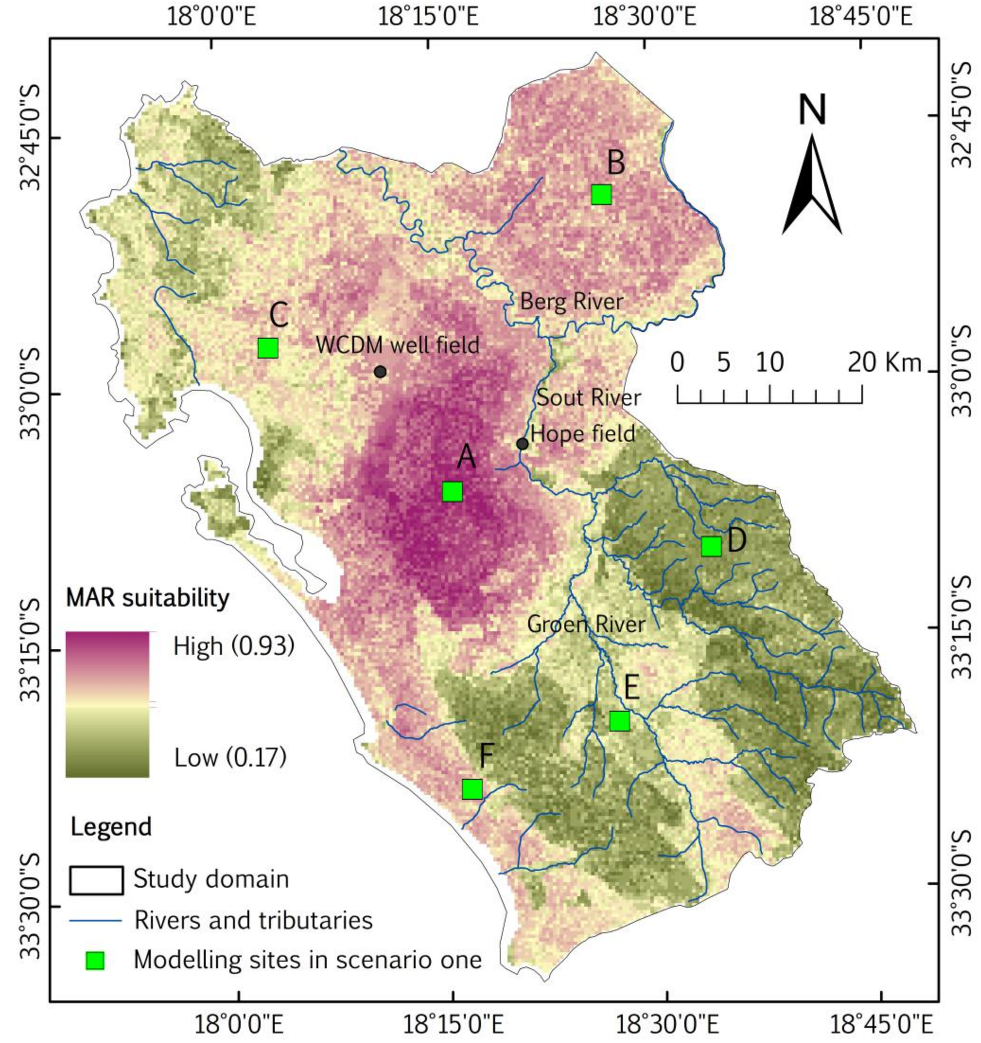


Figure 7-1 Modeling sites in suitable sites map of UAU in scenario one

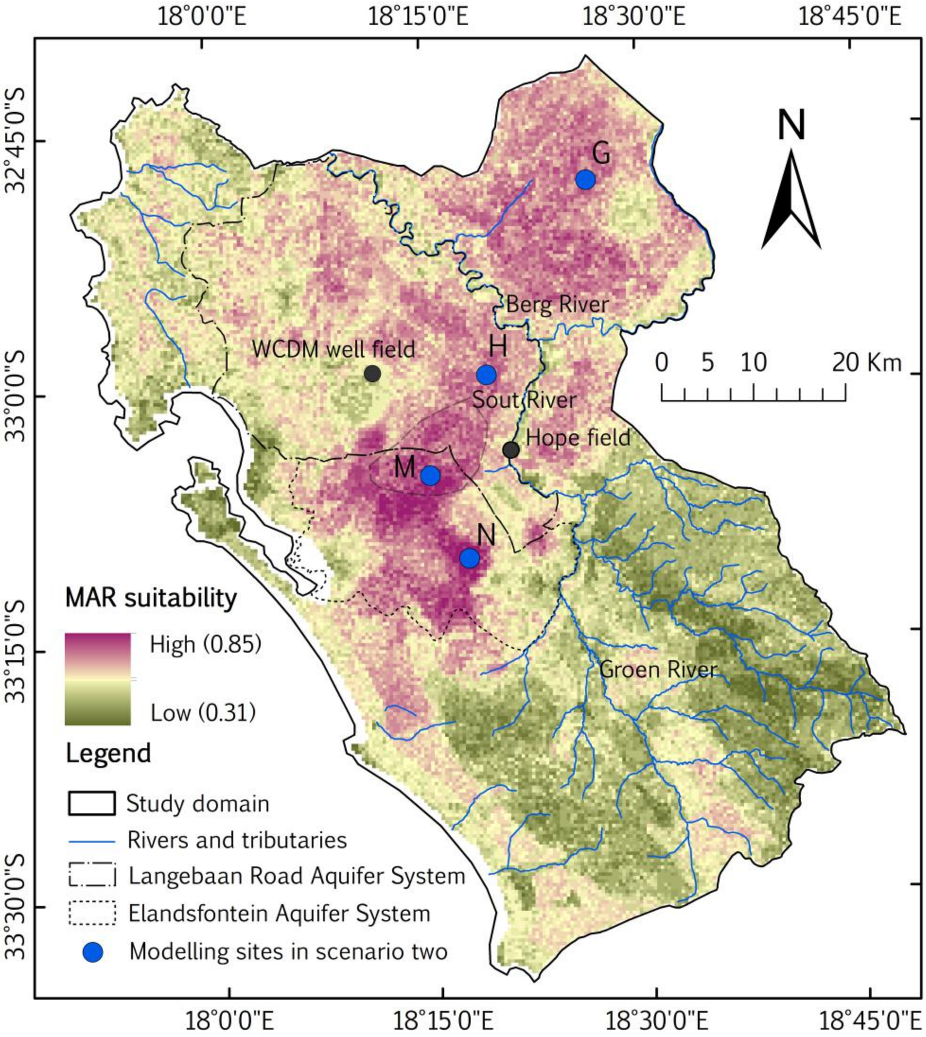


Figure 7-2 Modeling sites in suitable sites map of LAU in scenario two

7.1.2 Scenario one

The results of scenario one are shown in Figures 7-3 and 7-4, and Table 7-2. The artificial recharge results in rise in local groundwater level around the recharge sites. A comparison among these three groups of locations with different suitability indices, unsurprisingly the locations with higher suitability, could be characterized with a higher rise in the groundwater level at recharge sites, larger storage area, and longer flow path. The largest rise in groundwater level occurred at locations D and E with low suitability indices on the map instead of at locations of A and B, that is because the low permeability of lithology at D and E made it difficult for the recharged water to enter into the aquifer, leading to a comparatively higher rise in water level at the injection locations. In terms of the region of high rise in water level of locations D and E, it would take a long time for the recharged water to achieve the equilibrium state showed in the modeling, which is impractical when implementing a MAR scheme. From the simulation results of this scenario, the suitable sites map developed by using the GIS analysis method is verified to be reasonable.

Figure 7-4 showes the flow paths of the recharged water, and reflects the divergent flow directions and discharges when recharging at different locations. It seems that only implementing MAR at sites A and C is able to store water in the Langebaan Road aquifer system and Elandsfontein aquifer system.

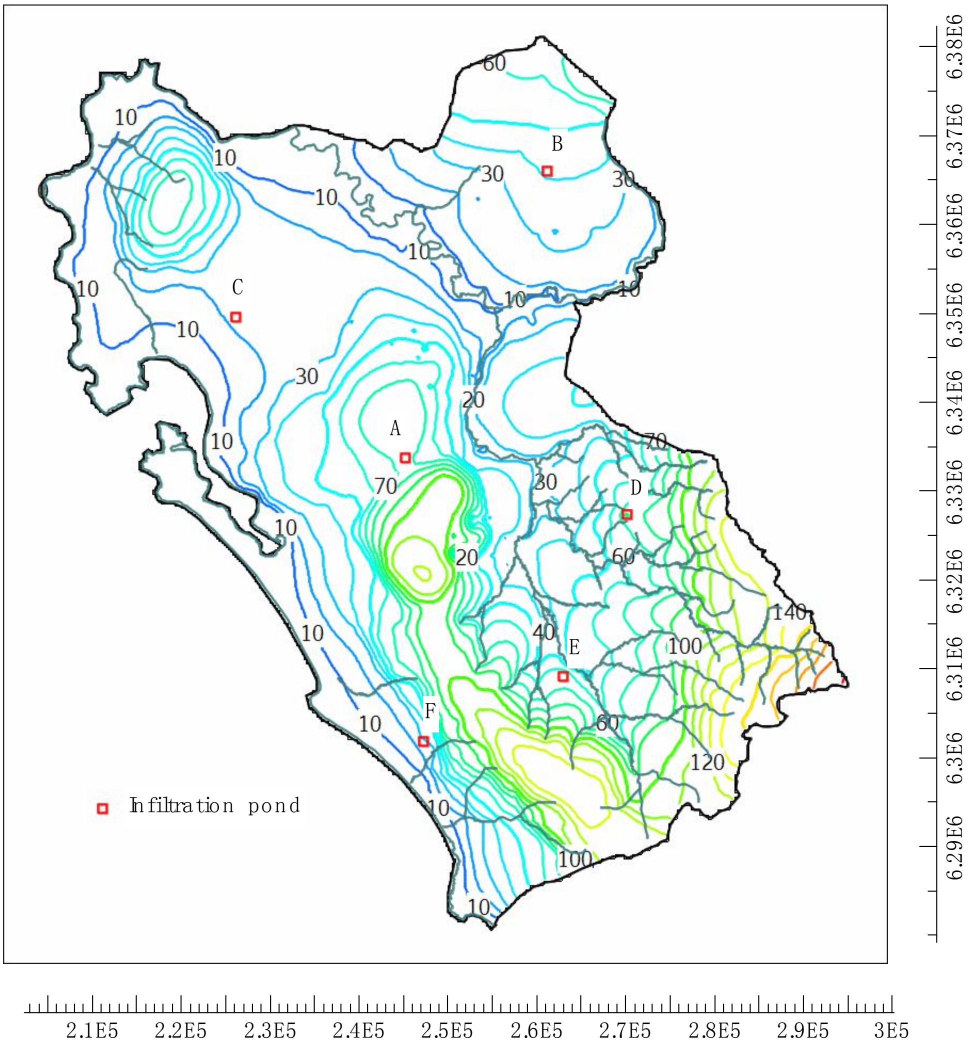


Figure 7-3 Simulated groundwater level map of the study area. The unit of the horizontal and vertical scale is in meters (m).

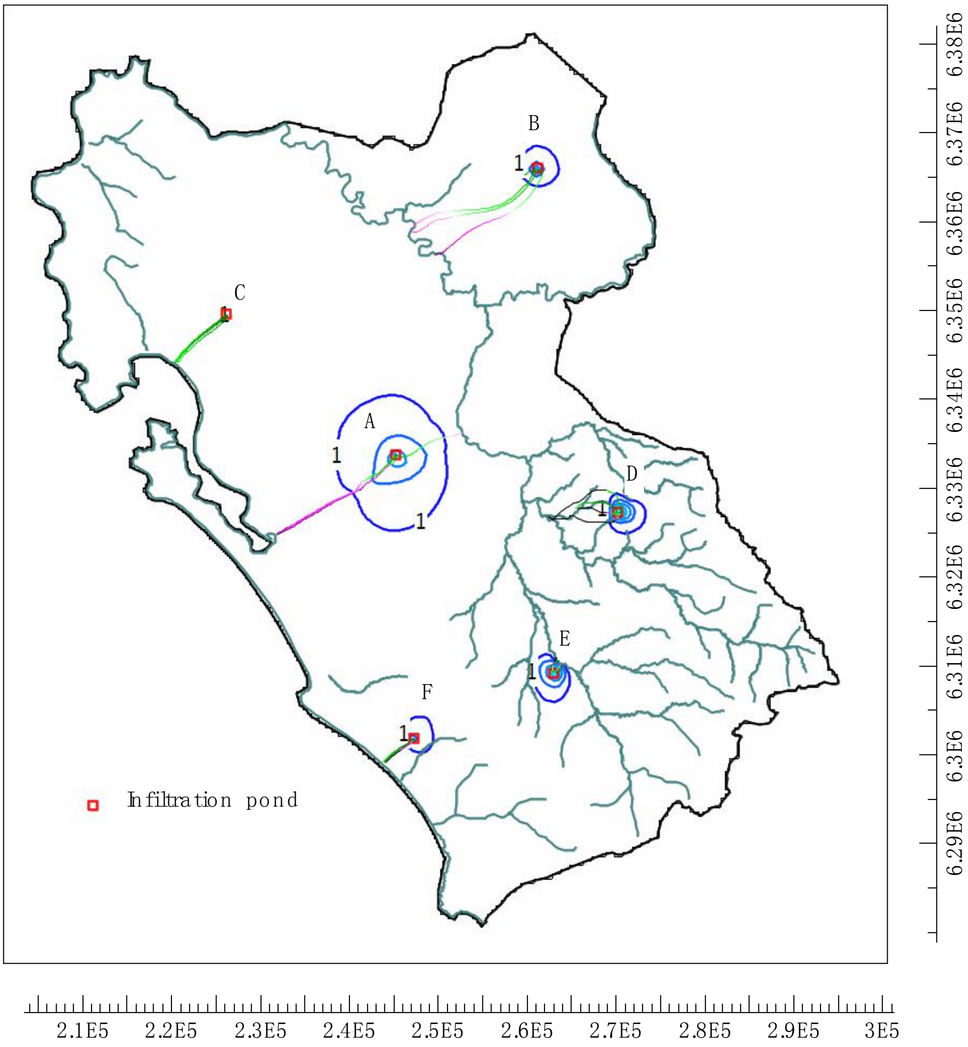


Figure 7-4 Rise in groundwater level and the flow paths of the recharged water. The unit of rise in groundwater contours is meters (m), and the interval of contours is 1 m. The color of the flow paths indicate the flow time: The greener the flow path, the shorter the flow time; and the more purple the flow path, the longer the flow time.

Table 7-2 Simulated results of implementing MAR in the UAU.

Location	**Suitability Map Site**	**Discharge Location**	**Length of Flow Path**	**Maximum Rise in Groundwater Level (m)**	**Region of Ground Water Level Rise above 1 m**
Infiltration pond A	Highest Suitability	Partly to tributary of Berg River, partly to Langebaan Lagoon	8300–16,300	+4.0	A nearly circular region with 13,000 m in diameter.
Infiltration pond B	High Suitability	Berg river	15,600–16,700	+5.0	A nearly circular region with 4600 m in diameter.
Infiltration pond C	Medium Suitability	Saldanha Bay	7900	+1.0	A nearly circular region with 250 m in diameter.
Infiltration pond D	Low Suitability	Tributary of Berg River	440–12,700	+12.0	A nearly circular region with 3700 m in diameter.
Infiltration	Low	Tributary of Berg	1200–1950	+8.0	A nearly circular

pond E	Suitability	River			region with 4100 m in diameter.
Infiltration pond F	Medium Suitability	Coastline	4300	+3.0	A nearly circular region with 3400 m in diameter.

7.1.3 Scenario two

In scenario two, four injection wells including G, H, M and N were placed at four different sites which are suggested by the GIS based analysis. The result of simulation is shown in Figure 7-5. It can be seen from the simulation that the artificial recharge results in rise in pizometric head around the recharge sites, and the scope of which ranges from 1 m (Location G) to 14 m (Location H). And similar to the artificial recharge in UAU, the water recharged at different sites shows divergent flow directions. However, the water recharged at site G (northeast of Berg River) flows southwest and finally discharged into Berg River rather than Langebaan Road aquifer system and the Elandsfontein aquifer system at west of Berg River.

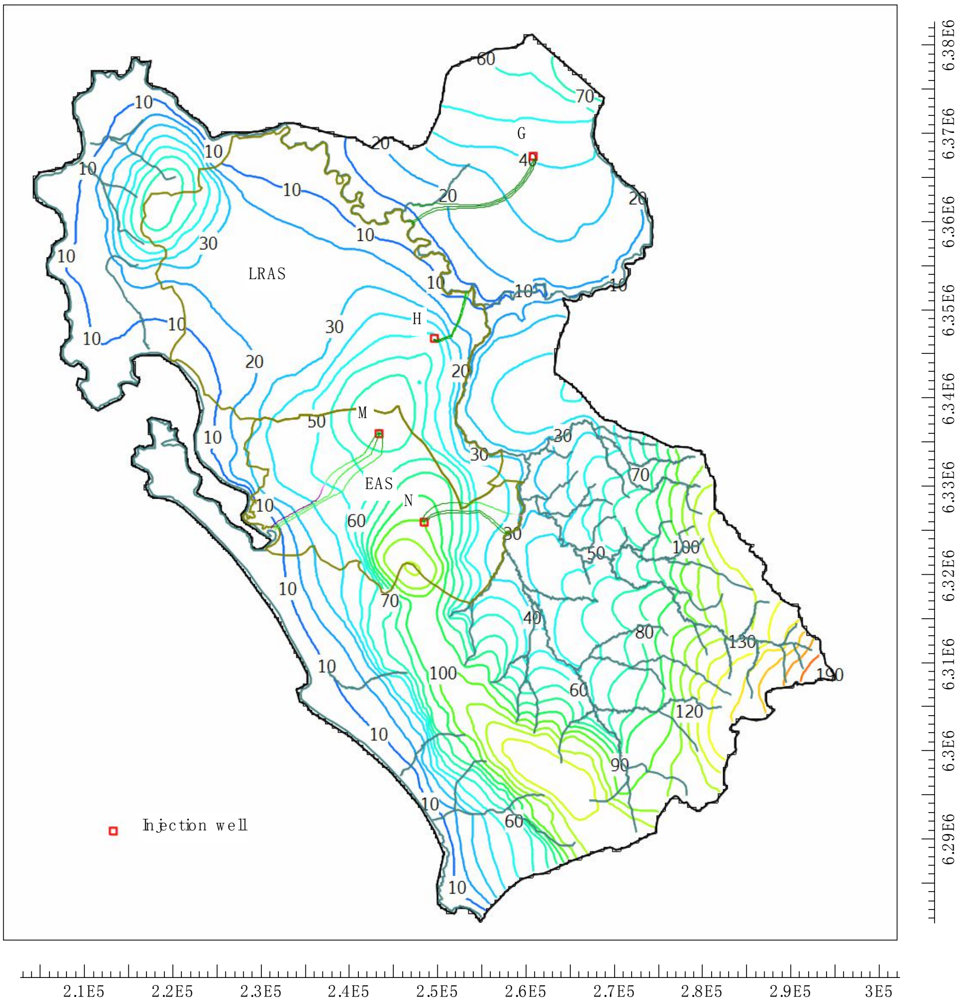


Figure 7-5 Simulated piezomic head in LAU and the flow paths of the recharged water. The unit of the horizontal and vertical scale is in meters (m). LRAS is short for the Langebaan Road aquifer system and EAS represents the Elandsfontein aquifer system.

7.1.4 Scenario three

From the simulation of scenarios one and two, the water artificially recharged in either UAU or LAU at northeast of Berg River would finally discharge to Berg River rather than continuing flow westward, thus the suitable sites for implementing MAR for Langebaan Road aquifer system and Elandsfontein aquifer system are located at west of Hopefield (Figure 6-7, Figure 6-11).

As is described in Chapter 3, there is a clay-missing window lying at west of Hopefield, which can be recognized as natural recharge area of LAU. Thus in this scenario, three injection wells including J, K and L were placed in northeast, north, and southwest of this clay-missing window area to simulate the influence of implementing MAR at this suggested location. In step 1, no abstraction was taken into consideration, and the simulated result is shown in Figure 7-6. Compared with the initial pizometric without artificial recharge (Figure 5-10), the injected water increases local groundwater piezometric head of LAU by about twenty meters in the vicinity of clay-missing window area.

From the simulated path lines of recharged water, it can be seen that the flow paths show divergent directions when injected water at different sites even at this small area. Water recharged at location J partly flows northeast toward Berg River, and partly flows east and discharges to Sout River. The water injected at location K flows northwest and then turns southwest to the Saldanha Bay. The flow of water recharged both in location J and K are distributed in Langebaan Road aquifer system. However, the water injected at location L flows southwest to the Langebaan Lagoon directly, the flow of which is distributed in Elandsfontein aquifer system.

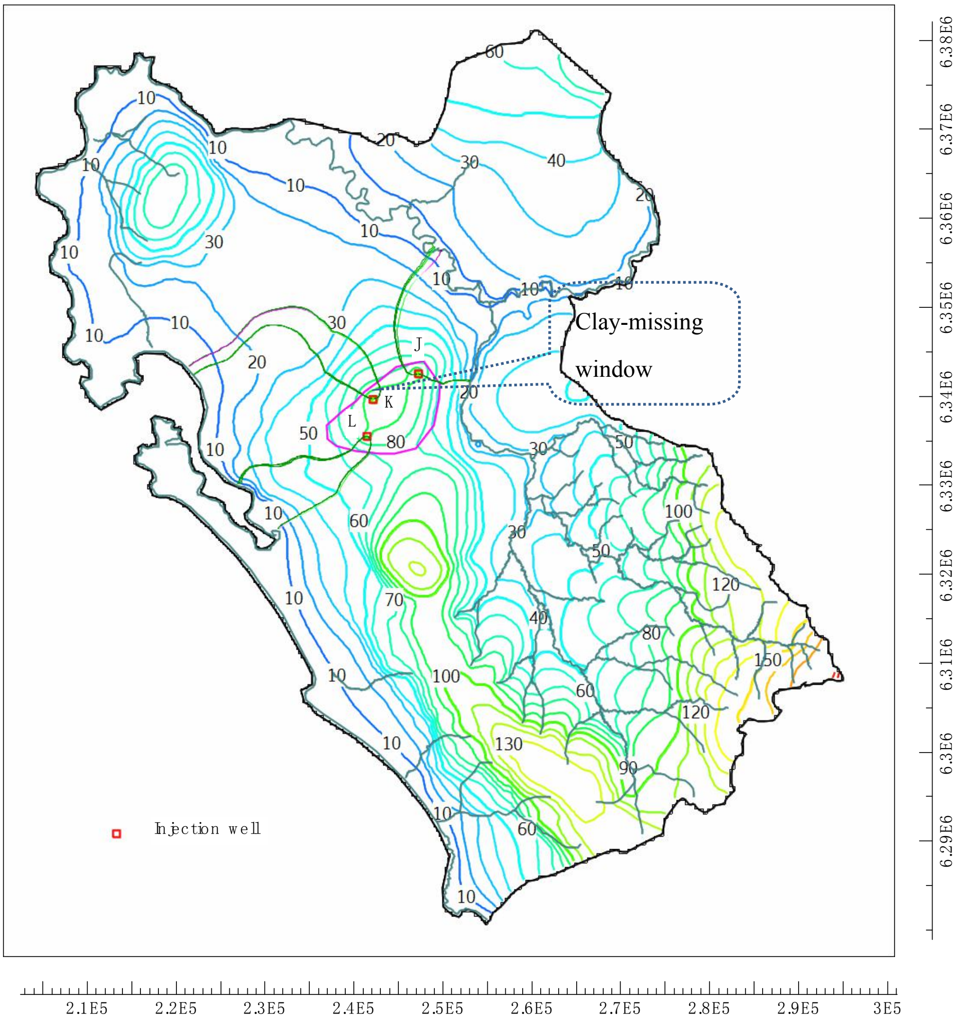


Figure 7-6 Simulated piezometric head in LAU and path lines of recharged water in step one

In the second step, three injection wells in clay-missing window including J, K and L were kept working as the same condition as step one. According to the abstraction data, there is only WCDM well field which was constructed to pump water in large-scale from LAU within Langebaan Road aquifer system. Thus, the abstraction boreholes 46032, 46033, 46034, 46036 at WCDM well field with the pumping rate of 500 m^3/d each from LAU were added to uncover the relationship between MAR and the abstraction of the WCDM well field. Simulated result is shown in Figure 7-7. Similar to step one, the recharged water increases local water head of LAU by about twenty meters at the clay-missing window area, and the rise is higher at the proximity location of recharging than at any of the other farther sites. At the same time, the pumping decreases the local groundwater piezometric head of WCDM well field area up to 8 m. The groundwater flow of the water recharged at location J and L is similar to step one. However, the water injected at location K flows northwest to the WCDM well field, and then be pumped out due to the function of abstraction instead of turning southwest to the Saldanha Bay, which indicates that the recharge around location K can benefit the WCDM well field of the LRAS.

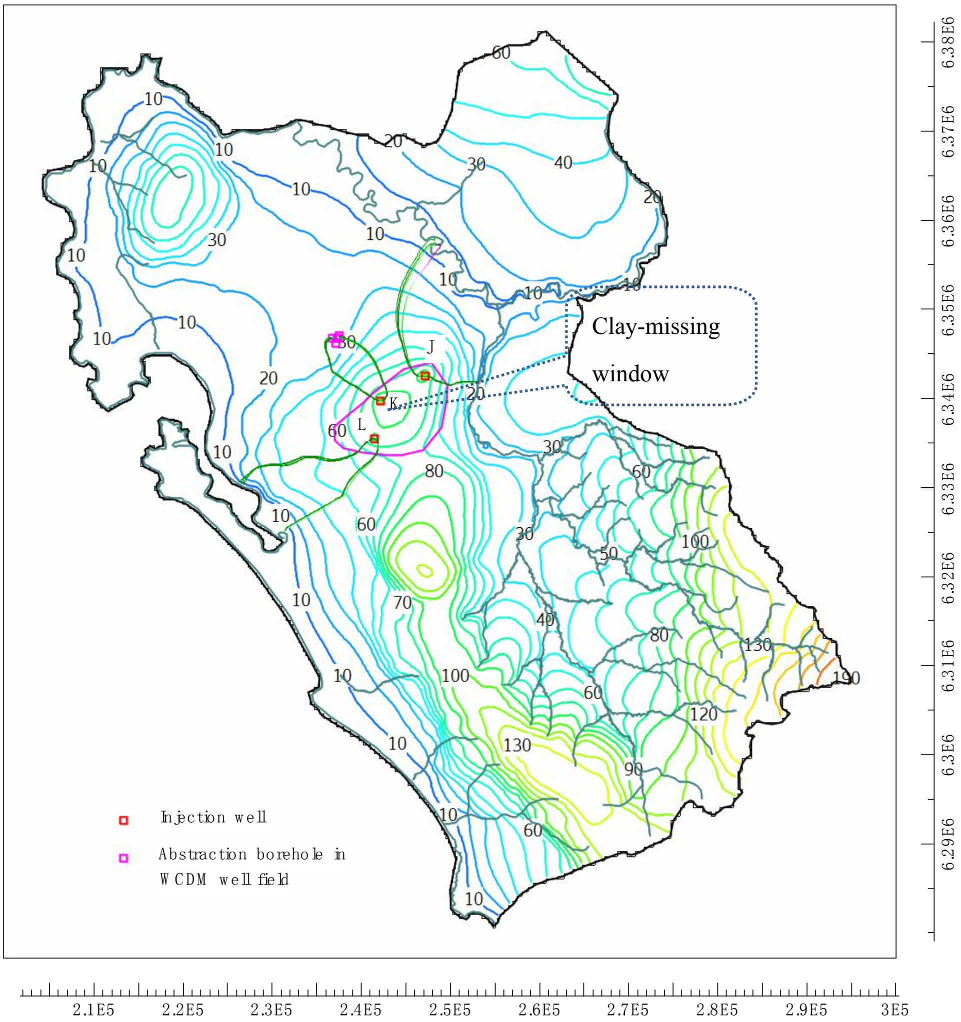


Figure 7-7 Simulated piezometric head in LAU and path lines of recharged water in step two

From the simulation of this scenario, it can be drawn that the implementation of MAR is closely linked with the abstraction. The suitable sites for MAR maybe cover a large area from the spatial aspect, however, there is a discount on the area of suitable sites which are able to benefit the target well field.

7.1.5 Scenario four

In scenario three, an internal connection is uncovered between recharge at north of the clay-missing window and the abstraction in WCDM well field. Thus in this scenario, the influence of different abstraction rate in WCDM well field was simulated. Injection well K with the recharge rate of 200 m^3/d was retained at the north of clay-missing window, and the abstraction borehole 46036 at WCDM well field was assigned with the pumping rate varied from 500 m^3/d to 1000 m^3/d, 2000 m^3/d and then 5000 m^3/d. Simulated results are shown in Figures 7-8, 7-9, 7-10 and 7-11. With the increase of abstraction, the piezometric head at the abstraction borehole decreases from 25 m to -5 m. According to the trace of flow lines, the recharged water is able to recharge the abstraction in WCDM well field only when the abstraction rate is over 1000 m^3/d. Meanwhile, with the abstraction rate increases from 1000 m^3/d to 2000 m^3/d, and then to 5000 m^3/d, the flow time decreases from 9.4×10^5 days to 2.15×10^5 days, and finally to 1.78×10^5 days. With the increase of pumping rate, the radius of influence caused by pumping is enlarged, and more water from farther places is able to flow and recharge the abstraction. Meanwhile, the increase of pumping rate also enlarges the hydraulic gradient of groundwater within the influence radius of pumping, thus decreases the groundwater flow time.

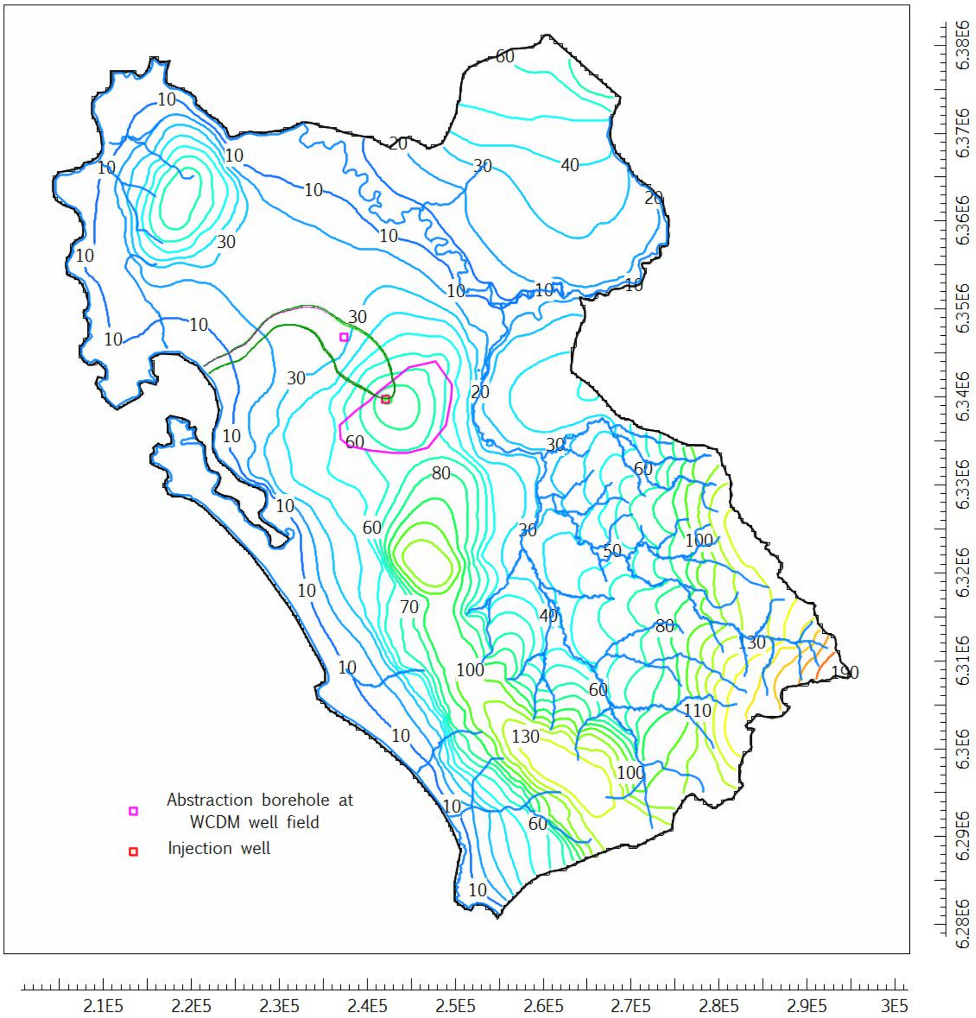


Figure 7-8 Simulated piezometric head in LAU and path lines of recharged water under abstraction rate of 500 m^3/d

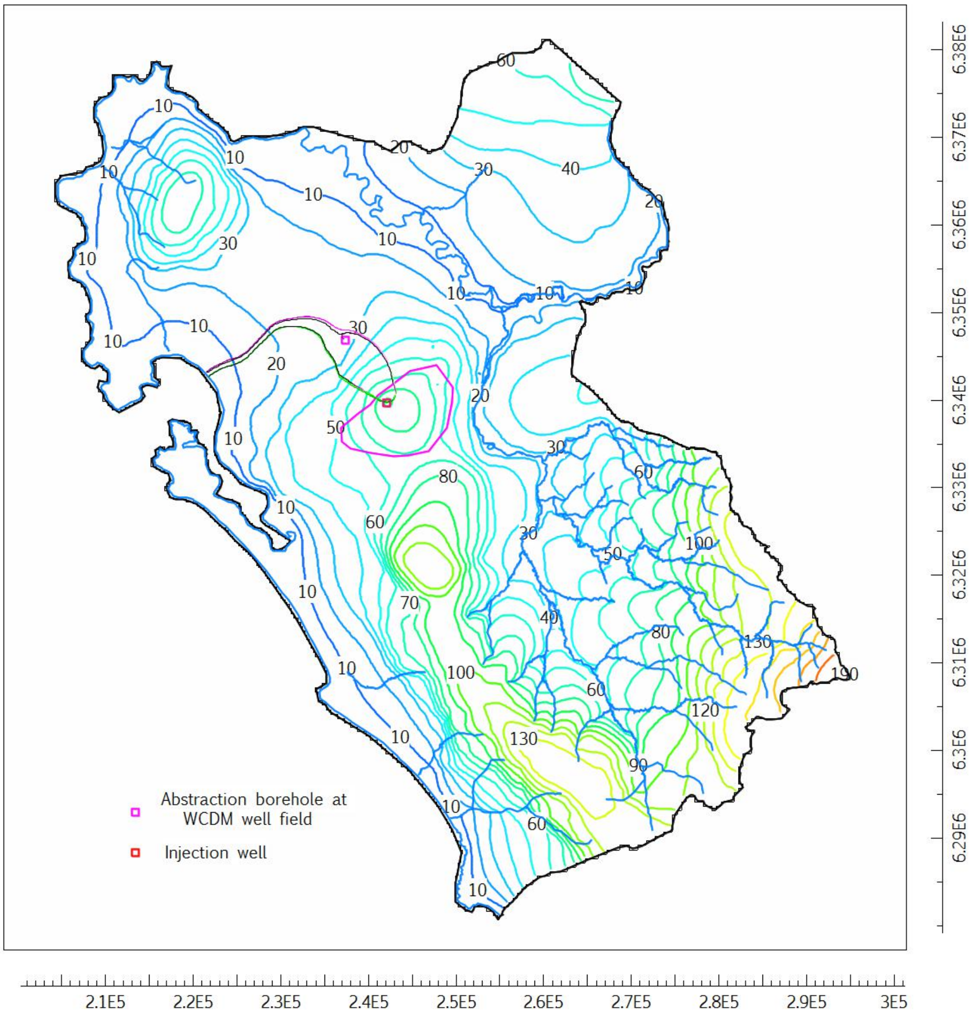


Figure 7-9 Simulated piezometric head in LAU and path lines of recharged water under abstraction rate of 1000 m^3/d

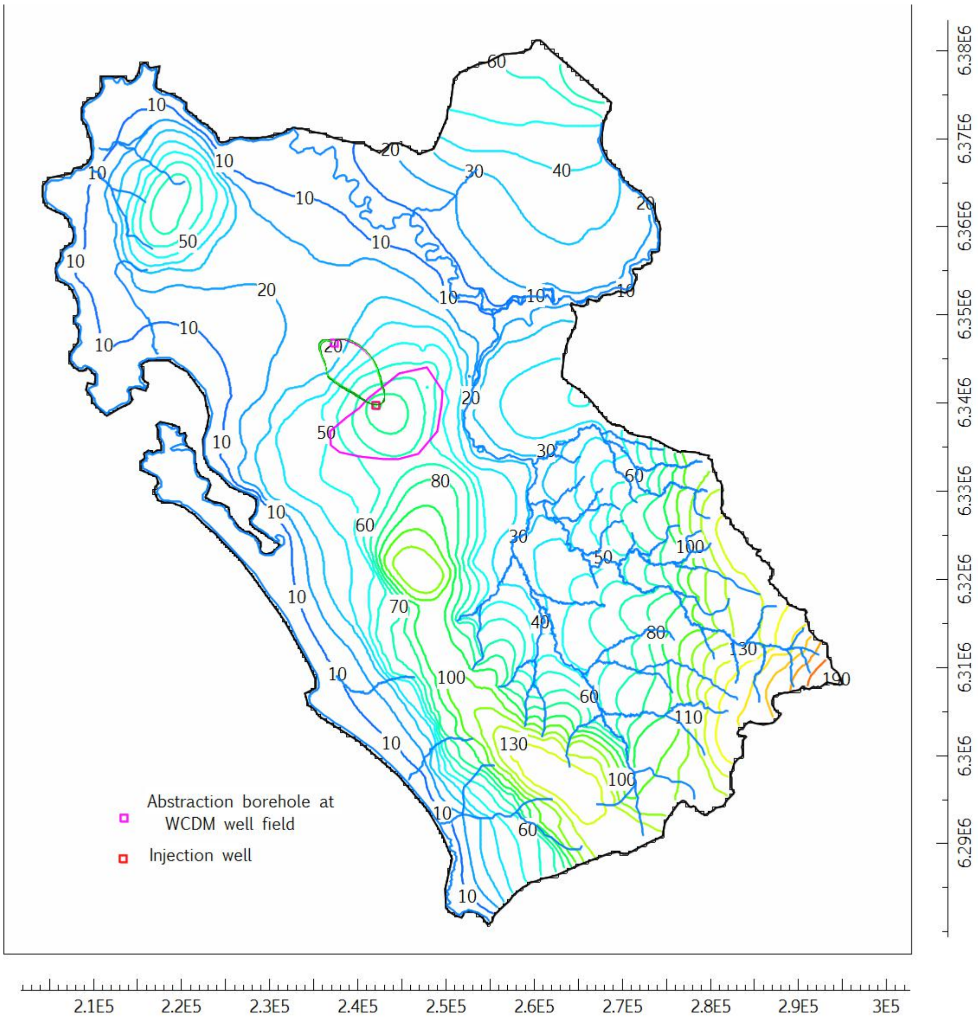


Figure 7-10 Simulated piezometric head in LAU and path lines of recharged water under abstraction rate of 2000 m^3/d

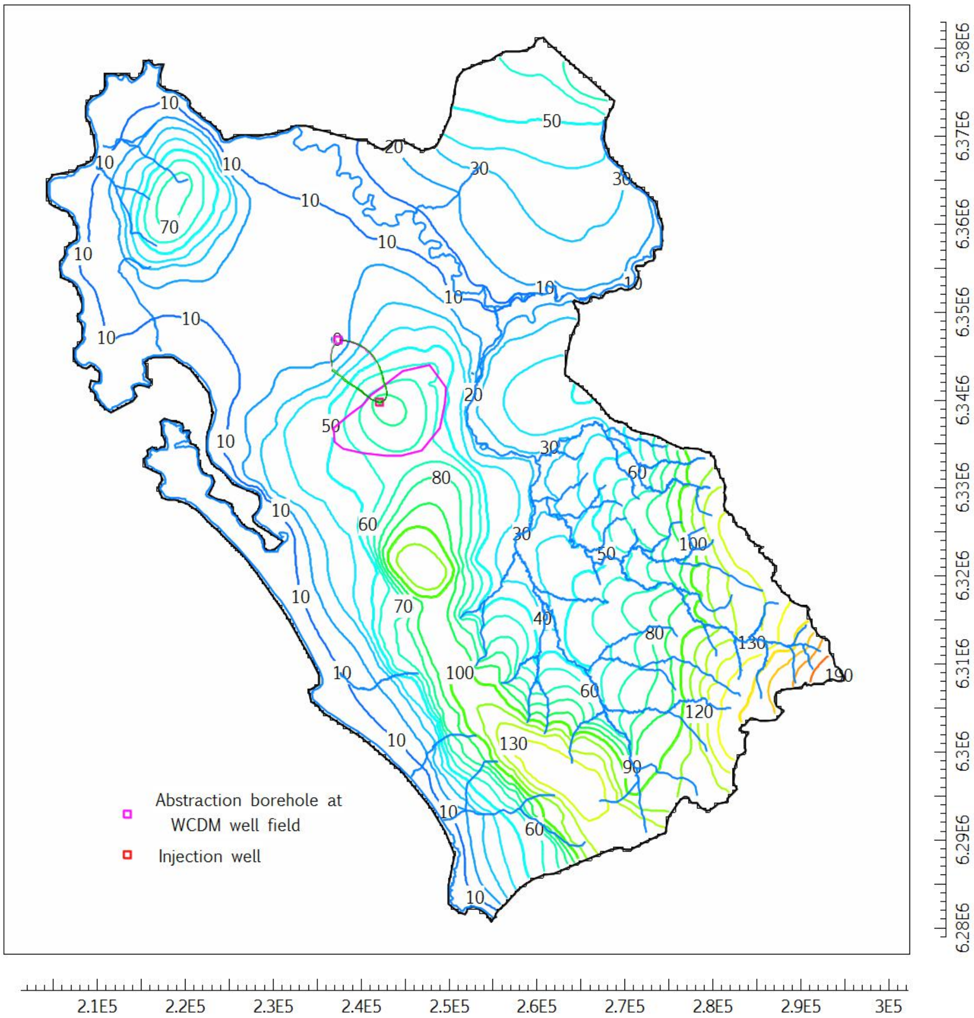


Figure 7-11 Simulated piezometric head in LAU and path lines of recharged water under abstraction rate of 5000 m^3/d

7.1.6 Scenario five

In scenario three and four, all the injection wells were assigned in the clay-missing window area, and the result of which shows that implementing MAR at this natural recharge area is able to recharge LAU of both Langebaan Road aquifer system and Elandsfontein aquifer system, and recharge at the north of the "window" is able to benefit the region of WCDM well field. The aim of this scenario is to simulate the difference of implementing MAR in clay-missing window and outside clay-missing window under varied abstraction quantity in WCDM well field. Thus the injection well K in the clay-missing window with the injection rate of 200 m^3/d which was simulated in scenario four was retained. An infiltration pond (250 m× 250 m× 3 m) with the recharge rate of 200 m^3/d was put outside the clay-missing window but closer to the WCDM well field. In order to find out the impact of abstraction, two steps were included in this scenario. At first, only abstraction borehole 46036 with the pumping rate of 500 m^3/d in LAU was assigned in the WCDM well field. Then abstraction boreholes 46032, 46033, 46034 with the pumping rate of 500 m^3/d each from LAU were added to enlarge the total abstraction ability of WCDM well field to 2000 m^3/d.

Simulated results are shown in Figure 7-12 and Figure 7-13. It can be seen from Figure 7-12 that the recharged water either from injection well or infiltration pond flows northwest to the WCDM well field and then turns southwest to the Saldanha Bay when the abstraction rate is 500 m^3/d. However, when the abstraction increased to 2000 m^3/d, it is obvious that the injected water from both injection well and infiltration pond finally flows to the WCDM well field under heavy pumping condition.

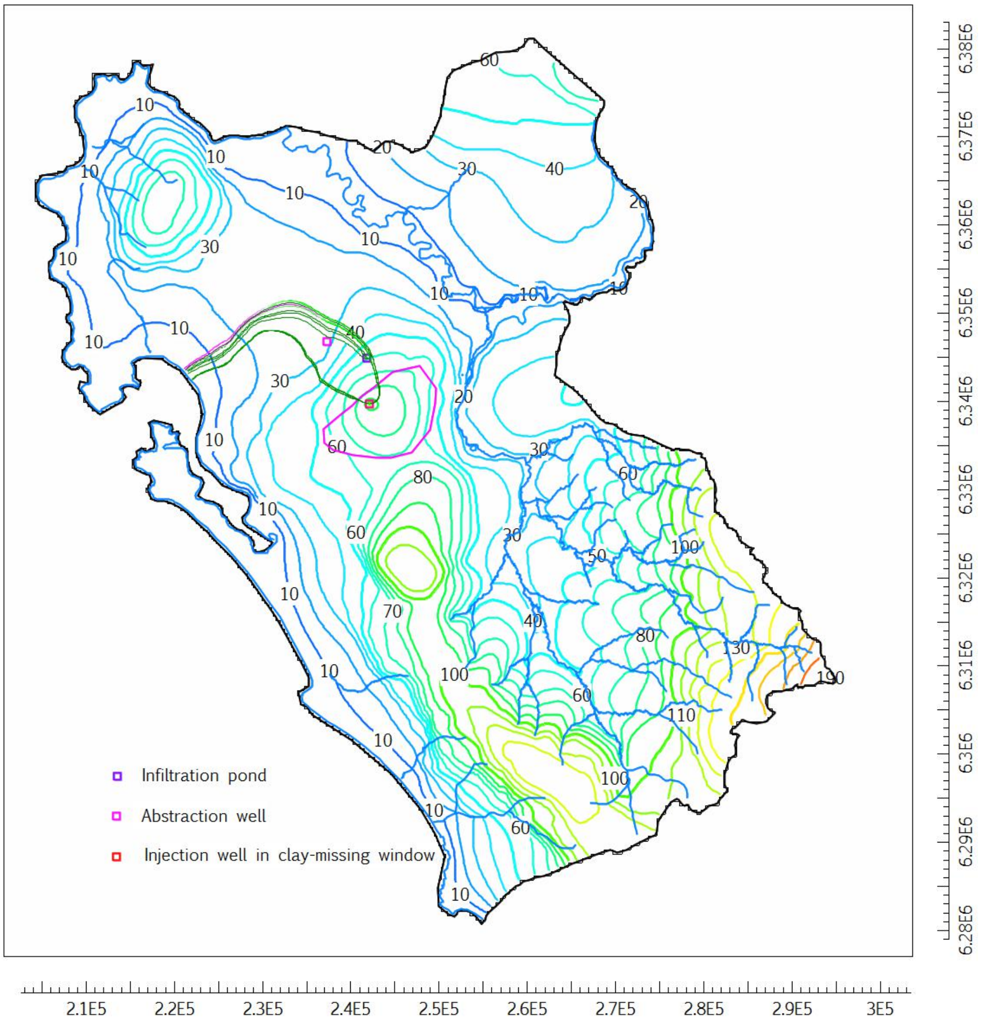


Figure 7-12 Simulated piezometric head in LAU and path lines under 500 m^3/d

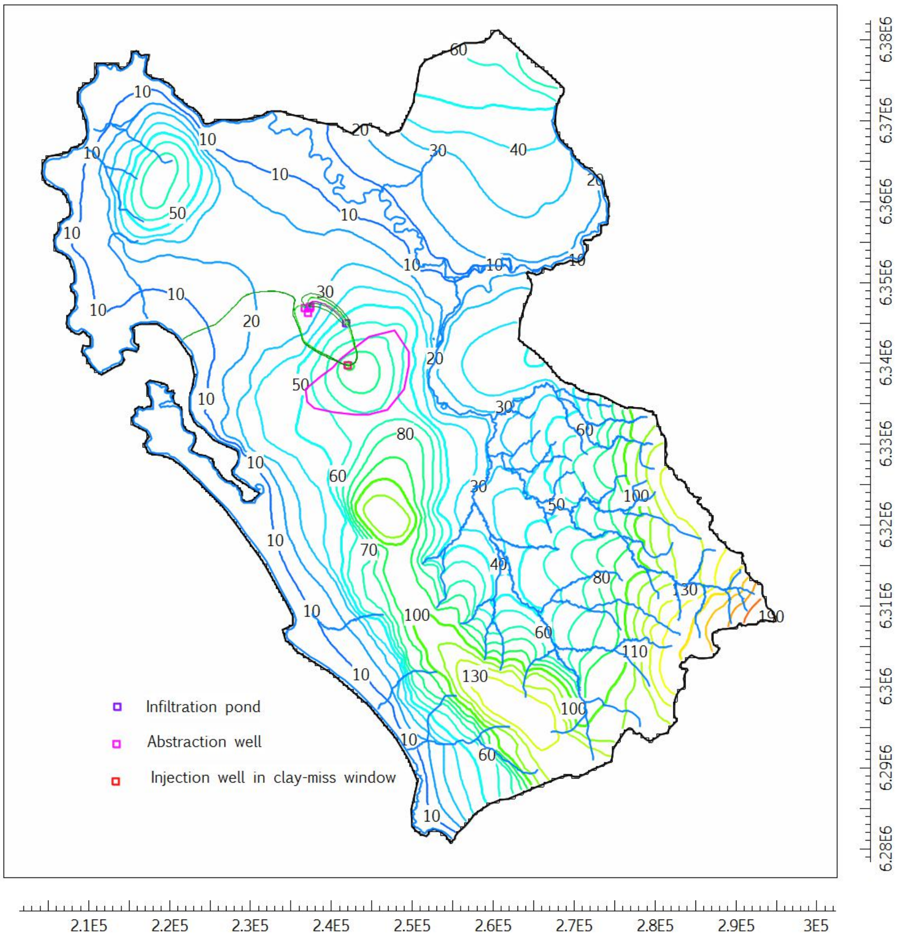


Figure 7-13 Simulated piezometric head in LAU and path lines under 2000 m^3/d

7.2 Discussion

7.2.1 Verification of GIS based analysis

The GIS based method is proven to be powerful in spatial analysis, thus it is helpful for the sites suitability analysis. The suitable sites selected by GIS based method are reasonable in spatial aspect. However, based on the simulation, due to the lack of groundwater flow information, the most suitable sites selected by the GIS based analysis are not necessarily the optimal sites in practice. Meanwhile, the implementation of MAR is closely linked with the abstraction, thus the suitable sites for MAR maybe a large area from the spatial aspect, but there is a discount on the area of suitable sites which are able to benefit the target well field.

Therefore, based on simulation and analysis, the role of GIS based analysis is suggested to be functioning in the following aspects:

(1) GIS based analysis works as a preliminary tool to screen out the initial suitable sites for the implementation of MAR, through which scope of the target can be narrowed, and the focus area is able to be identified. However, the results of GIS based analysis are suggested to be verified and optimized by modeling.

(2) GIS is very useful tool to preprocess the datasets for modeling, including hydrological, hydrogeological and geological data.

7.2.2 The implementation of MAR in UAU

Based on the simulations, implementing MAR in the aquifer of UAU can lead to a rise in local groundwater table. However, due to the difference in hydrogeological characteristics at different places, the rise of groundwater table showes a divergent result. It's observed from the simulation that the rise in groundwater level is mainly concerned with the hydraulic conductivity of the aquifer and its associated scale, the lower the hydraulic conductivity of the aquifer, the higher the rise in groundwater table. Meanwhile, the simulation also indicates that recharging at west of Hopefield (the natural recharge area) can benefit larger area than recharging at other places especially the discharge region such as Berg River and coastline. From the water flow paths, the recharged water will flow toward and discharge to the Berg River, Langebaan lagoon or the coastline.

Without taking the influence of abstraction into consideration, the flow time from infiltration ponds at different locations to the discharge area varies from decades to tens of thousands of years. This result is in agreement with the isotope studies of Tredoux and Talma (2009) and WCDM (2009), which indicated that mean groundwater residence time in the UAU is between 30 to 60 years from tritium analysis, and between recent to 9000 years from Carbon-14, while the residence time in the LAU ranged from 5000 to 28000 years. Therefore, the groundwater flows very slow in a natural condition, which should be taken into consideration when implementing MAR scheme in the studied area.

There is little research on the implementation of MAR in UAU of Langebaan Road aquifer system and Elandsfontein aquifer system. However, the town of Atlantis, which is located about 40 kilometers southeast of the Elandsfontein aquifer system, has practiced artificial groundwater recharge for almost 40 years. Treated wastewater together with storm water runoff were collected and artificially recharged in the Atlantis aquifer through two main recharge basins that were constructed up-gradient of the Witzand well field for about 500 to 1000 meters. It was estimated that the groundwater abstracted for the water supply of Atlantis represented a blend of 30% water derived from MAR and 70% natural groundwater (DWA, 2010b). The Atlantis aquifer is also formed of unconsolidated Cenozoic sediments, which is similar to the stratigraphy of Langebaan Road and Elandsfontein aquifer systems. Thus according to the analogy analysis, the practice of artificial recharge in Atlantis aquifer confirms the feasibility of implementing MAR in UAU, which also proves the reliability of modeling analysis. Based on the simulation and analogy analysis, the implementation of MAR in UAU is found to be hydrogeologically feasible, and the suitable sites are dependent largely on the recharging purpose. Based on the findings, it can be said that MAR can be implemented near the well fields when it is considered as a relatively straightforward choice to increase local water storage and supply. However, as described under the study area description section of the paper, the natural recharge area is the best site for a large quantity of water recharge, which benefits the largest area of the whole aquifer unit.

It’s also found that storage space for the recharged water is another key factor that affects the implementation of MAR in UAU. The depth of groundwater table map was drawn based on the water table data of 138 boreholes which were monitored in the rainy season of 2018 by Department of Water Sanitation of Western Cape. The range of depth of groundwater table varied from 0 to 41 m, which was shallower near the discharge area such as Berg River as well as Langebaan lagoon, but deeper near the southwest of Hopefield where it was regarded as the natural recharge area (Figure 7-14). Understanding such variation in relation to implementing MAR scheme was essential.

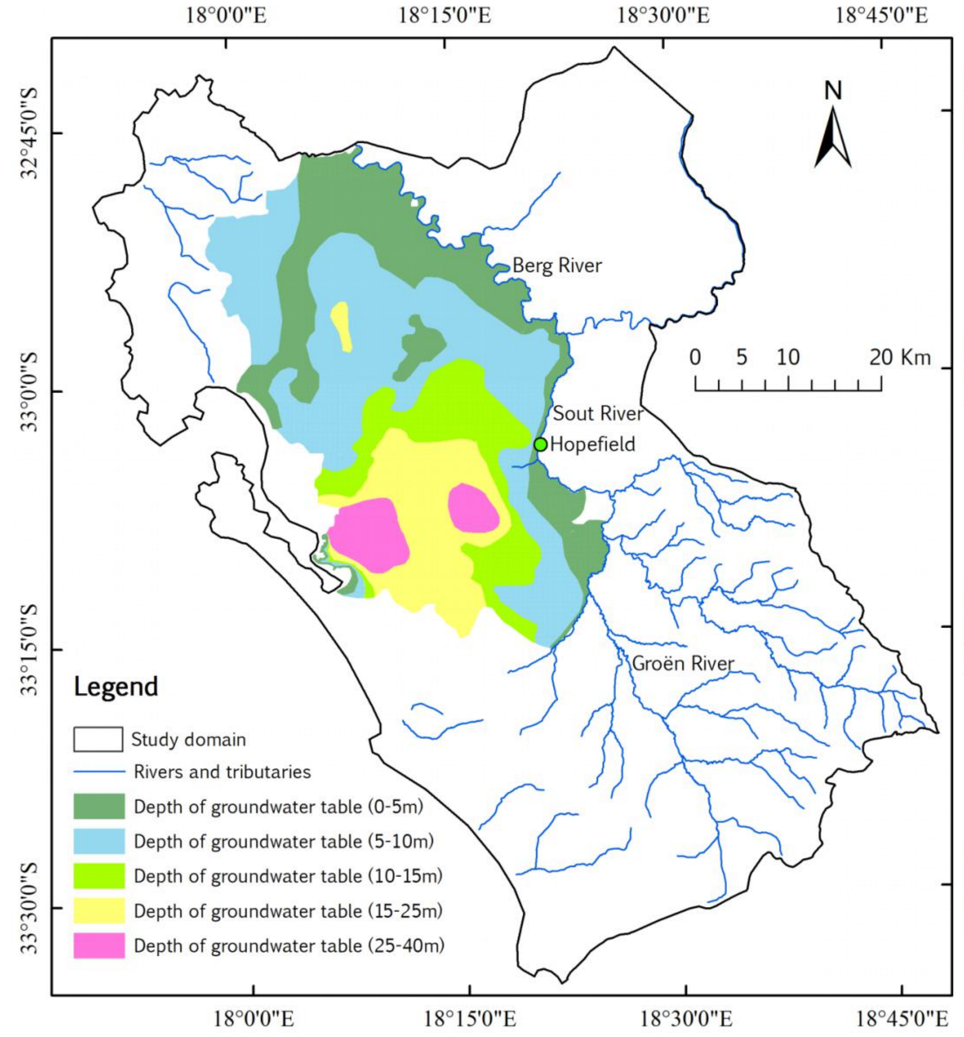


Figure 7-14 The depth of groundwater table map of the rainy season in 2018

On the basis of the depth of groundwater table map, it is possible to calculate the available space for MAR in UAU through equation (7-1), as presented in Table 7-3.

$$Q = \sum_{i=1}^{m} A \times H \times S_y \qquad (7\text{-}1)$$

Where: Q is the available space for implementing MAR; A is the area of the UAU aquifer; H is the thickness of unsaturated aquifer in UAU; S_y is the storage parameter, assumed to be a constant value here, valued 0.1; m is the number of aquifer units with the same unsaturated thickness.

Table 7-3 Estimate of available space for MAR in UAU

Aquifers	**Area of the aquifer (km^2)**	**Available Space for MAR in UAU (million m^3)**
Langebaan Road Aquifer System	907.1	366.2
Elandsfontein Aquifer System	433.6	549.5
Total		915.7

Recharge rate is another key issue for the implementation of MAR. Different recharge rates were simulated at location J in the modeling, result of which is shown in Figure 7-15.

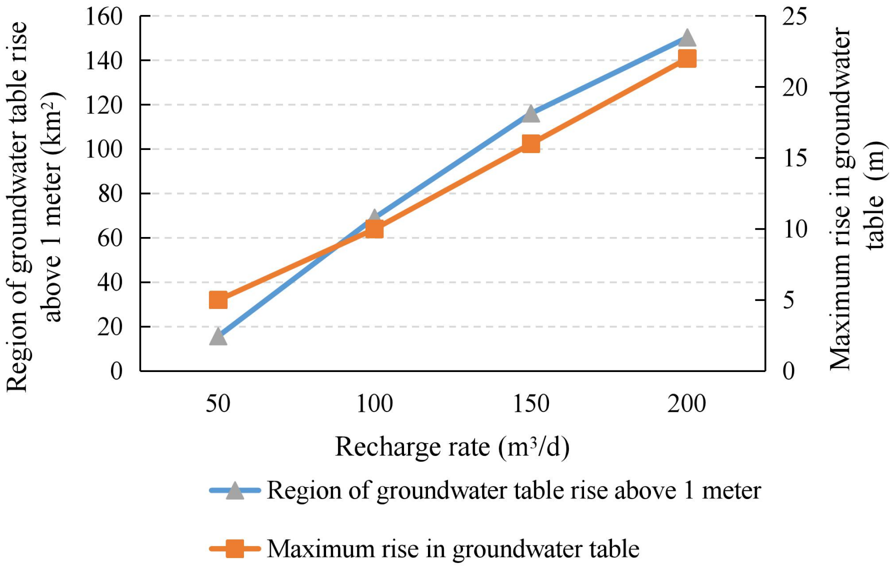


Figure 7-15 The relationship between the rise in groundwater table as well as spread region and different recharge rate at location K

It can be seen from Figure 7-15 that the maximum rise in groundwater level together with the benefit region show a positive correlation with the increase of recharge rate from 50 m^3/d to 200 m^3/d. According to the simulation, the groundwater level rises sharply at the centre of the injection location from 5m to 22m with the increase of recharge rate. The area of the infiltration pond simulated in the modeling is 250 m×250 m, thus the recharge rate of 200 m^3/d indicates the infiltration rate to be 0.003 m/d. The practice of MAR in Atlantis aquifer shows that the infiltration rate of the recharge basins varies from 0.01 m/d to 0.16 m/d (DWA, 2010b). The infiltration rate in the modeling of the study area is lower than the practice of Atlantis, which is a concern considering the low permeability of the soil of Langebaan

Formation at the recharge site. Therefore, considering the limitation of ground surface and the risk of flooding, the infiltration rate should be controlled when implementing MAR at the west of Hopefield, and the infiltration rate is suggested to be tested at the target location due to the heterogeneity of soil.

7.2.3 The implementation of MAR in LAU

When the sampled water from two aquifer system were analyzed, results showed that water quality in LAU was much better than groundwater in UAU, which had laid the foundation of LAU as an ideal source of potable water supply for the past few decades. Several previous efforts focused on implementing MAR directly in LAU, however, the pilot injection study carried out by Tredoux and Engelbrecht (2009) indicated that direct injection in LAU at the WCDM well field was failed to keep water stored underground as initially expected.

Based on the NGA borehole logs, a clay-missing window area locates at the west of Hopefield which is considered as natural recharge area. Subsequently, the scenario of recharging water at this clay-missing window was simulated by the numerical model, and the result of which showed that the water recharged at this clay-missing window would flow and recharge the LAU in both Langebaan Road aquifer system and Elandsfontein aquifer system, thereby concluding that the clay-missing window area is a suitable site for implementing MAR for the LAU. However, implementing MAR in LAU is more complicated than in UAU. According to the borehole logs, the top of the clay layer (the confining layer) around the clay-missing window is about 30 m a.m.s.l (Figure 3-9). Conversely, the piezometric head of groundwater in the vicinity of the clay-missing window showes very stable behaviour under the varied rainfall within the scope between 55 m and 80 m a.m.s.l according to the water head monitored by DWS from 2000 to 2017 (Figure 7-16). Comparison of the monitoring groundwater head with the elevation of the top of clay layer in the vicinity of the clay-missing window showes that groundwater piezometric surface is much higher than the confining layer. Such observation provides the evidence to argue that implementing MAR directly to LAU remains impractical because the prevailing results showes that lack of space in LAU to store recharged water at present.

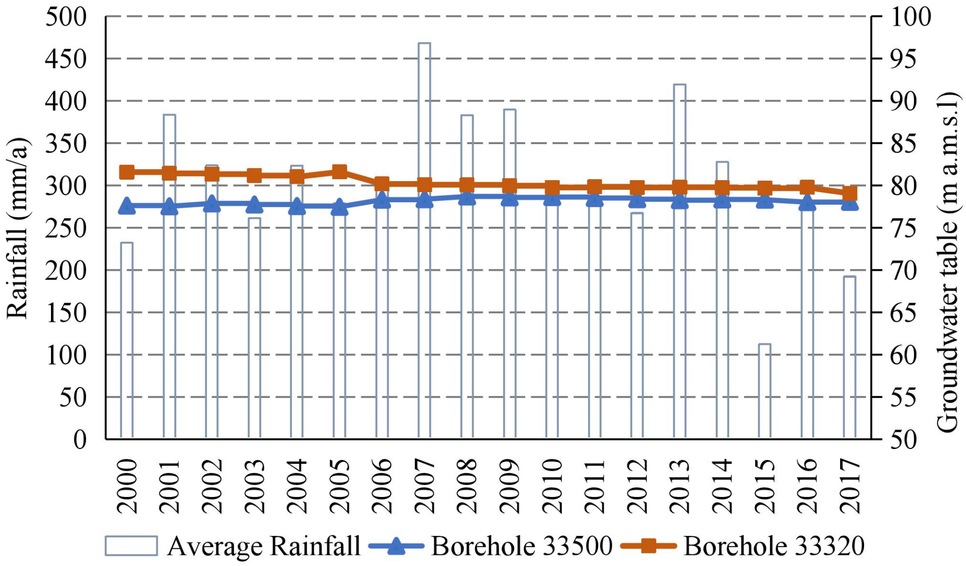


Figure 7-16 The relationship between average annual rainfall and groundwater table of boreholes 33500 and 33320, showing the groundwater table in the vicinity of the clay-missing window area hardly change with varied rainfall.

In addition, the result of the simulation in scenario five showes the recharge mechanism of LAU. Normally, LAU gets recharge from percolation of precipitation through the clay-missing window at the west of Hopefield. However, LAU also gets water through leaking recharge from UAU in locations where the clay was observed to be thin and the head difference between the upper and lower aquifer was reported to be large enough to drive vertical recharge (DWAF, 2008). Based on this information, another way to implement MAR for LAU would be to increase the leakage from UAU locally. Figure 7-17 shows the idea of artificial recharging LAU through leakage wells.

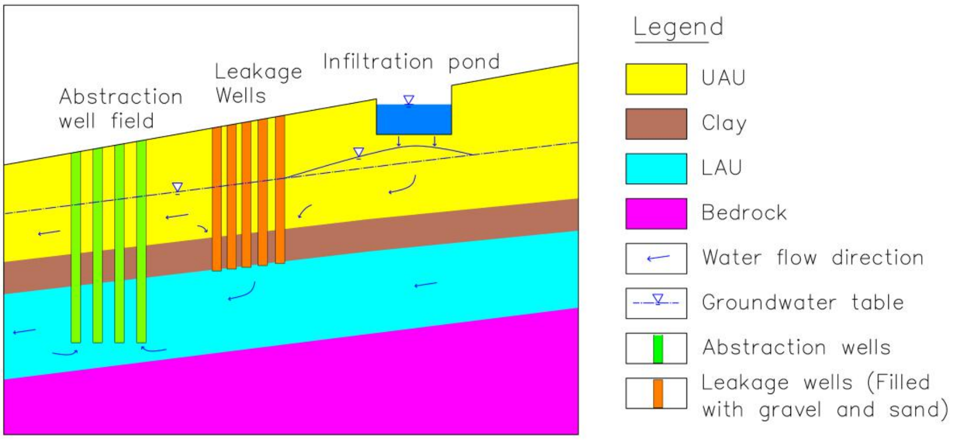


Figure 7-17 Sketch map of using leakage wells to increase leaking recharge for LAU from UAU

Figure 7-18 showes a simplified two-dimensional steady-state model, which considered the aquifer system of West Coast as a prototype and included UAU, clay, LAU and bed rock four layers. The model was developed to testify the idea of artificial recharging LAU through leakage wells (Figure 7-18a). After data were input to represent initial and boundary condition, three scenarios were assigned to analyze the groundwater flow.

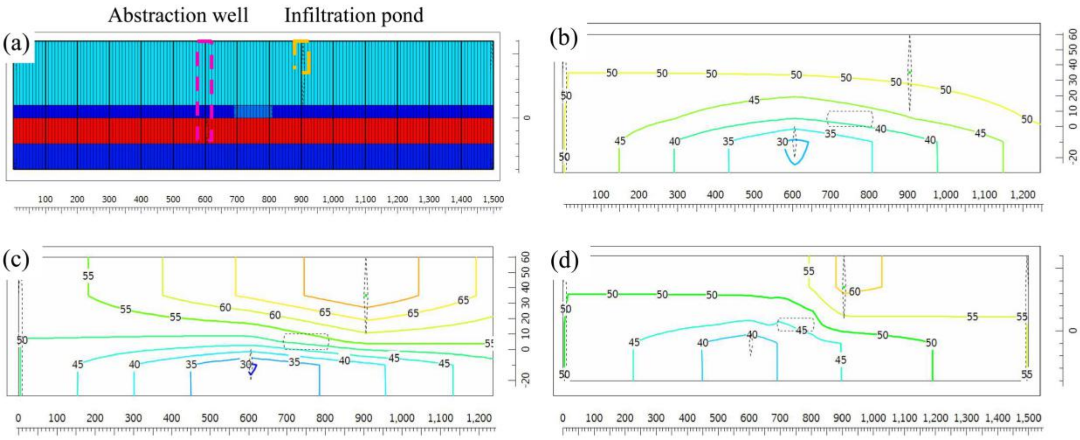


Figure 7-18 The finite-difference grid of the 2-D groundwater model and the simulated results. (a) The finite-difference grid of the groundwater model; (b) The simulated groundwater flow of scenario 1; (c) The simulated groundwater flow of scenario 2; (d) The simulated groundwater flow of scenario 3.

In scenario 1, an abstraction well with the pumping rate of 200 m^3/d from LAU was assigned in the model. It can be seen from Figure 7-18b that the pumping decreases the piezometric head of the LAU in the vicinity of abstraction well.

In scenario 2, the abstraction well was retained, and an infiltration pond with the recharge rate of 100 m^3/d in UAU was placed 300 m east of abstraction well. According to the simulated result (Figure 7-18c), the artificial recharge increases the water head of UAU from 50 m to 70 m around the infiltration pond, but it has little impact on the piezometric head of LAU.

In scenario 3, the condition of infiltration and abstraction remained the same as scenario 2, and leakage wells were added to enlarge the hydraulic conductivity of clay between the abstraction well and infiltration pond. The simulated result is shown in Figure 7-18d. Compared with the result of scenario 2, the leakage wells decreased the water head of the centre of infiltration pond by 10 m, however, they increased the piezometric head of the LAU in the vicinity of abstraction well by 10 m. Therefore, it can be stated that the idea of using leakage wells to increase leaking recharge for LAU from UAU is proved to be functioning.

Although results showes that this application is able to increase the quantity of groundwater abstraction from LAU through combining the aquifers of the local UAU and LAU, concerns remain a threat that the quality of recharge water from UAU might contaminate water of LAU (Meng et al., 2015) and that concerns would need to be ruled out through water quality testing which is beyond the scope of the current study for this thesis.

CHAPTER 8: Synthesis of results and discussion

8.1 Introduction

The primary objective of the thesis was to assess the implementation of MAR in terms of suitable sites as well as appropriate scheme. A case study approach was adopted using West Coast in South Africa. From source and sink theory, recharge through MAR and abstraction for use is able to be taking as source and sink items of water balance calculation, which lays the foundation of assessment of MAR using groundwater flow modeling approach. Groundwater flow conceptual model was developed using ModelMuse based on the analysis of the hydrogeological setting and the groundwater flow mechanism (Chapter 4 and Chapter 5). GIS was adopted to screen out the initial suitable sites of the implementation of MAR, and to preprocess the hydrological, hydrogeological and geological datasets which were used to develop the groundwater flow model (Chapter 4 and Chapter 6). Modeling together with designed scenario analysis is then adopted to verify and optimize the suitable sites, as well as to assess the implementing scheme of MAR (Chapter 4, Chapter 5 and Chapter 7). Thus, the assessment of MAR is fulfilled using the presented GIS based modeling approach.

8.2 Implementing managed aquifer recharge in West Coast, South Africa

8.2.1 Groundwater flow conceptual model of West Coast, South Africa

Based on the extensive information available on the West Coast of South Africa, the mainly aquifer units in the Langebaan Road aquifer system and Elandsfontein aquifer system are the upper unconfined aquifer unit (UAU) and the (semi) confined lower aquifer unit (LAU). The UAU is recharged directly from precipitation. Rainfall is greater in the higher lying areas in the south of the study area, and thus a recharge mound for Langebaan Road aquifer system and the Elandsfontein aquifer system has been postulated at southwest of Hopefield. Groundwater flow in UAU is topographically controlled and occurs from the recharge mound to the Berg River and its tributaries or the coastline.

The "clay-missing window" in the southwest of Hopefield would facilitate the downward percolation of the water into the LAU, then groundwater flows along the palaeochannels, and finally drains toward the Berg River or the coastline or the abstraction boreholes. Meanwhile, LAU also gets water through leaking recharge from UAU in locations where the clay is thin and the head difference between the upper and lower aquifer is large enough to drive vertical recharge. The groundwater flow mechanisms of Langebaan Road aquifer system and the Elandsfontein aquifer system is conceptualized in Figures 5-2 and 5-3.

The groundwater flow mechanism is generally consistent with the studies of Timmerman (1985b; 1988) and Seyler et al. (2016). However, the distribution map of the Elandsfontyn clay unit developed by WCDM (2005; 2009) is always continuous, which indicates either no clay-missing window or less area of clay-missing windows than that is shown in Figure 3-8 which was deprived from the NGA borehole logs. Due to the importance of the clay-missing windows to the groundwater flow mechanism of LAU, boreholes are needed to be constructed in the vicinity of the “clay-missing” areas to eliminate this uncertainty.

8.2.2 Implementing MAR in UAU of West Coast, South Africa

The implementation of MAR in UAU of West Coast is generally feasible. A GIS based analysis was adopted to screen out the suitable sites for the implementation of MAR. Based on the GIS analysis, the suitable sites are always characterized by the upper gradient area with proper permeability soil, thick aquifer and large thickness of vadose zone. If these basic spatial characteristics are satisfied, then the suitable sites are dependent largely on the recharge purpose. MAR can be implemented near the well field when it is considered as a relatively straightforward choice to increase local water storage and supply. While the natural recharge area is the best site for a large quantity of water recharge, which benefits the largest area of the whole aquifer unit. However, the groundwater flows very slow in the natural condition, which should be taken into consideration when making the implementing scheme plan of MAR. Based on the groundwater table measured in August 2017, the estimated available space for MAR in Langebaan Road aquifer system and Elandsfontein aquifer system is 366.2 million m^3 and 549.5 million m^3 respectively.

Infiltration pond is suggested to be adopted when implementing MAR in UAU, but it should be cautious when applied to the areas that are distributed with Langebaan Formation for the calcrete and clay embedded in the shallow subsurface stratum is concerned with extremely low permeability. Thus borehole recharge is suggested in these specialized areas. The estimated infiltration rate is 0.003 m/d in the vicinity of the clay-missing window area, which is a bit lower than the practice of MAR in Atlantis aquifer that shows an infiltration rate varies from 0.01 m/d to 0.16 m/d (DWA, 2010b). This low infiltration rate is related with the characters of the clay-missing window area where there is low permeability of soil and shallow depth to groundwater table. However, it is found that the hydraulic conductivity in each layer is highly heterogeneous during the process of model development, thus the infiltration rate is suggested to be tested in the filed at the target location before implementing MAR.

Further research including monitoring (groundwater level and quality), clogging analysis as well as artificial recharge pilot trials are suggested to be carried out in the vicinity of the target area in order to implement MAR in UAU.

8.2.3 Implementing MAR in LAU of West Coast, South Africa

The pilot injection study carried out by Tredoux and Engelbrecht (2009) indicated that direct injection in LAU at the WCDM well field through borehole was unable to keep the recharged water stored underground. Based on the GIS analysis and the modeling analysis, the clay-missing window area (natural recharge area) at west of Hopefield is the most suitable site for implementing MAR in LAU of Langebaan Road aquifer system and northwest part of Elandsfontein aquifer system. However, the present piezometric surface is much higher than the top of the confining-layer, therefore, there’s little space in LAU to store water if implementing MAR at present. However, in order to increase the water supply at local area, it is feasible to increase water availability of LAU through increasing leakage from UAU locally, but concerns remain a threat that the recharged water from UAU might contaminate the water of LAU.

Infiltration pond is suggested to be adopted when implementing MAR at clay-missing window area, however, borehole recharge is suggested to be adopted at the locations where the subsurface stratum is embedded with thick calcrete and clay.

Since there’s little space to support the implementation of MAR in LAU at present, monitoring work is suggested to be strengthened around the clay-missing areas which are located in the vicinity of natural recharge area. And more investigation work is suggested to be done to accurately understand the distribution of aquitard clay.

8.3 Evaluation of the study based on the results

Based on the analysis of the results of current study, it can be stated that the present study is strong or good for the following reasons although one aspect required reflection:

First, the use of GIS provided a strong spatial analysis of the study while the groundwater modeling was able to evaluate advantages and disadvantages of implementing MAR at a proposed location when combined with specific scenarios. With the advantage of spatial analysis in GIS environment and the seepage simulation in modeling software, the GIS based modeling analysis method provides a reliable solution to assessment of implementing MAR in the current study, thereby fulfilling the objective and research question of the study.

Secondly, the present study is part of the Water Research Commission funded project entitled “Towards the sustainable exploitation of groundwater resources along the West Coast of South Africa”. The project was implemented jointly by the CSIR, WCDWS and UWC. Being part of such collaborative research work strengthened the implementation of the present study. The members of this collaboration group had in-depth scientific knowledge on groundwater and they provided critical comments during the scheduled review progress meetings. Comments from these reviews provided useful insight to the progress of the current study.

Thirdly, the research design that started with comprehensive desktop approach which was followed by several field visits to groundtruth the modeled work, strengthen the interpretation of results from the modeling work. The combination of data collection and collation, field investigation, GIS analysis and modeling was an opportune strength of the current study.

Existing records provided useful database where only required information was screened and through review meetings such information was agreed as relevant. The field investigations were carried out jointly among the participating institutions. The quality control techniques were applied on the collected data during analysis to ensure that only reliable and valid data were incorporated in the GIS analysis and modeling analysis. These procedures were followed to ensure that reliable and valid interpretations were obtained.

Despite the above strengths of the study, lack of drilling boreholes and pumping test such boreholes for the current study weakened the analysis on the groundwater flow regime in the studied aquifers. Pumping tests would have provided the current parameter estimation of the studied aquifer and the derivative plots which could have refined the chosen groundwater model that was used in the current study. In addition, some uncertainties still exist due to limited data on the distribution of Elandsfontyn clay and palaeochannel, groundwater recharge and abstraction in the study area. Furthermore, the implementation of MAR also depends on other aspects, such as engineering, socio-economic, governance etc.

8.4 Implication of the results for practice

8.4.1 Implementing managed aquifer recharge to improving water security in drought-prone area

In light of the research and application in West Coast of South Africa, the following results can be used to guide the implementation of MAR in drought-prone area:

(1) Implementing managed aquifer recharge in an unconfined aquifer

With the support of hydrogeological condition which is usually characterized by the upper gradient area with proper permeability soil, thick aquifer and large thickness of vadose zone, the suitable sites for the implementation of managed aquifer recharge in an unconfined aquifer are dependent largely on the recharging purpose. MAR can be implemented near the well fields when it is considered as a relatively straightforward choice to increase local water storage and supply. However, the natural recharge area is the best site for a large quantity of water recharge, which benefits the largest area of the whole aquifer unit. The available space for MAR can be estimated through equation (7-1). Infiltration pond is suggested to be adopted, but it should be cautious when applied to the area where the shallow subsurface is embedded with low permeability stratum. Infiltration rate should be tested in the field before implementing MAR.

(2) Implementing managed aquifer recharge in a confined aquifer

The natural recharge area is considered as the suitable site for implementing MAR in the confined aquifer. The relationship between the water level and the confining-layer is a key issue which determines the way of implementing MAR. Based on the relationship between the water level and the confining-layer, three situations can be concluded and shown in Figure 8-1.

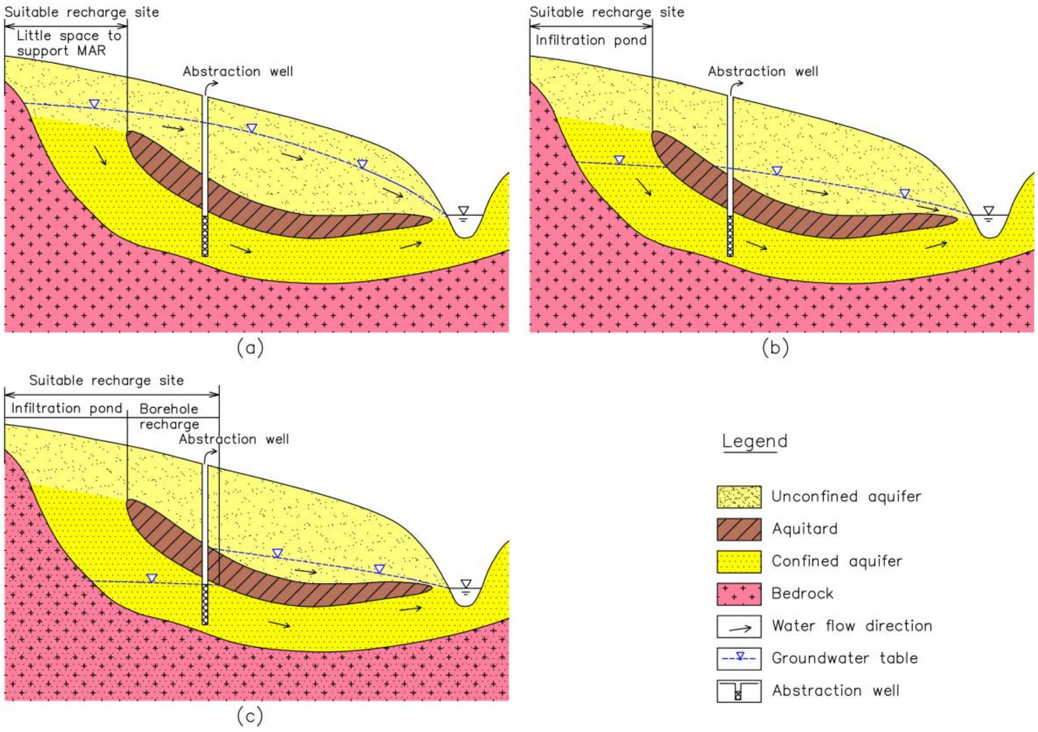


Figure 8-1 The suitable site for the implementation of MAR in confined aquifer under three situations. (a) The piezometric surface is above the confining layer; (b) The piezometric surface is lower than the confining layer in the vicinity of natural recharge area; (c) The piezometric surface is much lower than the confining layer.

It can be seen from Figure 8-1(a), the piezometric surface is above the confining layer, thus similar to the LAU of West Coast of South Africa, there's little space in the confined aquifer to support MAR. In Figure 8-1(b), the piezometric surface in the vicinity of the natural recharge area is lower than the top of the confining layer, therefore, the natural recharge area is the suitable site for implementing MAR, and infiltration pond is suggested. In Figure 8-1(c), the piezometric surface is much lower than the confining layer, which enlarges the area of suitable site for the implementation of MAR. In this situation, infiltration pond is suggested to be used at the aquitard-missing area, while borehole recharge is suggested to be adopted at the aquitard distribution area.

(3) The recharge is always closely linked with abstraction including borehole locations as well as pumping rates, therefore, managed aquifer recharge and abstraction should be considered as a whole rather than taking them into consideration separately. Not only should MAR be implemented at suitable sites, but it is suggested that new well fields should be constructed properly.

8.4.2 Assessment of MAR using GIS based modeling approach to improving water security in drought-prone area

Vast of studies has proved that managed aquifer recharge is an useful method to improving water security in drought-prone area, and the assessment approach is varied from case to case. The assessment of MAR presented in this study is concerned with suitable sites and appropriate scheme. GIS is powerful in spatial analysis, thus was adopted to prepare the spatial data as well as to screen out the initial suitable sites for MAR from the spatial aspect. However, due to the lack of groundwater flow information as well as the limitation resulting from data availability and classification, the suitable sites selected by the GIS based analysis are not necessarily the optimal sites in practice. Therefore, the verification of the suitable sites selected by GIS based analysis is needed. Groundwater flow modeling is famous for its ability to analyze groundwater flow, and it is also able to evaluate the advantages and disadvantages of implementing MAR at a proposed location when combined with specific scenarios. Therefore, a three-step analysis approach is speculated through combining the GIS based analysis with groundwater flow modeling to assess the implementation of MAR in terms of suitable sites and appropriate scheme (Figure 8-2).

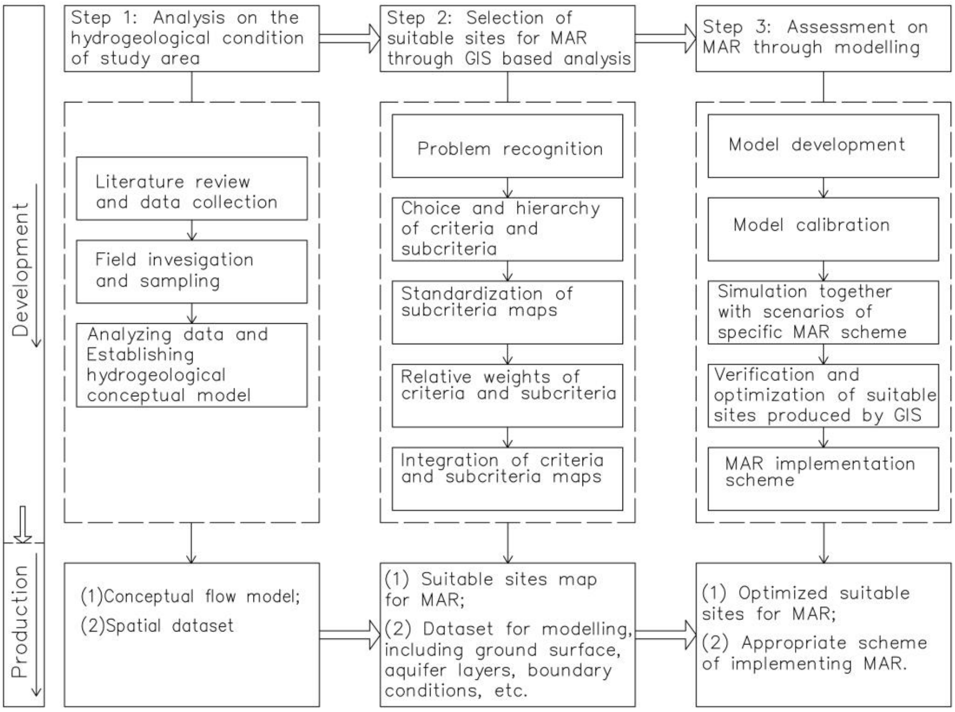


Figure 8-2 Technology road-map of the suggested GIS based modeling approach

It should be emphasized that during the entire process, the consistency of data used in the GIS and modeling must be maintained, thus the data sets including topography, geology, groundwater and other data used in the modeling must be those that were used or generated in the GIS based analysis. With the advantages of both spatial analysis in GIS and the seepage simulation in modeling, this three-step GIS based modeling approach provides a reliable way to assess the implementation of managed aquifer recharge to improving water security in drought-prone area.

8.5 Chapter summary

The GIS based modeling approach provided conducive insights for the successful implementation of the MAR in West Coast, South Africa. The implementation of MAR in UAU of West Coast is generally feasible. The suitable sites for UAU are characterized by the upper gradient area with proper permeability soil, thick aquifer and large thickness of vadose zone. Besides, the suitable sites are also dependent largely on the recharge purpose.

Infiltration pond is suggested to be adopted when implementing MAR in UAU, but borehole recharge is suggested in these specialized areas where the shallow subsurface stratum is concerned with extremely low permeability. The hydraulic conductivity in each layer of Langebaan Road aquifer system and Elandsfontein aquifer system is highly heterogeneous, thus the infiltration rate is suggested to be tested in the filed at the target location before implementing MAR. The clay-missing window area (natural recharge area) at southwest of Hopefield is the suitable site for implementing MAR in LAU. However, the present piezometric surface is much higher than the top of the confining-layer, therefore, there's little space in LAU to store water if implementing MAR at present. The research results are applicable in areas of similar characteristics.

This study has also shown that the presented three-step GIS based modeling approach provides a reliable way to assess the implementation of managed aquifer recharge to improving water security in drought-prone area.

CHAPTER 9: Conclusion and recommendation

9.1 Introduction

Around the topic of the assessment of managed aquifer recharge in West Coast of South Africa, this study addressed a three-step GIS based modeling approach: i) understanding groundwater systems and developing the groundwater flow conceptual model; ii) evaluating the suitable sites using GIS based analysis; iii) assessing the scheme for the implementation of MAR using modeling approach.

9.2 Conclusion and recommendation on groundwater flow conceptual model of West Coat, South Africa

The mainly aquifer units in the Langebaan Road aquifer system and Elandsfontein aquifer system of West Coast, South Africa are the upper unconfined aquifer unit (UAU) and the (semi) confined lower aquifer unit (LAU). The UAU is recharged directly from precipitation, and groundwater flow is generally topographically controlled and occurs from the higher areas in the southwest of Hopefield to the Berg River and its tributaries or the coastline. The Elandsfontyn clay is not continuous, thus the clay-missing windows in the vicinity of southwest Hopefield would facilitate the downward percolation of the water into the LAU via a “piston-flow” mechanism, then groundwater generally flows along the palaeochannels, and finally drains toward the Berg River, the coastline or the abstraction boreholes.

As currently uncertainty still exist in the aspects of distribution of Elandsfontyn clay and palaeochannels, as well as ascribing the monitoring data with the right aquifer unit, which limit the understanding of the aquifers system and groundwater flow mechanism of LAU. More boreholes are suggested to be carried out in the vicinity of the clay-missing areas as well as the connectivity area between Langebaan Road aquifer system and Elandsfontein aquifer system. Meanwhile, a more detailed analysis of the existing available groundwater monitoring boreholes together with their construction logs is suggested to correspond the monitoring data with the right aquifer. Then an optimized monitoring plan is able to be developed.

9.3 Conclusion and recommendation on suitable sites for implementing MAR in West Coat, South Africa

The suitable sites for UAU are always characterized by the upper gradient area with proper permeability soil, thick aquifer and large thickness of vadose zone. If these basic spatial characteristics are satisfied, the suitable sites are dependent largely on the recharge purpose. MAR can be implemented near the well field when it is considered as a relatively straightforward choice to increase local water storage and supply; while the natural recharge area is the best site for a large quantity of water recharge, which benefits the largest area of the whole aquifer unit. The clay-missing window areas (natural recharge area) at west of Hopefield are the most suitable sites for implementing MAR in LAU.

The performance of the application of GIS based analysis method to select suitable sites for implementing MAR in the LAU is not as good as in UAU, thus the improvement of the GIS based analysis is needed. More criteria including suitable aspects and constraint aspects are suggested to be incorporated in the analysis. The GIS based multicriteria decision analysis (Bonilla Valverde et al., 2016) seems to provide a direction of improvement. Meanwhile, the result of GIS based analysis need to be verified by modeling.

9.4 Conclusion and recommendation on appropriate schemes for implementing MAR in West Coat, South Africa

The implementation of MAR in UAU of West Coast is generally feasible. The available space for MAR is able to be estimated through equation (7-1). Based on the groundwater table measured in August 2017, the estimated available space for MAR in Langebaan Road aquifer system and Elandsfontein aquifer system is 366.2 million m^3 and 549.5 million m^3 respectively. Infiltration pond is suggested to be adopted when implementing MAR in UAU, but it should be cautious when applied to the area distributed with Langebaan Formation for the calcrete and clay embedded in the shallow subsurface stratum is concerned with extremely low permeability. Borehole recharge is suggested in these specialized areas. The estimated infiltration rate is 0.003 m/d in the vicinity of the clay-missing window area at west of Hopefield. Due to the fact that the hydraulic conductivity is highly heterogeneous in study area, the infiltration rate is suggested to be tested in the filed at the target location before implementing MAR.

The clay-missing window area (natural recharge area) at west of Hopefield is one of the suitable sites for implementing MAR in LAU of Langebaan Road aquifer system and Elandsfontein aquifer system. However, the present piezometric surface is much higher than the top of the confining-layer, thus there’s little space in LAU to store water if implementing MAR at present. Meanwhile, it is feasible to increase water availability of LAU through increasing leakage from UAU locally, but concerns remain a threat that the recharged water from UAU might contaminate the water of LAU. Infiltration pond is suggested to be adopted when implementing MAR at clay-missing window area, while borehole recharge is suggested to be adopted at the locations where the subsurface stratum is embedded with thick calcrete and clay or those areas distributed with aquitard.

The need for additional research on certain key aspects are identified as follows.

(1) Monitoring work is suggested to be strengthened and optimized especially around the clay-missing areas which are located in the vicinity of natural recharge area. Meanwhile, clogging analysis is suggested to assist the implementation of MAR.

(2) Although the steady-state groundwater model showed the reasonable results for the implementation of MAR in a regional scale, however, it is unable to reflect the actual process of implementing MAR. Thus a transit-state numerical model of local scale at the target area is strongly suggested.

(3) Recharge pilot trials and related field tests are suggested to be carried out in the vicinity of the target area to verify the results of this research, and guide the implementation of MAR.

(4) The uncertainties on the datasets around groundwater abstraction, recharge volumes and areas need to be further considered so as to improve the assessment.

9.5 Conclusion and recommendation on assessment of MAR to improving water security in drought-prone area

The addressed research provides positive implications to guide the implementation of MAR in unconfined aquifer and confined aquifer in other drought-prone area. These implications include: i) the natural recharge area is usually the suitable site for the implementation of MAR; ii) for the confined aquifer, the relationship between the water level and the confining-layer is a key issue which determines the the possibility and method of implementing MAR; and iii) the recharge is always closely linked with abstraction, thus managed aquifer recharge and abstraction should be considered as a whole.

Furthermore, the presented three-step GIS based modeling approach (Figure 8-2) provides a reliable way to assess the implementation of managed aquifer recharge to improving water security in drought-prone area in terms of suitable sites and appropriate scheme. This approach is applicable in areas of similar characteristics.

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11 APPENDICES

Most of this research work have been disseminated through publications and presentations as indicated below, and relevant sources for the data, publishing houses as well as conference organizers have been acknowledged.

11.1 Publication

JOURNAL ARTICLE:

(1) **Zhang H**, Xu Y, Kanyerere T (2019) Site assessment for MAR through GIS and Modeling in West Coast, South Africa. Water 11, 1646. (see Appendix A)

(2) **Zhang H**, Xu Y, Kanyerere T (2019) A modeling approach to improving water security in a drought-prone area, West Coast, South Africa. Physics and Chemistry of the Earth 114 (2019) 102797. https://doi.org/10.1016/j.pce.2019.08.005. (see Appendix B)

(3) **Zhang H**, Xu Y, Kanyerere T (2020) A review of the managed aquifer recharge: Historical development, current situation and perspectives. Physics and Chemistry of the Earth 118-119 (2020) 102887. https://doi.org/10.1016/j.pce.2020.102887.

PROJECT REPORT:

(1) **Zhang H**, Israel S, Kanyerere T, Jovanovic N (2019) Deliverable 6 - Technical report: modeling managed aquifer recharge report, as part of the project “Towards the sustainable exploitation of groundwater resources along the West Coast of South Africa”. Report to the Water Research Commission of South Africa. June 2019.

(2) Jovanovic N, Funke N, Tredoux G, Israel S, Kanyerere T, Andries C, **Zhang H** and Nel J (2019) Deliverable 7 - Stakeholder workshop proceedings, as part of the project “Towards the sustainable exploitation of groundwater resources along the West Coast of South Africa”. Report to the Water Research Commission of South Africa. August 2019.

11.2 Conference proceedings: (Oral and Poster presentations)

Heng Zhang, Yongxin Xu, Thokozani Kanyerere. Modeling drought-resilient aquifer system for implementing managed aquifer recharge, a poster presentation made at Research open Days, Agulhas, South Africa, 2017.

Heng Zhang, Yongxin Xu, Thokozani Kanyerere. A review of managed aquifer recharge, a poster paper submitted for 19th WaterNet/WARFSA/GWP-SA Symposium, Livingstone, Zambia, 2018.

Heng Zhang, Yongxin Xu, Thokozani Kanyerere. Modeling managed aquifer recharge for improving water security in drought-prone area, west coast, South Africa, a paper submitted together with presentation was made for 19th WaterNet/WARFSA/GWP-SA Symposium, Livingstone, Zambia, 2018.

Heng Zhang, Yongxin Xu, Thokozani Kanyerere. Modeling managed aquifer recharge in West Coast, South Africa, a presentation in the workshop of WRC project "Towards the sustainable exploitation of groundwater resources along the west coast of South Africa", West Coast Fossil Park, South Africa, 2019.

Appendix A

water

MDPI

Article

Site Assessment for MAR through GIS and Modeling in West Coast, South Africa

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Abstract: Towns along the West Coast of South Africa are facing water shortages due to climate change and increasing water demand. Managed aquifer recharge (MAR) is considered as a solution to improve water security. This paper presents a two-step method of combining geographic information system (GIS) based analysis with numerical modeling to select suitable sites for implementing MAR in the West Coast area. Many factors were taken into account to generate the initial map for suitable sites through GIS based analysis. Subsequently, groundwater flow modeling was adopted to verify and optimize the suitable sites selected by GIS based analysis. The result showed that the map for suitable sites produced by the GIS based analysis was reasonable from a spatial aspect, but due to the lack of groundwater seepage information, the most suitable sites developed are not necessarily the optimal choices in practice. With the aid of both the spatial analysis in GIS and seepage simulation, this two-step analysis approach provides a reliable solution to identify suitable sites for implementing MAR. This approach provides a much better reference to the study of suitable sites and possible impacts of implementing MAR in an aquifer in similar areas with water stress.

Keywords: managed aquifer recharge; suitable sites; geographic information systems; numerical modeling; South Africa West Coast

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1. Introduction

Due to climate change, rapid urbanization, and population expansion, the water demand and supply is showing increasing fluctuations, especially in the drought-prone areas of arid or semi-arid regions [1]. One of the most important water resource management strategies to improve water security in these drought-prone areas is managed aquifer recharge (MAR) [2,3]. MAR was developed to recharge groundwater purposefully and increase its storage to overcome the temporal imbalance between local water demand and availability, thus improving water security of the water supply.

The towns along the West Coast area of South Africa have been confronted with water shortages due to extreme drought weather conditions since 2014. Under great pressure from increasing water demand and decreasing water availability, the West Coast District Municipality (WCDM), together with the Department of Water Affairs of South Africa (DWA), plans to implement MAR in the West Coast area with water from the Berg River and other sources in the rainy season. In fact, given the increasing water demand at the rapidly growing holiday and residential status of the Langebaan Lagoon area, the plan of implementing MAR in this drought-prone area was first initiated in 2007 [4]. Subsequently, two borehole injection trials were conducted directly in the aquifers between September 2008 and March 2009 [5]. However, in order to eliminate the high cost of pipeline construction, the injection borehole was drilled in the WCDM well field instead of at ideal sites. Two weeks after the injection, several boreholes in the downstream area were over flowing [6], which showed that the injection recharge at the WCDM well field failed to keep water stored underground as initially expected. Therefore, despite the fact that several attempts on MAR have been conducted in the aquifers of the West Coast, the issue of suitable sites, which are of utmost importance for the correct functioning of the MAR system, is still unknown [5,6].

The assessment of suitable sites, which has been defined as the evaluation of a variety of needs for the prospective location and the suggestion of an area on the basis of a proper assessment of the land, is the main issue and the prime prerequisite for a MAR scheme [7]. Many factors need to be considered during the site selection process such as complex regional characteristics, heterogeneities in surface and/or subsurface characteristics, variable groundwater qualities, and other factors including political, social, and economic factors, which make the site assessment for MAR a challenge [8,9]. Computational tools play an important role in evaluating MAR scenarios and screening potential sites, particularly because they can be applied on regional spatial scales, and allow for the testing of operational scenarios, hydrologic conditions, and other management options [10]. GIS based integration of spatial data pertinent to groundwater recharge has widely been applied to case studies, with data coverage being classified and weighted before generating suitable sites map [11–14]. However, the initial GIS based integration method is weak in dealing with uncertainty and risks, therefore there is a large possibility of losing important information, which in turn may lead to poor decisions [15]. Several efforts have been made to improve the GIS based integration method by incorporating the knowledge of Fuzzy Mathematics or Operational Research into the process of GIS analysis. Malekmohammadi et al. [16] developed a method involving the integration of a multi-criteria decision making tool, GIS, and a fuzzy inference system, which was considered to be an effective method in MAR site selection. Rahman et al. [9] developed a spatial multi-criteria decision analysis software tool, which was based on the combination of non-compensatory screening, criteria standardization and weighting, and the analytical hierarchy process with weighted linear combination and ordered weighted averaging, and obtained a reasonably suitable site map for MAR when applied to the Querença Silves Aquifer of Portugal. Aside from the GIS based methods, numerical modeling can also help to identify suitable sites for MAR, and can be used to estimate the potential benefits of MAR projects on regional hydrologic conditions under a range of future climate, water use, and management scenarios [17]. Groundwater flow and transport models are applied to plan and optimize MAR facilities, quantify the impact on the local groundwater, and determine geochemical processes and the resulting recovery efficiency as well as to evaluate the feasibility of a MAR method at a suggested site [18–20].

Based on the above-mentioned literature review, the GIS based method seems to have a strong spatial data analysis ability, but is weak in dealing with uncertainty and risks. Although several efforts have been made with some progress achieved by incorporating fuzzy mathematics and other means, however, this method only provided a preliminary result without verification. Groundwater modeling is able to evaluate the advantages and disadvantages of implementing MAR at a proposed location when combined with specific scenarios. The application of GIS based analysis and modeling separately is well known, however, few studies (to the author's knowledge) have been performed together to assess the suitable sites for implementing MAR [10,21]. Combining GIS based analysis with numerical modeling can allow a more detailed and quantitative assessment of MAR opportunities and impacts.

This study presents a two-step method of combining GIS based analysis with groundwater modeling to select the suitable sites for implementing MAR in the West Coast area of South Africa where MAR is planned as a solution to the water shortage problem.

2. Materials and Methodology

2.1. Study Area

The study area is located between 17.8413°E and 18.7981°E and 33.5871°S and 32.6981°S along the West Coast of South Africa, which is about 100 km northwest of Cape Town city. The study area is composed of three catchments including G10M, G10L, and G21A, with the area of 4670 km^2. The area is bounded to the northwest and west by the Atlantic Ocean. The Berg River is the dominant perennial river in the region, which drains north westward into the Atlantic Ocean at Saint Helena Bay.

The overall terrain is low in the north and high in the south, with the ground elevation ranging from 0 to 550 m above mean sea level (a.m.s.l). The dominant topography is the flat-lying plains of the Berg River with an elevation less than 100 m a.m.s.l (Figure 1). Intrusive granite pluton generating koppies reach up to 550 m a.m.s.l in the south of the study area. The land use is dominated by shrubland, low fynbos, and commercial cultivated land, which is followed by small built-up and industrial areas that occur in the small towns of the study area.

The climate in the region is considered Mediterranean, with mean annual potential evaporation exceeding mean annual precipitation [22]. The daily average temperature is about 17 °C. From 1970 to 2017, the average annual rainfall varied from 185 mm in the northwest to 450 mm in the south. The monthly average rainfall data indicates that the rainy season is from June to August.

The predominant geology of the region is the unconsolidated Cenozoic sediments of the Sandveld Group (Figure S1). The underlying bedrocks are the Malmesbury Group Shale in the east and the Vredenburg and Darling Plutons of the Cape Granite Suite in the west with the inferred contact between the granite and shale of study area coinciding with the Colenso Fault [23,24]. The Cenozoic Sandveld Group unconformably overlies the bedrock.

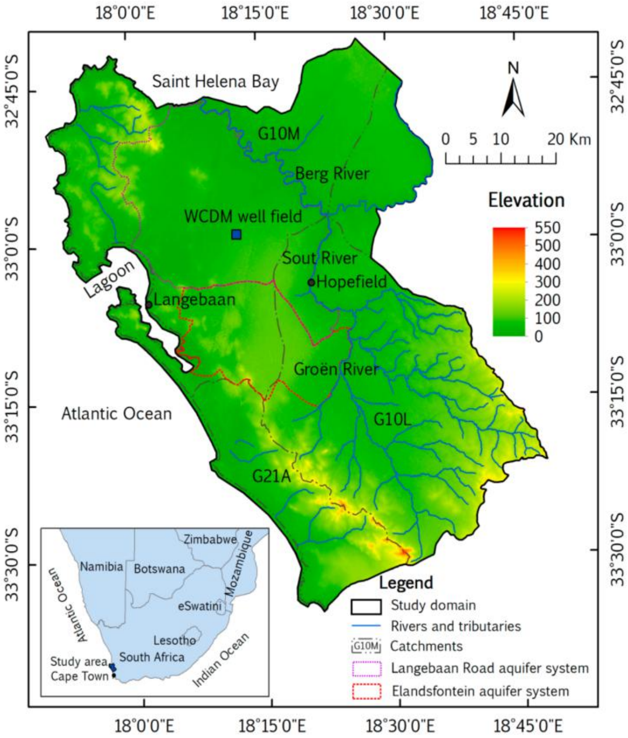

Figure 1. Topographic elevation and geographical location of the study area.

The Elandsfontyn Formation, which occurs only in bedrock depressions of palaeochannels, coincides with thick water-bearing sedimentary sequences that form the most important aquifers, namely the Langebaan Road aquifer system (LRAS) and Elandsfontein aquifer system (EAS) in the West Coast [25]. It is commonly accepted that aquifer systems are composed of four key units [22,26–28]:

1. The upper unconfined aquifer unit (UAU): The variably consolidated sands and calcretes with the interbedded peat clay of the Sandveld Group (except for Elandsfontyn Formation) can be considered as a single unconfined aquifer at the regional scale.
2. The aquitard clay: The clay layer of the upper Elandsfontyn Formation acts as an aquitard to (semi) confine the basal gravels of the lower aquifer. Borehole logsheets from the National Groundwater Archive of South Africa (NGA) were used to piece together a map of the clay distribution, which was discontinuous. In particular, in the west of Hopefield, a "clay-missing window" existed (Figure 2).
3. The (semi) confined lower aquifer unit (LAU): The LAU is composed of the basal gravels of the Elandsfontyn Formation. Due to the thickness (up to 60 m in some area) and large spatial extent of this aquifer unit, it is considered as the most important aquifer of the West Coast. However, the aquifer is restricted to palaeochannels based on its depositional environment.
4. The bedrock: Compared with Cenozoic sediment aquifers, the bedrock is considered as regionally impermeable, although some limited areas are of potential higher permeability.

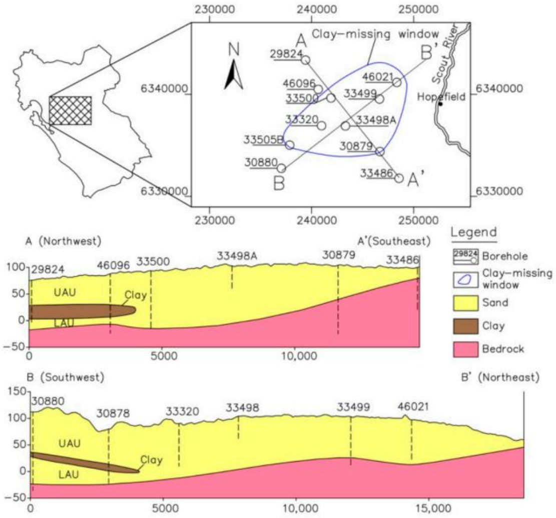

Figure 2. Geological cross section made by NGA data showing a clay-missing window at the west of Hopefield.

The UAU is recharged directly from precipitation. A recharged groundwater mound has been postulated within the three catchments of G10M, G10L, and G21A, southwest of Hopefield. Groundwater flow in the UAU is topographically controlled and occurs from the recharge mound to the Berg River or the coastline. The "clay- missing window" in the vicinity of the recharge mound would facilitate the downward percolation of the water into the LAU, then groundwater flows along the palaeochannels, and finally drains toward the Berg River or the coastline (Figure 3). Another significant way of discharge is abstraction through boreholes. Since municipal water supply targeting the LAU was significantly reduced after 2009 due to infrastructure vandalism, the abstraction mainly from the UAU recorded in the database was about 6.9 million m^3/a by 78 registered private users.

According to the chemical analysis of the groundwater samples, the dominant water type was Na, Ca–Cl, with an average pH of 8. Electrical conductivity (EC) in the UAU is often over 250 mS/m, while the EC is commonly less than 120 mS/m in LAU.

The groundwater flow mechanisms of the LRAS and EAS are conceptualized in Figure 3.

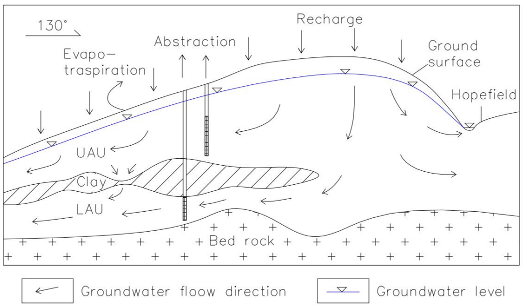

Figure 3. Conceptual cross-section of the groundwater flow mechanisms (not to scale, after Department of Water Affairs, 2010 [6]).

Compared with the UAU, the LAU has better water quality, hence is a desirable target aquifer for MAR. However, a comparison of the monitoring groundwater table with the elevation of the top part of the clay layer in the vicinity of the clay-missing window (natural recharge area of LAU) showed that the groundwater piezometric surface was much higher than the top clay layer (the confining layer), which makes the idea of implementing a MAR directly to the LAU impractical. Therefore, in this paper, the research into the site assessment on MAR was assumed to target the UAU. Meanwhile, in order to eliminate the high cost of construction on the abstraction wells as well as pipelines, the implementation of MAR was assumed to be able to benefit the WCDM well field (Figure 1).

2.2. Methodology

As described above, the assessment approach aimed at suitable site selection for MAR is a two-step method composed of GIS based analysis and numerical modeling. The first step of the approach was to make use of GIS based techniques to produce an initial map of suitable sites. Subsequently, groundwater modeling was applied to verify and optimize the map of the suitable sites generated by step one. In order to keep the data consistent and ensure the reliability of the analysis, several datasets including topography, geology, groundwater, pumping wells, and other data used in the modeling must be those that were used or generated in the first step. If better results in terms of water level, flow paths, impact of a MAR scenario are obtained by running the simulation model in the recommended sites than those in other locations, then the suitable site map that is developed is deemed to be reliable. Otherwise, the map for suitable sites is considered unreliable. Thus, improvement on the GIS based analysis in step one is repeated until the map of the suitable sites is verified by meeting the set criteria. This assessment procedure is shown in Figure 4.

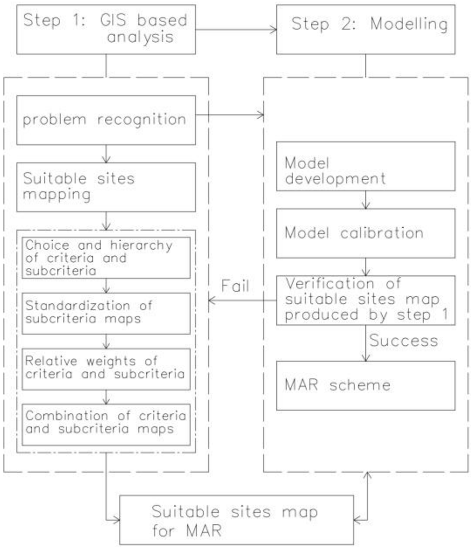

Figure 4. The two-step analysis procedure of suitable sites for MAR.

2.2.1. Step 1: GIS Based Analysis

In the site selection process, due to the fact that the volume of geographical data is huge and the analysis is very complex and time-consuming, the application of GIS will be inevitable [16]. Five sub-steps are included to serve as a reference for the basic method of GIS based analysis for the site suitability assessment of MAR.

1. Problem recognition

In a range of water resource management interventions, MAR has been proven to be an effective option. MAR is helpful for the recovery of groundwater levels, the improvement of groundwater quality, and for the storage of water and as a barrier against the intrusion of salinity. As problems differ from place to place, so do the techniques. Even if they are used for the same problems, the techniques required would vary from one case to another. A successful MAR scheme depends largely on the recognition of specific problems associated with a project.

2. Choice and hierarchy of criteria and subcriteria.

For any MAR site selection, different types of data are required. Considerations must be given to data availability and the objective of the analysis during the selection data of the type. The choice of datasets is divergent from case to case [9–11,29–37], however, the primary data adopted include surficial geology (Figure S1), soil infiltration capacity, land use (Figure S2), elevation (topographic slope, Figure S3), verified (measured) infiltration and recharge rates from observational studies (Figure S6), aquifer thickness (Figure S4), aquifer hydraulic conductivity, aquifer storativity, residence time, vadose zone thickness (Figure S5), historical changes in water table elevation, and groundwater quality (Figure 5).

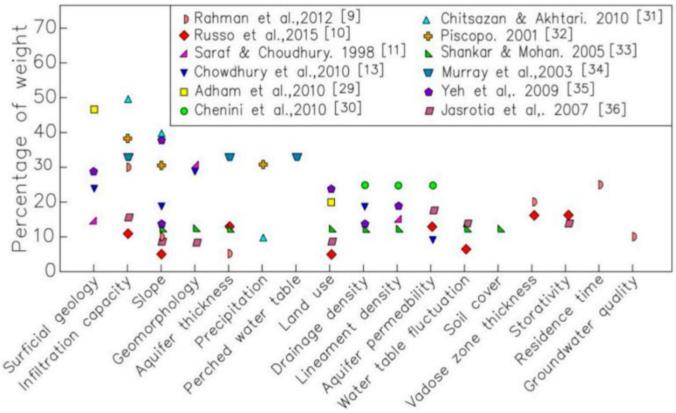

Figure 5. Comparison of the criteria and weights used in other similar studies (after Russo et al. 2015 [10]).

These datasets have proven to be functional in previous studies. However, due to the internal relationship between themselves, a good result cannot be expected by simply combining them together. The analytical hierarchy process (AHP), introduced by Saaty [38], has proven to be useful for spatial decision problems with a large number of criteria [39]. It can be used to combine all the representative criteria into a "criteria tree", with different levels of priorities accordingly [9,13,40,41]. Therefore, AHP was introduced to assist the choice criteria and weight determination to improve the accuracy of GIS based analysis. The application of AHP involves the decomposition of the ultimate goal into a three-level hierarchy consisting of subcriteria of the goal. The top of the hierarchy is the goal of the analysis, relating to the "suitable sites map". The middle level contains more specific criteria with regard to the objective, and the bottom level refers to the most specific criteria, which are related to the main criteria in the middle level.

High MAR suitability means that if a water supply of sufficient quantity and quality is available, the surface and subsurface conditions are likely to be favorable for developing a MAR project [10]. Accordingly, criteria including source water availability, infiltration capacity, and storage capacity are taken into account as the middle level. In light of the presence of abstraction wells in the study area, the influence of pumping wells was considered as a criterion of the middle level. For the most specific subcriteria level, source water quantity, water quality, and distance were chosen to support the source water availability analysis; land use, slope, and soil hydraulic conductivity were adopted to support the infiltration capacity analysis; the aquifer thickness, vadose zone thickness, residence time and ground water quality were taken into account to support the storage capacity analysis based on the assumption that the storativity of aquifer is constant; and the distance from the WCDM well field as well as negative influence of other pumping wells were considered to support the influence of pumping wells.

3. Standardization of subcriteria maps

Each subcriterion in the criteria tree is represented by a map of different types such as a classified map (e.g., land use) or a value map (e.g., slope, aquifer thickness). For decision analysis, the values and classes of all of the maps should be converted to the same scale to reduce the dimensionality. Such conversions are known as standardization [42]. Different standardization methods may be applied to different maps, and linear, piece-wise linear, and step functions for standardization are usually adopted. The outcome of the function is always a value between 0 and 1. The function is chosen in such a way that cells in a map that are highly suitable for achieving the goal obtain high standardized values and less suitable grids obtain low values.

4. Relative weights of criteria and subcriteria

The next step in the site selection procedure is to assign values of importance for all criteria and subcriteria, which is planned by assigning a weight to each specific criterion. Different weighting methods are available, however, pair-wise comparison and direct weighting were used here. The subcriteria under each main criterion were compared amongst themselves and an initial weight was assigned to each one. Next, a sensitivity analysis of the weight for the subcriteria was conducted by using the perturbation method to obtain the reasonable value range of weight of each subcriterion. The weight of each subcriterion was finally obtained by the correction of the initial weight based on the sensitivity analysis, as were the main criteria evaluated.

5. Combination of criteria and subcriteria maps

After standardization and weighting, the next step is to obtain the overall suitability index of each alternative. The index value is given to the cells of the map. For each grid cell in the analysis, an index is calculated by summing the products of value and weight for each subcriterion:

$$Index(x, y) = \sum_{i=1}^{n} v_i(x, y)w_i. \tag{1}$$

where n is the total number of subcriteria; v_i is the standardized value for subcriterion i at location (x,y); and w_i is the weight assigned to subcriterion i.

This process is called the weighted linear combination (WLC), which is available by using overlay method in GIS. Then, the map of suitable sites for implementing the MAR is produced.

2.2.2. Step 2: Groundwater Flow Modeling

The purpose of this step is to verify and optimize the suitable sites developed by step one, as well as to assess the appropriate MAR scheme based on the designed scenarios if needed. ModelMuse, together with the MODFLOW and MODPATH packages, were used in this work [43]. During the entire process, the consistency of data used in the GIS and modeling must be maintained. Once the process of development, calibration, and validation of the groundwater flow model is performed, several scenarios can be applied to verify the suitable sites map produced by step one. If the selected sites map pass verification, specific scenarios are applied to optimize the suitable sites or assess the MAR scheme. Otherwise, the process of step one is adjusted to generate a new suitable sites map that is able to go through the verification again.

3. Results

3.1. Distribution of Suitable Sites for MAR in West Coast

The hydrogeological characteristics and all of the available data of the study area were analyzed and the main hierarchical structure with the criteria and subcriteria is shown in Figure 6. In terms of the criterion of source water availability, the source water is supposed to be the runoff of the Berg River in the rainy season, thus both the water quantity and quality are satisfied for the purpose of artificial recharge; subsequently, the source water availability mainly depends on the distance between the source and the recharge sites.

The subcriteria, or thematic layers, were standardized and are shown in Figure 7.

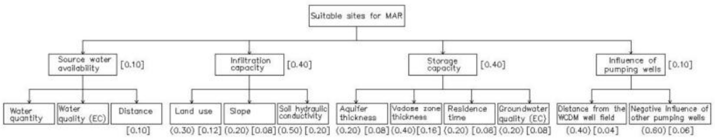

Figure 6. Criteria for the suitability mapping and hierarchical structure with local weights given in "( )"and global weights given in "[ ]".

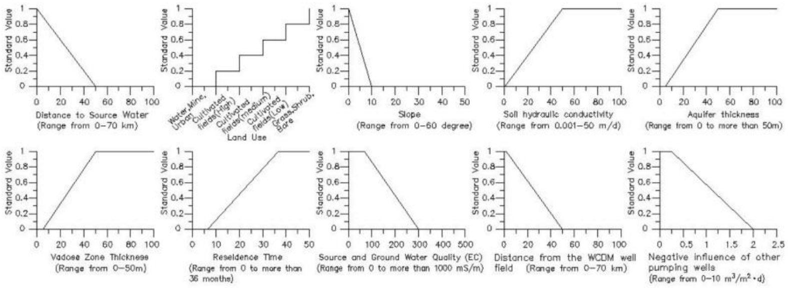

Figure 7. Procedure for the subcriteria standardization used in this study (range indicates the limit of the criteria value present in the study area).

Maps of source water availability, infiltration capacity, storage capacity, and influence of pumping wells were classified and are shown accordingly in Figure 8. Since the water availability is mainly dependent on the distance to the Berg River, the greater the proximity, the more suitable the site (Figure 8a). For the criterion of infiltration capability, the area distributed with Cenozoic sediments was more suitable than the area with an outcrop of bedrocks, which indicates the significant influence of lithology (Figure 8b). The suitability map of the storage capacity criterion showed that the high suitability sites were located west of Hopefield, where the aquifer thickness and the depth to groundwater table were greater than at any other place, while the low suitability sites were located in areas close to the discharge area including the Berg River and coastline (Figure 8c). For the criterion of the influence of pumping wells, it can be seen from Figure 8d that the high suitability sites were located in the vicinity of the WCDM well field but to the south, where the pumping rate of other wells was relatively low (see Figure S7).

The datasets of the criteria for the classified maps were combined to generate an integrated site map across the West Coast area, with a nominal resolution of 30 × 30 m (Figure 9). The calculated MAR suitability indices ranged from 0.18 to 0.91 in the order of increasing suitability, with a mean value of 0.58 and a standard deviation of 0.16. The area of suitable sites (Index > 0.60) was 2337.2 km^2, accounting for 50% of the total assessed area. The area of sites with a high suitability (Index > 0.80) was 237 km^2, which was located southwest of Hopefield, which is commonly regarded as the natural recharge area of the LRAS and EAS, followed by of the area north of the Berg River in G10M. The area of low suitability sites (Index < 0.60) was mainly located in the southeast parts of G10L in the study area and had an area of 2337.5 km^2, accounting for 50% of the total assessed area.

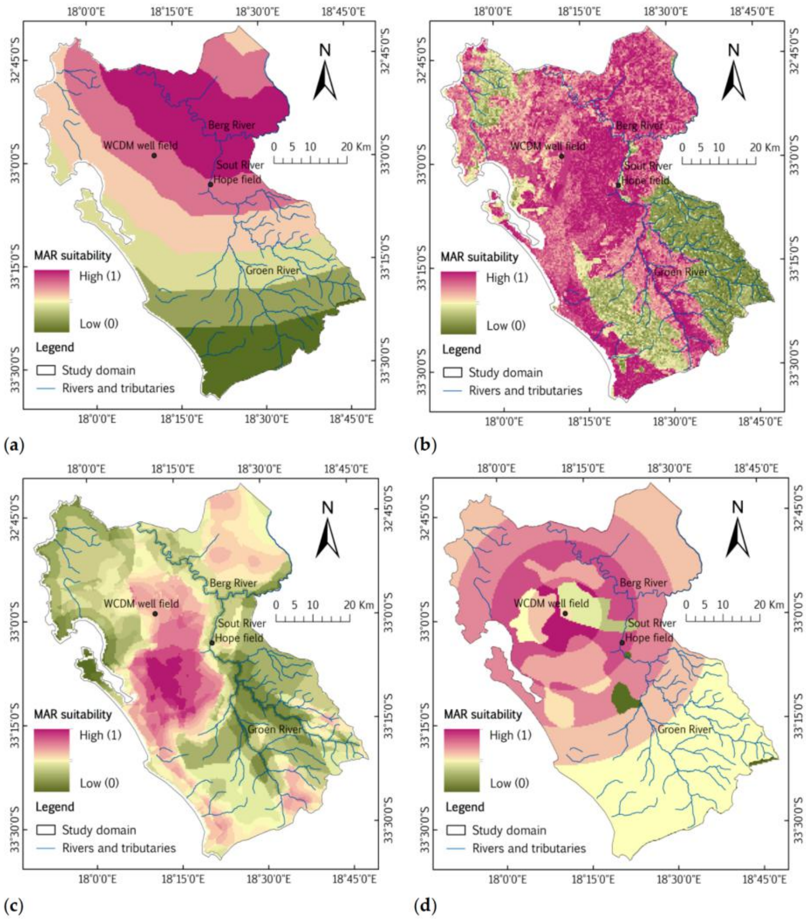

Figure 8. Criteria map used to determine the relative MAR suitability: (**a**) Source water availability; (**b**) Infiltration capability; (**c**) Storage capability; and (**d**) Influence of pumping wells.

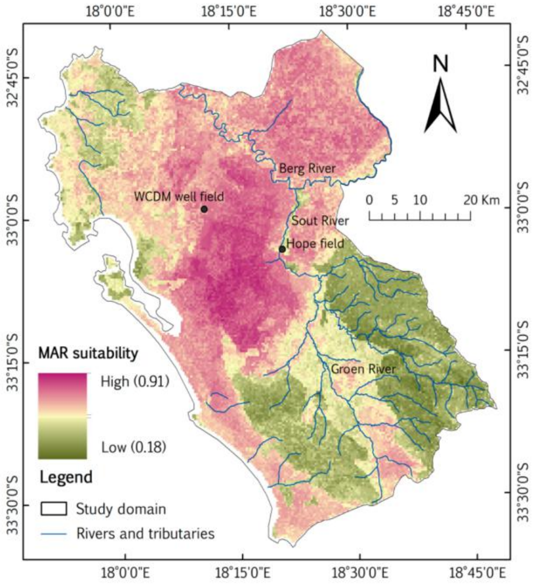

Figure 9. Suitable sites map integrated by the GIS based analysis.

3.2. Modeling the Influence of Various Options for MAR Project

A groundwater flow model covering the same area as the GIS based analysis was developed using ModelMuse to study the groundwater flow system and verify the suitable sites that were shown by the map that was integrated by the GIS based approach. The model was divided into four layers with varying thicknesses. The layer arrangement of the model is shown in Table 1.

Table 1. Layer arrangement for the numerical model.

Layer in Model	Representing	Thickness (m)	Data Source
1	UAU	0.1–121.0	Layer top: DEM Layer bottom: UAU bottom as defined through NGA lithology data
2	Clay layer	0–84.0	Layer top: UAU bottom as defined through NGA lithology data. Layer bottom: clay bottom as defined through NGA lithology data.
3	LAU	0.1–64.5	Layer top: clay bottom as defined through NGA lithology data. Layer bottom: bedrock elevation defined through NGA lithology data.
4	Bedrock	20.0	Layer top: bedrock elevation defined through NGA lithology data. Layer bottom: bedrock elevation—20 m

The model started to run after all the required data representing the boundary condition and initial condition were input (Table S1). The groundwater level data of 59 boreholes across the study area were adopted to calibrate the model, which was calibrated for steady-state conditions representing the flow regime before 2014 when there was no significant decrease in rainfall (Table S2). The calibration process proceeded until the best fit between the simulated and observed piezometric heads was achieved, during which the hydraulic conductivities were required to be maintained in the range provided in Table 2. By comparing the observed and simulated piezometric heads (h_{obs} and h_{sim}, respectively), the goodness of fit of the model was calculated using the root mean square error (RMSE) and the normalized root mean square error (NRMSE) with the help of Equations (2) and (3), with h_{max} and h_{min} as the maximum and minimum observed piezometric head, respectively.

$$RMSE = \sqrt{\frac{\sum (h_{obs} - h_{sim})^2}{n}} \tag{2}$$

$$NRMSE = \frac{RMSE}{h_{\max} - h_{\min}} \tag{3}$$

Finally, a RMSE of 5.4 m and a NRMSE of 5.3%, together with the correlation coefficient value of 0.95 between the simulated and observed piezometric heads, were achieved after continuous improvement, which represents an acceptable calibration for the intended modeling purpose [26].

Table 2. Stratigraphy and hydrogeological characteristics of the West Coast (after Seyler et al. 2016 [26]; Roberts and Siegfried 2014 [44]).

Group	Formation	Origin	Lithology	Function in Aquifer System	Thickness (m)	Hydraulic Conductivity K_x (m/d)
Sandveld	Witzand	Aeolian	Semi consolidated calcareous dune sand.	Upper unconfined aquifer (UAU)	0~121	0.09~60
	Springfontyn	Aeolian	Clean quartzitic sands, a decalcified dune sand. Dominates in the coastal zone.			
	Langebaan	Aeolian	Consolidated calcareous dune sand. The Aeolian deposit accumulated during the last glacial lowering of sea level when vast tracks of un-vegetated sand lay exposed on the emerging sea floor.			
	Velddrif	Marine	Beach sand. Associated with the last interglacial sea level rise with 6–7 m above present level.			
	Vaarswater	shallow-marine, estuarine, marsh and fluvial.	Deposits include a coarse basal beach gravel member, peat layers, clay beds, rounded fine to medium quartzes sand member and palatal phosphate rich deposits.			
	Elandsfontyn	Fluvia	Clays and peat in the upper sections.	Aquitard	0~84	4.3×10^{-5}~2
			Coarse fluvial sands and gravels, deposited in a number of palaeochannels filling depressions.	Confined lower aquifer unit (LAU)	0~64.5	0.5~70
Cape Granite Suite			Granites	Aquitard	/	4.3×10^{-3}~0.26
Malmesbury Group			Metamorphosed shales			

Once the model was calibrated, two scenarios were adopted to understand the influence of recharging through infiltration ponds at different sites (Figure 10). Details of the scenarios are shown in Table 3.

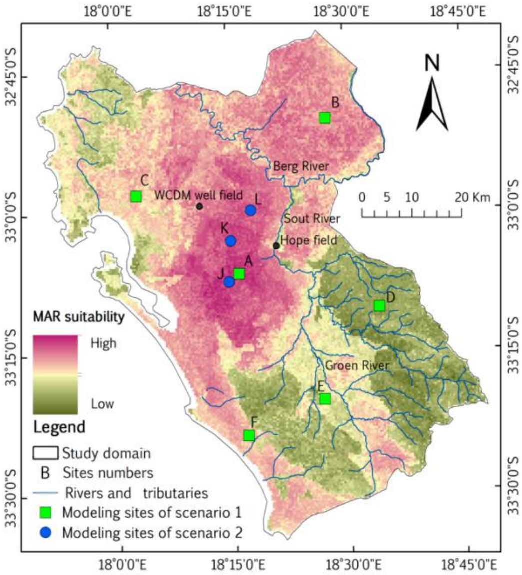

Figure 10. Recharge sites of the MAR in the modeling shown on the suitable sites map.

Table 3. Details of the modeling scenarios.

Scenario No.	Aim	Scenario Description
Scenario one	Modeling the influence of recharging at different sites	Six infiltration ponds (Length × Width × Depth: 250 m × 250 m × 3 m) with the recharge rate of 200 m^3/d respectively are placed at the different sites. A and B representing locations with high suitability; C and F representing locations with medium suitability; D and E representing locations with low suitability. MODPATH is used to trace the recharged water.
Scenario two	Modeling the impact to WCDM well field when implementing MAR.	Three infiltration ponds (250 m × 250 m × 3 m) with the recharge rate of 200 m^3/d each are placed at the locations with high suitability. The order of suitability index is J > K, L. Two abstraction wells located at WCDM well field pump water at the rate of 1000 m^3/d each. MODPATH is used to trace the recharged water.

The results of Scenario one are shown in Figures 11 and 12 and Table 4. A comparison among these three groups of locations with different suitability indices, unsurprisingly the locations with higher suitability, could be characterized with a higher rise in the groundwater level at recharge sites, larger storage area, and longer flow path. The largest rise in groundwater level occurred at locations D and E with low suitability indices on the map instead of at locations of A and B, that is, because the low permeability of lithology at D and E made it difficult for the recharged water to enter into the aquifer, leading to a comparatively higher rise in water level at the injection locations. In terms of the region of high rise in water level of locations D and E, it will take a long time for the recharged water to achieve the equilibrium state showed in the modeling, which is impractical when implementing a MAR scheme. From the results of this scenario, the suitable sites map developed by step one using the GIS analysis method was verified to be reasonable.

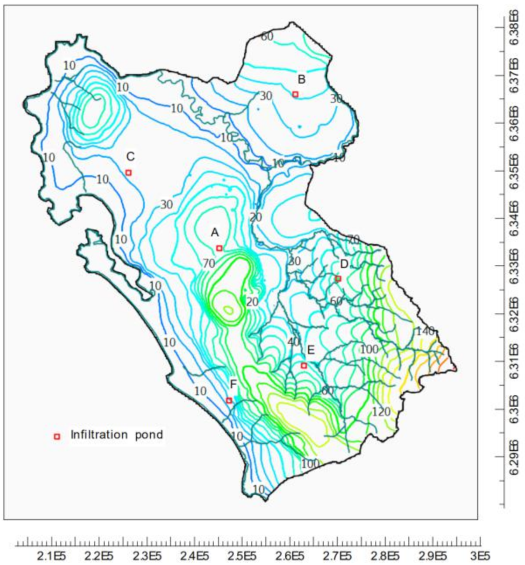

Figure 11. Simulated groundwater level map of the study area. The unit of the horizontal and vertical scale is in meters (m).

Figure 12 shows the flow paths of the recharged water, and reflects the divergent flow directions and discharges when recharging at different locations. It seems that none of the sites simulated in Scenario one were concerned with the purpose of benefiting the WCDM well field when implementing MAR. Thus, scenario two, which included three infiltration ponds located at the high suitability sites and two abstraction wells located at WCDM well field, was designed to uncover the relationship between MAR and the abstraction for the WCDM well field.

From the result of Scenario two (Figure 13), there was an obvious rise in the groundwater level around the three infiltration ponds, and the rise was higher at the proximity location of recharging than at any of the other farther sites. The largest rise in groundwater level was 25 m at location L, while about 20 m in rise occur at locations J and K. Although the three infiltration ponds are located at high suitability sites in the west of Hopefield, where it is usually considered as the natural recharge area of the LRAS and EAS, the flow paths showed divergent directions. Water recharged at location J flowed southwest toward Langebaan Lagoon, while water recharged at location L flowed northeast and discharged to the Berg River. For the water recharged at location K, it partly flowed toward Langebaan Lagoon, and partly flowed northwest toward the WCDM well field and discharged by abstraction through boreholes, which indicates that the recharge around location K can benefit the WCDM well field of the West Coast.

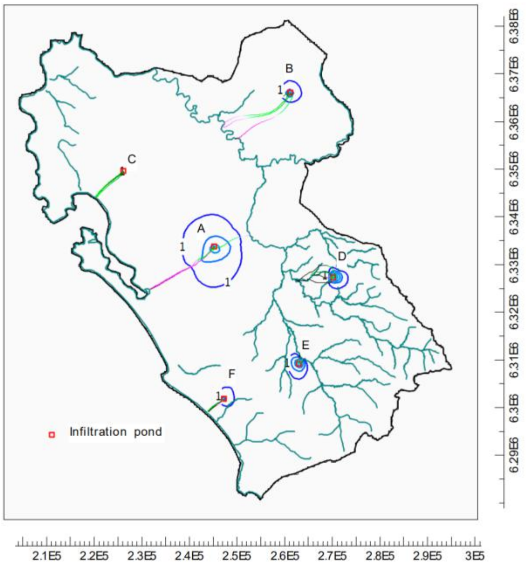

Figure 12. Rise in groundwater level and the flow paths of the recharged water. The unit of rise in groundwater contours is meters (m), and the interval of contours is 1 m. The color of the flow paths indicate the flow time: The greener the flow path, the shorter the flow time; and the more purple the flow path, the longer the flow time.

Table 4. Simulated results of implementing MAR in the UAU.

Location	**Suitability Map Site**	**Discharge Location**	**Length of Flow Path**	**Maximum Rise in Groundwater Level (m)**	**Region of Ground Water Level Rise above 1 m**
Infiltration pond A	Highest Suitability	Partly to tributary of Berg River, partly to Langebaan Lagoon	8300–16,300	+4.0	A nearly circular region with 13,000 m in diameter.
Infiltration pond B	High Suitability	Berg river	15,600–16,700	+5.0	A nearly circular region with 4600 m in diameter.
Infiltration pond C	Medium Suitability	Langebaan Lagoon	7900	+1.0	A nearly circular region with 250 m in diameter.
Infiltration pond D	Low Suitability	Tributary of Berg River	440–12,700	+12.0	A nearly circular region with 3700 m in diameter.
Infiltration pond E	Low Suitability	Tributary of Berg River	1200–1950	+8.0	A nearly circular region with 4100 m in diameter.
Infiltration pond F	Medium Suitability	Coastline	4300	+3.0	A nearly circular region with 3400 m in diameter.

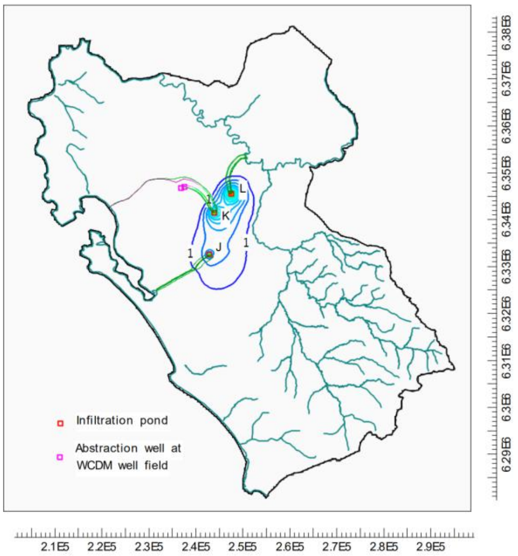

Figure 13. Simulated rise in groundwater level and the flow paths of recharged water in Scenario 2. The unit of rise in groundwater contours is in meters (m), and the interval of contours is 1 m. The color of flow paths indicates the flow time: the greener the flow path, the shorter the flow time; and the more purple the flow path, the longer the flow time.

4. Discussion

Due to the powerful spatial analysis ability of GIS, the GIS based method has been widely applied to suitability analysis. Among these studies, most GIS based studies on assessing the recharge properties and processes have focused on natural or incidental recharge, rather than MAR. The most popular method from the literature has been to integrate the criteria with different weights, despite the adopted criteria and weighting methods being divergent from different cases. Due to the limitation resulting from data availability and classification, some extent of error was incurred [16]. However, a few earlier studies have attempted to verify the results of the GIS based analysis for accuracy or applicability. The attempts addressed the above issue by developing a two-step approach of combining the GIS based analysis with modeling to select suitable sites for MAR.

For the GIS based analysis, efforts to improve the analysis of sites have never stopped. Criteria selection and weight determination have been the issues focused on in these studies. In fact, not only were suitable criteria the focus, but several studies have also concentrated on using the constraint criteria to screen out the areas where MAR are actually non-feasible [9,45,46]. In this paper, we attempted to incorporate the AHP into the criteria choice during the process of mapping suitable sites. The AHP method was adopted to develop a three-level criteria tree based on the fact that the MAR project is largely dependent on the factors of source water availability, infiltration capacity, storage capacity, and influence of pumping wells. Then, subcriteria including source water quantity, water quality, distance, land use, slope, soil permeability, aquifer thickness, vadose zone thickness, residence time, ground water quality, distance from the WCDM well field, and negative influence of other pumping wells were chosen to support these four criteria. The combination of AHP with WLC can provide a more effective way for spatial decision problems. When this method was applied to the case study of the West Coast of South Africa, a reasonable result was achieved. The area of suitable sites (Index > 0.60) was 2337.2 km^2, accounting for 50% of the total assessed area.

Modeling is widely applied to the analysis of groundwater flow. In this paper, groundwater modeling was adopted in the second step to verify the suitable sites map integrated by the GIS based analysis, and further optimize the sites map. Results of the modeling showed that higher suitability areas in the West Coast were characterized by a higher rise in groundwater level, larger storage space, and longer flow path. However, the Scenario two modeling results also showed that the water flow in the aquifer of the West Coast was not concerned with the suitability index. Recharging at location J, which had the highest suitability index, could not recharge the WCDM well field, but flows away toward Langebaan Lagoon, while recharging only around location K could benefit WCDM well field. The area of suitable sites (Index > 0.6) able to benefit the WCDM well field was about 57.1 km^2, which accounted for only 2.4% of the suitable sites mapped by the GIS based analysis (Figure 14). This difference was caused by the groundwater flow, which was not considered in the GIS based analysis. It can be seen from Figure 14 that the area that benefited the WCDM well field through MAR with a high suitability index was located northwest of Hopefield, instead of in the vicinity of the WCDM well field, which is due to the relatively larger values in soil hydraulic conductivity, aquifer thickness as well as vadose zone thickness northwest of Hopefield. Meanwhile, there are sparse pumping wells present between the recharge area and the WCDM well field, which allows water more than 5 km upstream to be able to flow and recharge in the WCDM well field downstream. However, the idea of not constructing any more new well fields would sharply limit the options to select new suitable sites for implementing MAR, which constrains the implementation of MAR in the West Coast to increase the water supply. Therefore, to alleviate the pressure on the water supply of the West Coast, not only should MAR be implemented at suitable sites, but it is suggested that new well fields should be constructed properly.

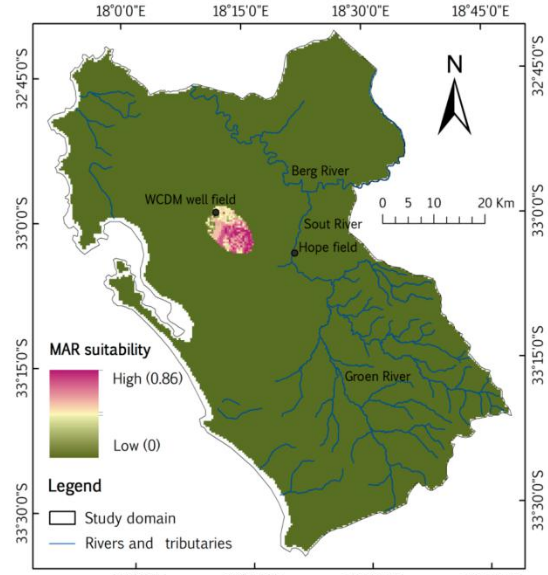

Figure 14. Optimized suitable sites of MAR that benefit the UAU of the WCDM well field.

Based on the above-mentioned, the suitable sites map developed by the GIS based analysis was reasonable from the spatial aspect. However, due to the lack of groundwater flow information, the most suitable sites selected by the GIS based analysis are not necessarily the optimal sites in practice. Therefore, the role of GIS based analysis is suggested to screen out the initial suitable sites for the implementation of MAR, and the results of GIS based analysis need to be verified by modeling. GIS based analysis is powerful in spatial analysis, while modeling is famous for its ability to analyze groundwater flow. Combining these two methods into a two-step analysis approach has proven to be a reliable way to identify suitable sites for implementing MAR.

5. Conclusions

A two-step approach of combining GIS based analysis with groundwater modeling presented a series of methods for integrating spatial surface and subsurface data using GIS to identify sites that may be suitable for the implementation of MAR in the West Coast of South Africa, together with a method of verification and optimization by using a numerical model. The suitable sites mapped by the GIS based analysis showed that an area of 2337.2 km^2 was suitable to implement MAR in the West Coast. However, the modeling indicates that recharging only in the vicinity of location K with an area of 57.1 km^2 could benefit the WCDM well field. Therefore, the idea of using the WCDM well field without the construction of new well fields would constrain the implementation of MAR in the West Coast. In order to alleviate the pressure on the water supply of the West Coast, not only should MAR be implemented at suitable sites, but that new well fields should be constructed properly.

The suitable sites mapped by the GIS based analysis were reasonable from a spatial perspective. However, due to the lack of groundwater seepage information, the most suitable sites developed by the GIS based analysis method are not necessarily the optimal sites in practice. With the advantages of both spatial analysis in GIS and the seepage simulation in modeling, this two-step analysis approach provides a reliable solution to screen out the suitable sites for implementing MAR.

Future improvements including more factors (e.g., political, economic, ecological factors, etc.) together with their weights and more specific modeling scenarios may need to be considered in the analysis process of suitable site selection. With respect to the West Coast of South Africa, the next step in determining a MAR project site is to conduct field injection tests at selected field locations and obtain the parameters needed for the implementation of MAR. Data from future additional studies will be helpful in calibrating both the GIS based analyses and the regional hydrogeologic model, and finally improving the MAR scheme. The approach presented in this paper is not limited to the West Coast, and can be replicated to study the suitable sites and possible impacts of implementing MAR in an aquifer with similar characteristics to improve the water security of drought-prone areas.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4441/11/8/1646/s1, Figure S1: Geological map of the study area. Figure S2: Land use of the study area. Figure S3: Slope of the study area. Figure S4: Aquifer thickness of the study area. Figure S5: Vadose zone thickness of the study area. Figure S6: Recharge distribution used in the modeling (from DWAF 2006 [47]). Figure S7: Pumping wells in the groundwater modeling (from DWAF, 2008 [22]; Seyler, 2016 [26]). Table S1: Description of the model boundaries. Table S2: Modeled versus observed groundwater table values of the steady-state calibration.

Author Contributions: Conceptualization, Methodology, Software, Formal Analysis, Investigation, Resources, Data Curation, Writing—Original Draft Preparation, H.Z.; Writing—Review & Editing, Supervision, Y.X.; Writing—Review & Editing, Project Administration, Funding Acquisition, T.K.

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Appendix B

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A modelling approach to improving water security in a drought-prone area, West Coast, South Africa

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ABSTRACT

Due to severe droughts and rapid urbanization, Cape Town municipality including small towns along the West Coast of South Africa are facing water shortages. Managed aquifer recharge (MAR) seems to offer a solution to improve water security in this drought-prone area. This paper presents a conceptual framework within which numerical modelling of the aquifers system is operated to improve water security of West Coast. The ModelMuse software that included MODFLOW and MODPATH packages was used. Scenarios which considered recharge aspects were used to evaluate suitable sites and appropriate scheme of implementing MAR. The result showed that it is feasible to implement MAR in the upper unconfined aquifer unit (UAU) which had estimated available space for MAR of 915.7 million m^3. For the semi-confined lower aquifer unit (LAU), the clay-missing window area located at west of Hopefield was a suitable site to implement MAR. However, the prevailing little space in LAU to store recharged water was a limiting factor to support the implementation of MAR scheme. Details on the possibility of implementing MAR scheme for West Coast aquifers system were discussed based of the simulations that were carried out. Although the modelling approach does not provide precise areas but a management tool, it provides key insights that are applicable in aquifer systems of similar characteristics.

1. Introduction

Climate change and global change including urbanization, population expansion, pose an increasing risk to water resource management especially in a drought-prone area. Currently, Cape Town and its neighbouring towns along the West Coast of South Africa are facing water shortages. This situation might be persistent as signs of drought seem unabated. Managed Aquifer Recharge (MAR), which is the intentional recharge of an aquifer for later recovery or environmental benefits and represents a valuable method for sustainable water resource management, seems to offer a solution to improve water security (Dillon, 2009; Ringleb et al., 2016). Under the great pressure from increasing water demand and decreasing water availability, the West Coast District Municipality (WCDM) together with Department of Water Affairs of South Africa plans to implement MAR in the West Coast area with water from Berg River and other sources during the rainy season. The plan of implementing MAR in this drought-prone area was first initiated in 2007 (DWAF, 2007). Subsequently, two borehole injection trials were conducted directly in the confined lower aquifer unit (LAU) of West Coast between September 2008 and March 2009 (Tredoux and Engelbrecht, 2009). However, due to constraints on the high cost of pipeline construction, the injection borehole was drilled in the WCDM well field instead of ideal sites as per an initial plan. Two weeks after the injection, several boreholes in the downstream area were overflowing (DWA, 2010a), which indicated that the injected recharge at the WCDM well field failed to keep water stored underground as initially expected. Although such attempts on MAR were made in the aquifers of West Coast, the management of groundwater, in particular, the suitable sites and volumes of artificial recharge which are important for proper functioning of the system are still unknown (DWAF, 2008; Tredoux and Engelbrecht, 2009; DWA, 2010a).

Numerical modelling is seen as a useful tool to help interrogate groundwater flow and contaminant transport, and to simulate conditions that cannot be replicated through experiments or trails or for which outcomes need to be known a priori (Jovanovic et al., 2017). Thus numerical models are often used for the assessment of MAR schemes, and then outputs of which can be translated into recommendations in support of sound decision-making (Ringleb et al., 2016). Groundwater flow and transport models are applied to plan and optimize MAR facilities, to quantify the impact on the local groundwater, and to determine geochemical processes and the resulting recovery efficiency, as well as to investigate the feasibility of a MAR method at a proposed site (Kloppmann et al., 2012; Maliva, 2015; Ringleb et al., 2016). Despite adaptive approaches for example, using

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trial and error, modelling is a valuable tool to estimate the feasibility of a MAR method (Ringleb et al., 2016). In general, previous literature indicated the suitability of using numerical modelling in support of MAR, in particular with MODFLOW and compatible packages (Ringleb et al., 2016; Jovanovic et al., 2017; Glass et al., 2018). However, it also highlighted the need to set up and calibrate models for specific sites with intrinsic parameters, as findings could not readily be extrapolated to other sites of similar features.

This paper demonstrates the application of modelling techniques to implementing MAR for improving water security in terms of showing suitable sites for MAR and predicting effects of implementing artificial recharge. The present work is divided into three parts. Firstly, the framework of the conceptual model is presented, which informed the designing of a 3D finite differences model. Secondly, the description of the numerical model followed was guided by the developed or existing conceptual model. Thirdly, several scenarios are applied to evaluate the suitable sites for MAR and appropriate scheme for implementing MAR after the process of calibration and validation of the model was performed.

2. Materials and methods

2.1. Study area

2.1.1. Geographic setting

The study area is located between 17.8413°E and 18.7981°E and 33.5871°S and 32.6981°S along the West Coast of South Africa, which is about 100 km northwest of Cape Town city. The area is bounded to the northwest and west by the Atlantic Ocean. Berg River is the dominant perennial river in the region, which drains northwestwards into the Atlantic Ocean at Saint Helena Bay. The Sout River and Groën River (and their tributaries) drain northwards into the Berg River.

The overall terrain is low in the north and high in the south, with the ground elevation ranging from 0 to 550 m above mean sea level (a.m.s.l). The dominate topography is the flat-lying plains of Berg River with elevation less than 100 m a.m.s.l (Fig. 1). Intrusive granite plutons generating koppies reach up to 550 m a.m.s.l in the south of study area.

The land use is dominated by shrub-land, low fynbos, and

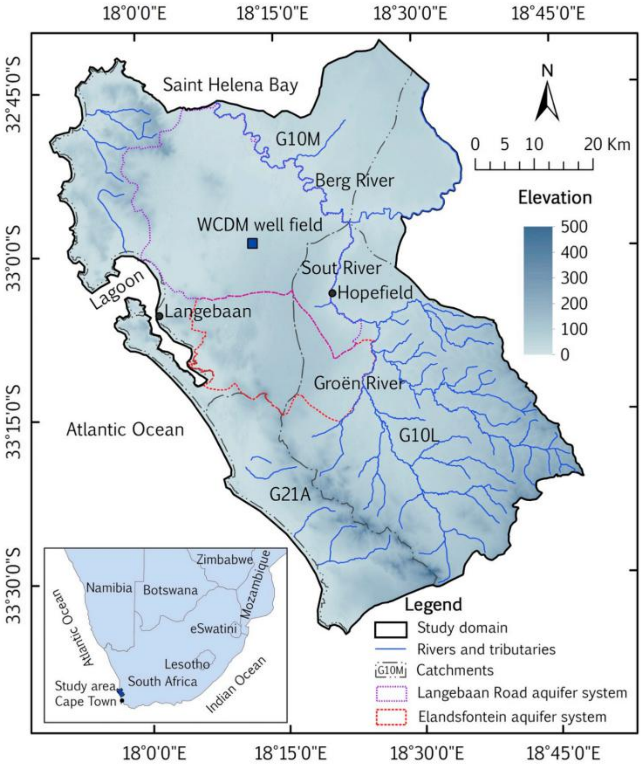

Fig. 1. Topographic elevation and location of the study area.

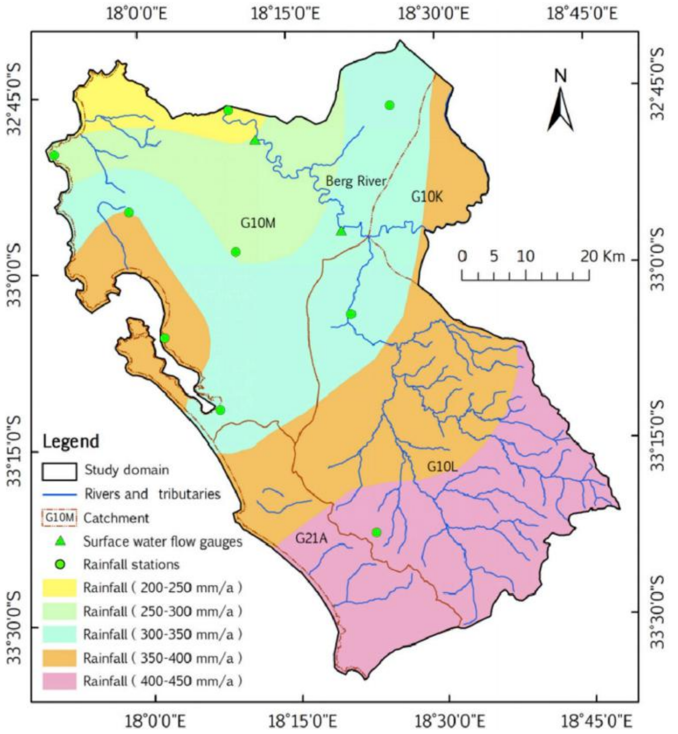

Fig. 2. Average annual rainfall distribution of the study area from 1970 to 2017, showing average annual rainfall ranges from 200 mm/a in the north to 450 mm/a in the south.

commercial cultivated land, which is followed by small areas of built-up and industrial sites occurring in the small towns of the study area (DWAF, 2008).

2.1.2. Hydrological setting

The climate in the region is considered Mediterranean (DWAF, 2008). The daily temperature varies from 2.4 to 36.8°, with an average value of 17°. According to the data collected from 9 rainfall stations which are distributed in the study area, the average annual rainfall varies from 185 mm in the northwest to 450 mm in the south (Fig. 2). The rainy season is from June to August, during which rainfall accounts for over 50 percent of the annual amount.

The monitoring data of water flow gauge G1H023, which is located about 4.3 km northwest of the junction between Berg River and Sout River, shows that the hourly water level of Berg River fluctuates from 0.46 m to 4.35 m. The water level usually peaks during the rainy season shortly after rainfall and then falls back to less than 1 m a.m.s.l in the dry season. Understanding such fluctuation pattern is fundamental towards the implementation of the MAR scheme.

2.1.3. Geologic and hydrogeological setting

The predominant geology of the region is the unconsolidated Cenozoic sediments of the Sandveld Group. The underlying bedrocks are the Malmesbury Group Shale in the east and the Vredenburg and Darling Plutons of the Cape Granite Suite in the west. The inferred contact between the granite and shale of the study area coincides with the Colenso Fault (Timmerman, 1985a, 1985b). The Cenozoic Sandveld Group unconformably overlies the bedrock (Fig. 3, Table 1).

Palaeo-channels which represent the palaeo-courses of previous rivers were found based on the geophysical and borehole investigation (DWAF, 2008). Thus there are divergent opinions on certain key features of the palaeo-topography due to the limited data. However, the area of the palaeo-channels coincides with thick water-bearing sedimentary sequences, which have been named the Langebaan Road aquifer system and the Elandsfontein aquifer system respectively (Woodford and Fortuin, 2003). The presents of palaeo-channels environments have implication with regards to the MAR scheme in terms of aquifer storativity, transmissivity and yield. The Elandsfontyn Formation of Sandveld Group is a marker layer with a fluvial origin, which distributes only in bedrock depressions of palaeo-channels (Roberts and

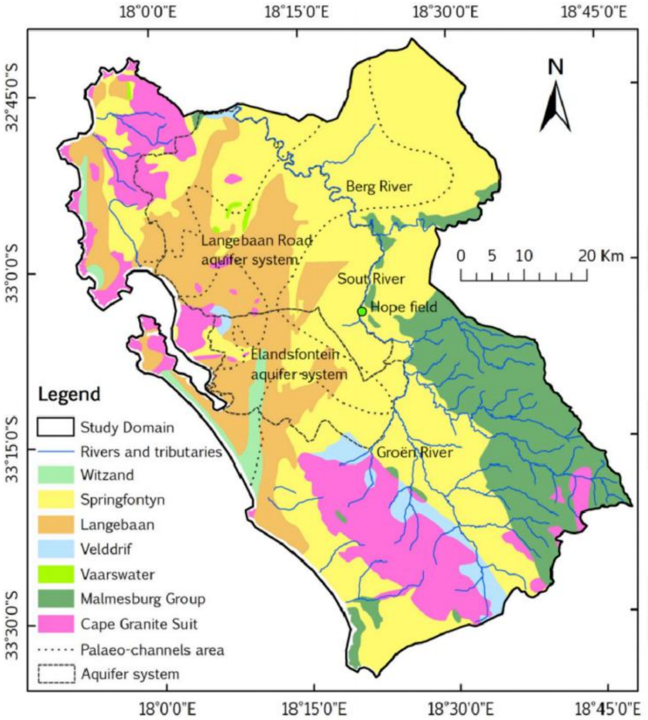

Fig. 3. Geological map of the study area (after DWAF, 2008; Seyler et al., 2016).

Siegfried, 2014). The upper layer of the Elandsfontyn Formation includes a significant thickness of the clay, which forms the layer of aquitard between the upper aquifer and lower aquifer (Fig. 4, Table 1).

The complex hydrostratigraphy of the study area can be represented on the regional scale by three aquifer key units according to the vertical distribution of lithology (Timmerman, 1988; DWAF, 2008; WCDM, 2009; Seyler et al., 2016):

2.1.3.1. Upper unconfined aquifer unit (UAU). The variably consolidated sands and calcretes, together with interbedded peat and clay of the Witzand, Springfontyn, Langebaan, Velddrif and Vaarswater Formations form the UAU, can be considered as a single unconfined aquifer. However, Timmerman (1985b) cautions that UAU especially in the Elandsfontein aquifer system is a very complex succession of up to four aquifer-aquitard layers at the local scale, hence the single unconfined aquifer needs be cautioned.

The UAU is recharged directly from precipitation. A recharged groundwater mound in Langebaan Road aquifer system and Elandsfontein aquifer system has been postulated within the three catchments of G10M, G10L and G21A near Hopefield (Fig. 2). This recharge mound may also be related to the lower permeability sediments within the region (Timmerman, 1985b). Groundwater flow in the UAU is topographically controlled from the recharge mound to the Berg River or the coastline. On average, the Berg River together with its tributaries gains from the aquifer as there is a strong hydraulic gradient towards it. However, it is possible that the Berg River recharges the UAU during the rainy season.

The dominant water type is Na, Ca–Cl, with an average pH of 8 according to the chemistry analysis of water samples. Electrical conductivity (EC) of groundwater in the UAU is often over 250 mS/m, and often exceeds 500 mS/m where close to the Berg River and coastline. In general, the water quality in Elandsfontein aquifer system is better than in Langebaan Road aquifer system in terms percentages of salinity.

2.1.3.2. Aquitard clay. The clay of the upper Elandsfontyn Formation acts as aquitard to semi-confined the lower basal aquifer. DWAF (2008) considers that this clay layer is distributed in a wide area over the centre of the Langebaan Road aquifer system, Elandsfontein aquifer system and north of the Berg River, to cover all areas of the basal gravel sediments. However, WCDM (2005) cautions that the clay layer is not always present, and it leads to indistinguishable identification of the LAU and UAU in some places. This argument has implication for MAR implementation. A total of 212 boreholes with logsheets from National Groundwater Archive of South Africa (NGA) were processed to produce

Table 1
Stratigraphy and hydrogeological characteristics of the study area (after Roberts and Siegfried, 2014; Seyler et al., 2016).

Group	Formation	Origin	Lithology	Function in the aquifer system	Thickness (m)	Hydraulic conductivity K_x (m/d)
Sandveld	Witzand	Aeolian	Semi-consolidated calcareous dune sand.	Upper unconfined aquifer (UAU)	0–121.0	0.09–86.4
	Springfontyn	Aeolian	Clean quartzitic sands, a decalcified dune sand. Dominates in the coastal zone.			
	Langebaan	Aeolian	Consolidated calcareous dune sand. The Aeolian deposit accumulated during the last glacial lowering of sea level when vast tracks of unvegetated sand lay exposed on the emerging sea floor.			
	Velddrif	Marine	Beach sand. Associated with the last interglacial sea level rise with 6–7 m above the present level.			
	Vaarswater	shallow marine, esturine, marsh and fluvial.	Deposits include a coarse basal beach gravel member, peat layers, clay beds, rounded fine to medium quartzes sand member and palatal phosphate rich deposits.			
	Elandsfontyn	Fluvia	Clays and peat in the upper sections.	Aquitard	0–84.0	4.3×10^{-5} –2.0
			Coarse fluvial sands and gravels, deposited in a number of palaeo-channels filling depressions.	Lower (semi) confined aquifer (LAU)	0–64.5	0.1–70.0
Cape Granite Suite			Granites	Aquitard	/	4.3×10^{-3} –0.26
Malmesbury Group			Metamorphosed shales			

a map of clay distribution. The results showed that the clay layers occurred in a discontinuous pattern and there were clay-missing windows in some areas in the west of Hopefield (Fig. 5).

2.1.3.3. Semi-confined lower aquifer unit (LAU). LAU is composed of the basal gravels of the Elandsfontyn Formation. Due to the thickness (up to 60 m in some area of Langebaan Road) and large spatial extent of this aquifer unit, it is considered as the most important aquifer of the West Coast area. However, this aquifer is restricted to palaeo-channels based on its depositional environment.

Due to lack of outcrop of the Elandsfontyn Formation and its separation from the UAU by the clay layer across most of the interior, the recharge mechanism of the LAU is more complex. The low permeability of UAU sediments together with "clay-missing window" around the recharge mound (southwest of Hopefield), would facilitate the downward percolation of the recharged water into the LAU, and then this water flow laterally in a north-westerly direction towards the Langebaan Road aquifer system and south-westerly towards Elandsfontein aquifer system via a "piston-flow" mechanism under confining pressures (Timmerman, 1985b). Recharge to the LAU also occurs through leakage from the UAU in locations where the clay is thin and the head difference between upper and lower aquifer is large enough to drive vertical recharge downwards (DWAF, 2008). Flow in the LAU occurs along the axes of the palaeo-channels, and finally discharges to the Berg River and the coastline.

The dominant water type is Na, Ca–Cl, with an average pH of 8. EC of groundwater is commonly less than 120 mS/m, which represents better water quality when compared with UAU.

From the above mentioned, the conceptual model of groundwater flow is established on the basis of the analysis on hydrogeology of the study area (Fig. 6), which lays the foundation of the numerical simulation.

2.2. Numerical modelling

2.2.1. Model development

To achieve the objective of identifying suitable sites and proper scheme of implementing MAR, the use of a numerical model based on the knowledge of similar studies (Hsieh et al., 2010; Russo et al., 2015; Jovanovic et al., 2017) was identified as appropriate methodical approach. ModelMuse is a graphical user interface from the U.S. Geological Survey models where MODFLOW–2005 and PHAST were chosen as appropriate methods. Various scholarships have shown that ModelMuse has been proven to be a useful software for groundwater modelling (Winston, 2009), hence the use of such software package for the current study for this paper. The numerical model was developed using ModelMuse where MODFLOW and MODPATH packages were selected. The grid of model comprises four layers with varying thickness, together with 77059 (Rows 293, columns 263) cells within each layer that covers area of 4670 km^2 (Table 2).

Numerical model boundaries in the model which were defined at positions where a known hydraulic head, known flux of groundwater and known loss of groundwater from the groundwater system existed (Table 3).

Estimates including grid-based GIS modelling technique, chloride mass balance approach, and water balance model showed that the recharge rates vary from 3% to 10% of multi-year average precipitation (Timmerman, 1988; Woodford and Fortuin, 2003; DWAF, 2008). The recharge distribution developed by DWAF (2006) suggested that a recharge rate between 6% and 7% be adopted in the model. Recharge was set according to four zones with the recharge rate varying from 5 mm/a to 35 mm/a.

The West Coast District Municipality (WCDM) operates a well field with the license of abstracting 1.46 million m^3/a water from the LAU within Langebaan Road aquifer system for municipal water supply. During the time between December 1999 and July 2009, the WCDM

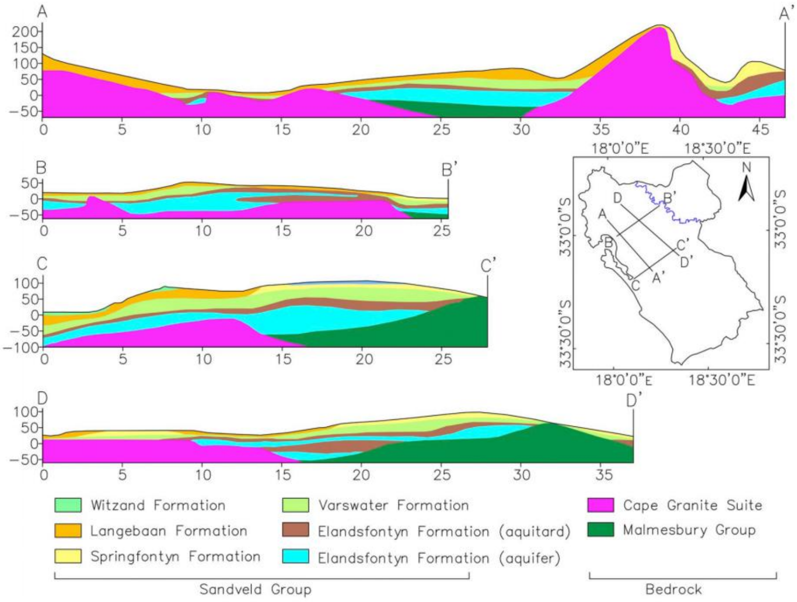

Fig. 4. Geological cross section of Langebaan Road aquifer system and Elandsfontein aquifer system (after DWAF, 2008).

utilized 80% of licensed allocation per year. However, abstraction reduced significantly after July 2009 due to the vandalism of well field pump and infrastructure. Besides the municipal water supply, there are 78 private users with a total registered abstraction of 6.9 million m^3/a. Although some private groundwater users access LAU, the majority of private users are assumed to take water from the UAU (DWA, 2010a).

2.2.2. Model calibration

The numerical model started to run after input the data representing initial and boundary condition. Then the model was calibrated by using groundwater monitoring data from 61 boreholes found in the area of Langebaan Road aquifer system and Elandsfontein aquifer system. Among these boreholes, 33 of them represented groundwater table of UAU, and the other 28 boreholes represented the piezometric head of LAU. The model was calibrated for a steady-state condition representing the flow regime before 2014 when there was no significant decrease in rainfall. The resulting correlation between observed and simulated piezometric heads is shown in Fig. 7, which indicated that most of the data distributed close to the 1:1 line, and the correlation coefficient value is 0.943. Usually, the root mean square error (RMSE) and normalized root mean square error (RMSE) are used as quantitative indicators for the adequacy of the fit between the observed (h_{obs}) and simulated (h_{sim}) water heads:

$$RMSE = \sqrt{\frac{\sum (h_{obs} - h_{sim})^2}{n}} \tag{1}$$

$$NRMSE = \frac{RMSE}{h_{\max} - h_{\min}} \tag{2}$$

After the model debugging and improvement, the result of RMSE of 5.4 m and NRMSE of 5.3% was achieved, with a mean error of 1.04 m. Normally, the value of RMSE and NRMSE less than 10 is generally considered acceptable (Seyler et al., 2016), thus the calibration is considered to be acceptable for the intended modelling purpose. The range of calibrated hydraulic conductivities for each model layer is shown in Table 4.

2.2.3. Model simulation

In order to simulate the suitable sites and proper scheme of MAR implementation, four predictive scenarios were designed showing the aim of each scenarios and its associated description (Table 5).

3. Results

3.1. Scenario one

Simulated result of groundwater contours of UAU is shown in Fig. 8, which indicates a rise in local groundwater table near the eight infiltration ponds (Table 6). In comparison with the initial groundwater table without recharging artificially, the rise in water table changes significantly at the location of G and H, while it changes only 1 m at location A and C. Generally speaking, the rise in groundwater table is larger when recharging at southwest of Hopefield which is regarded as

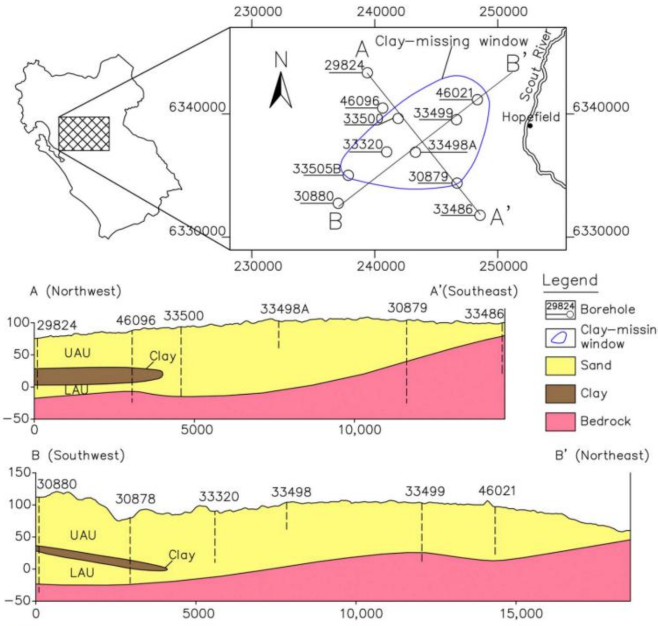

Fig. 5. Geological cross section made by NGA data showing a clay-missing window exited at the west of Hopefield.

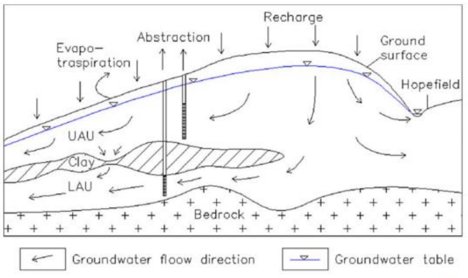

Fig. 6. Conceptual cross-section for groundwater flow mechanisms (after DWA, 2010a).

natural recharge region than the discharge area near Berg River and coastline.

From the simulated flow path lines (Fig. 9), the water recharged at location A and B flow northeast to Berg River, while the water recharged at location C, D, F and G flow west to Langebaan lagoon. The water recharged at location E and H partly flow west to Langebaan lagoon and coastline, partly flow east and discharge to the Berg River and its tributaries. The water recharged at the natural recharge area has longer path lines in terms of longer resident time in comparison with the water injected near the discharge area.

3.2. Scenario two

In this scenario, three injection wells including J, K and L were placed respectively in north, northeast and south within the clay-missing window area in west of Hopefield. Compared with the initial

Table 2
Layer arrangement for the numerical model (Timmerman, 1988; WCDM, 2009; Seyler et al., 2016).

Layer	Representing	Thickness (m)	Data source	Hydraulic conductivity *Kx* (m/d)
1	UAU	2.0–119.0	Layer top: DEM Layer bottom: UAU bottom as defined through NGA lithology data (The thickness this layer is assumed to be equal to or greater than 2.0 m).	0.1–86.4
2	Clay layer	0–84.0	Layer top: UAU bottom as defined through NGA lithology data. Layer bottom: clay bottom as defined through NGA lithology data.	4.3×10^{-5}–2.0
3	LAU	0.1–64.5	Layer top: clay bottom as defined through NGA lithology data. Layer bottom: bedrock elevation defined through NGA lithology data.	0.1–34.6
4	Bedrock	20.0	Layer top: bedrock elevation defined through NGA lithology data. Layer bottom: bedrock elevation – 20 m	4.3×10^{-3}–0.26

Table 3
Description of model boundaries.

Location	Conceptual Description and assumptions	Numerical Translation
Atlantic coastline (Northwest and west border of the model)	Atlantic ocean works as a regional drainage datum plane and accepts the discharge from aquifers.	Constant head boundary is applied along the coastline.
Berg River and Sout River	The Berg River and Sout River are assumed to be in contact with the UAU, without deeply incised.	River boundary is applied.
Ephemeral Rivers (Groën River together with the tributaries and gullies)	Work as a water drainage channel of the model.	Drain boundary is applied.
Watershed of northeast, south and southeast mountain area	It is assumed that there is no flux across the boundary of the catchment.	No-flow boundary is applied.
Model domain	Recharge from precipitation.	Recharge boundary is applied.
Model domain	Recharge or abstraction from aquifers.	Well boundary is applied.

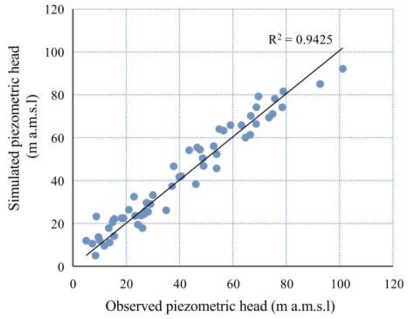

Fig. 7. Simulated and observed piezometric heads of calibration boreholes, showing most of the simulated and observed data distribute close to the 1:1 line with the correlation coefficient value of 0.943.

state without injection, the local water head of LAU was increased about 20 m at the injection area (Fig. 10).

There were diversities in flow directions for the water injected at different sites in this window area. The water injected at K partly flowed northeast to the Berg River, and partly flowed east to the Sout River. However, the water injected at J flowed northwest to the WCDM well field and then turned southwest to the Langebaan lagoon, while the water injected at L flowed southwest directly to the Langebaan lagoon.

3.3. *Scenario three*

In this scenario, three injection wells in scenario two were retained, and four abstraction wells at WCDM well field including 46032, 46033, 46034, 46036 with the abstraction rate of 1000 m^3/d each were added. Simulated results are shown in Fig. 11. Similar to scenario two, the local water head increased by 20 m in the vicinity of the injection sites, however, groundwater seepage showed a divergent behaviour as a function of abstraction. There was a flow direction transformation for the water injected at location K and L compared with their flow paths in scenario two. However, the biggest change due to abstraction was that the water injected at J flowed northwest to the WCDM well field and it was pumped out by abstraction.

3.4. *Scenario four*

In scenario four, the injection well J with the recharge rate of 200 m^3/d in scenario three was retained. Outside the clay-missing window, an infiltration pond (250 m × 250 m × 3 m) with the recharge rate of 200 m^3/d was placed close to the WCDM well field. Simulated results are shown in Fig. 12. Similar to scenario three, the water injected in clay-missing window flowed northwest toward the WCDM well field and was pumped out through abstraction. However, the flow path of the water recharged at infiltration pond outside the "window" showed a divergent behaviour. In addition, part of the recharged water flowed into the abstraction well and partly flowed west to the Langebaan lagoon, and the rest flowed east to Berg River.

4. Discussion

4.1. *MAR in upper unconfined aquifer unit (UAU)*

Based on the field investigation and follow-up simulations, implementing MAR in the aquifer of UAU can lead to a rise in local groundwater table. However, due to the difference in hydrogeological characteristics at different places, the rise of groundwater table showed a divergent result. It was observed from the simulation that the rise in groundwater level was mainly concerned with the hydraulic conductivity of the aquifer and its associated scale, the lower the hydraulic conductivity of the aquifer, the higher the rise in groundwater table.

Table 4
Calibrated hydraulic conductivities of modelling.

Model layer	Hydraulic conductivity (m/d)			Remarks
	Kx	Ky	Kz	
1	0.05–9	Kx	Kx/10	The low values are usually concerned with the stratigraphy of Langebaan Formation, which is mainly distributed at the area of Elandsfontein aquifer system together with the connection area between Langebaan Road aquifer system and Elandsfontein aquifer system. High values are usually concerned with the stratigraphy of Springfontein Formation, which is mainly distributed at Langebaan Road aquifer system.
2	0.001–0.008	Kx	Kx/10	/
3	0.2–50	Kx	Kx/10	The low values are mainly distributed at the area of Elandsfontein aquifer system together with the connection area between Langebaan Road aquifer system and Elandsfontein aquifer system. High values are usually distributed at Langebaan Road aquifer system.
4	0.02–0.2	Kx	Kx/10	/

Table 5
Details of predictive scenarios in simulation.

No.	Aim	Scenario description	Software Package
Scenario one	To simulate the suitable sites and impact of recharging in UAU	Eight infiltration ponds (length × width × depth: 250 m × 250 m × 3 m) with the recharge rate of 200 m^3/d each are placed at the different recharge locations of the Langebaan Road aquifer system and Elandsfontein aquifer system. MODPATH is adopted to trace the recharged water.	MODFLOW, MODPATH
Scenario two	To simulate the suitable sites and impact of recharging in LAU	Three injection wells whose depth extending from model top to LAU bottom, are placed at three different sites within the clay-missing window area with recharging rate of 200 m^3/d each. MODPATH is adopted to trace the recharged water.	MODFLOW, MODPATH
Scenario three	To simulate the suitable sites and impact of recharging in LAU	Based on scenario two, four abstraction boreholes at the WCDM well field (including 46032, 46033, 46034, 46036) are pumping groundwater from LAU with the abstraction rate of 1000 m^3/d separately. MODPATH is adopted to trace the recharged water.	MODFLOW, MODPATH
Scenario four	To simulate the suitable sites and impact of recharging in LAU	Based on scenario three, one borehole is left at the site within the clay-missing window area, another infiltration pond (250 m × 250 m × 3 m) is added outside the clay-missing window but closer to the WCDM well field. The recharge rate of both borehole and infiltration pond are 200 m^3/d. MODPATH is adopted to trace the recharged water.	MODFLOW, MODPATH

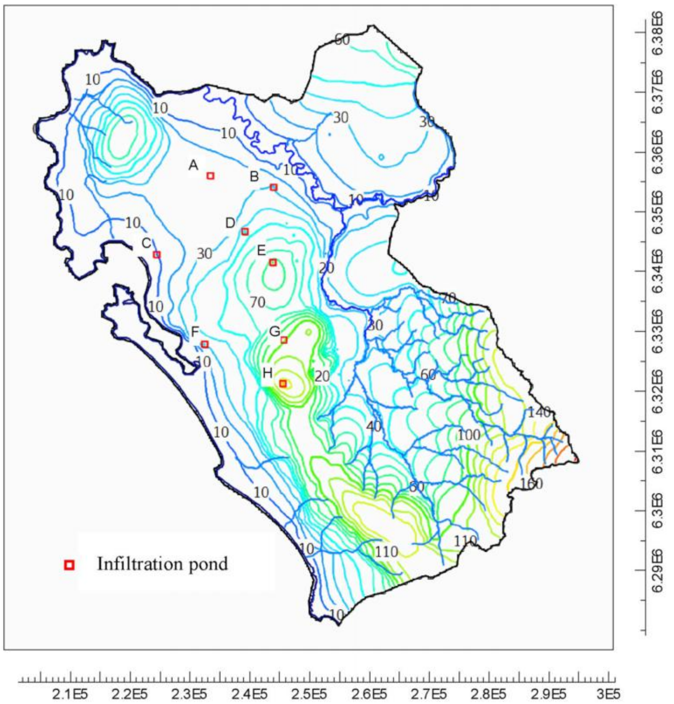

Fig. 8. Simulated groundwater contours of UAU, showing a rise in local groundwater table appeared in the vicinity of the recharge sites.

Meanwhile, the simulation also indicated that recharging at the natural recharge area (southwest of Hopefield) can benefit larger area than recharging at other places especially the discharge region such as Berg River and coastline. From the water flow paths, the recharged water will flow toward and discharge to the Berg River, Langebaan lagoon or the coastline. Without taking the influence of abstraction into consideration, the flow time from infiltration ponds at different locations to the discharge area varies from decades to tens of thousands of years. This result is in agreement with the isotope studies finished by Tredoux and Talma (2009) and WCDM (2009), which indicated that mean groundwater residence time in the UAU is between 30 and 60 years from tritium analysis, and between recent to 9000 years from

Table 6

Simulated results of implementing MAR in UAU, showing artificial recharge at the eight infiltration ponds causes rise in local groundwater table. The recharge at infiltration pond D, E, G and H shared the characteristics of longer flow time, larger rise and area in groundwater table.

Location	Aquifer	discharge location	Horizontal distance of tracing (m)	Flow time of tracing (day)	Maximum rise in groundwater table (m)	Plane region of groundwater table rise above 1 m
Infiltration pond A	Langebaan Road aquifer system	Berg River	10600-12500	2.23×10^5–5.99×10^6	+1.3	A nearly circular region with 500 m in diameter.
Infiltration pond B	Langebaan Road aquifer system	Berg River	5300–8000	9.5×10^4–7.91×10^5	+19	Elliptical region with the long axis 8500 m and the short axis 6000 m; The long axis is approximately parallel to the Berg River.
Infiltration pond C	Langebaan Road aquifer system	Langebaan lagoon	1900–1960	1.28×10^4–1.79×10^4	+1.1	A nearly circular region with 50 m in diameter.
Infiltration pond D	Langebaan Road aquifer system	Langebaan lagoon	20900-22800	2.42×10^5–8.46×10^5	+25	A nearly circular region with 9000 m in diameter.
Infiltration pond E	Langebaan Road aquifer system	Langebaan lagoon	28500-34000	6.61×10^5–2.54×10^7	+20	A nearly circular region with 13500 m in diameter.
Infiltration pond F	Elandsfontein aquifer system	Langebaan lagoon	3700–4400	2.79×10^4–3.17×10^5	+18	A nearly circular region with 3000 m in diameter.
Infiltration pond G	Elandsfontein aquifer system	Langebaan lagoon	16000-18000	1.90×10^5–3.17×10^5	+39	Elliptical region with the long axis 17000 m, and the short axis 13800 m; The long axis is approximately parallel to the Sout River.
Infiltration pond H	Elandsfontein aquifer system	Langebaan lagoon, Ocean and Groën River	14700-17000	1.82×10^6–8.76×10^6	+40	Irregular elliptical region with the long axis 17500 m, and the short axis 12500 m; The long axis is approximately parallel to the Groën River.

Carbon-14, while the residence time in the LAU ranged from 5000 to 28000 years. Therefore, the groundwater flows very slowly in a natural condition, which should be taken into consideration when implementing MAR scheme in the studied area. These results are applicable in areas of similar characteristics.

There is little research on the implementation of MAR in UAU of Langebaan Road aquifer system and Elandsfontein aquifer system. However, the town of Atlantis, which is located about 40 km southeast of the Elandsfontein aquifer system, has practiced artificial groundwater recharge for almost 40 years (DWA, 2010b; Bugan et al., 2016). Treated wastewater together with storm-water runoff were collected and artificially recharged in the Atlantis aquifer through two main recharge basins that were constructed up-gradient of the Witzand well field for about 500–1000 m. It was estimated that the groundwater abstracted for the water supply of Atlantis represented a blend of 30% water derived from MAR and 70% natural groundwater (DWA, 2010b). The Atlantis aquifer is formed of unconsolidated Cenozoic sediments, which is similar to the stratigraphy of Langebaan Road and Elandsfontein aquifers system. Thus according to the analogy analysis, the practice of artificial recharge in Atlantis aquifer confirms the feasibility of implementing MAR in UAU of West Coast, which also proves the reliability of modelling analysis. Based on the simulation and analogy analysis, the implementation of MAR in UAU was found to be hydrogeologically feasible, and the suitable sites are dependent largely on the recharging purpose. Based on the findings, it can be said that MAR can be implemented near the well fields when it is considered as a relatively straightforward choice to increase local water storage and supply. However, as described under the study area description section of the paper, the natural recharge area is the best site for a large quantity of water recharge, which benefits the largest area of the whole aquifer unit.

It was founds that storage space for the recharged water is another key factor that affects the implementation of MAR in UAU. The depth of groundwater table map was drawn based on the water table data of 138 boreholes which were monitored in the rainy season of 2018 by Department of Water Sanitation (DWS). The range of depth of groundwater table varied from 0 to 41 m, which was shallower near the discharge area such as Berg River as well as Langebaan lagoon, but deeper near the southwest of Hopefield where it was regarded as the natural recharge area (Fig. 13). Understanding such variation in relation to implementing MAR scheme was essential.

On the basis of the depth of groundwater table map, it was possible to calculate the available space for MAR in UAU through equation (3), as presented in Table 7.

$$Q = \sum_{i=1}^{m} A \times H \times S_y \tag{3}$$

Where.

Q is the available space for implementing MAR;
A is the area of the UAU aquifer;
H is the thickness of unsaturated aquifer in UAU;
S_y is the storage parameter, assumed to be a constant value here, valued 0.1;
m is the number of aquifer units with the same unsaturated thickness.

Recharge rate is another key issue for the implementation of MAR. Different recharge rates were simulated at location J in the modelling, result of which is shown in Fig. 14.

It can be seen from Fig. 14 that the maximum rise in groundwater level together with the benefit region showed a positive correlation with the increase of recharge rate from 50 m^3/d to 200 m^3/d. According to the simulation, the groundwater level rose sharply at the centre of the injection location from 5 m to 22 m with the increase of recharge

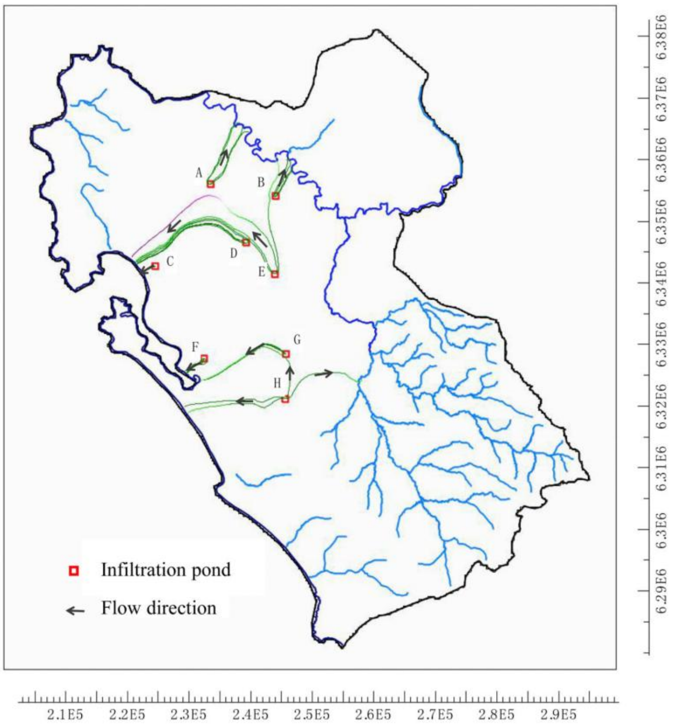

Fig. 9. Simulated flow path lines of recharged water, showing water recharged at different sites varied in discharge directions.

rate. The area of the infiltration pond simulated in the modelling was 250 m × 250 m, thus the recharge rate of 200 m^3/d indicates the infiltration rate to be 0.003 m/d. The practice of MAR in Atlantis aquifer showed that the infiltration rate of the recharge basins varied from 0.01 m/d to 0.16 m/d (DWA, 2010b). The infiltration rate in the modelling of the study area was lower than the practice of Atlantis, which was a concern considering the low permeability of the soil of Langebaan Formation at the recharge site. Therefore, considering the limitation of ground surface and the risk of flooding caused by MAR, the infiltration rate is suggested to be controlled less than 0.003 m/d at the west of Hopefield.

4.2. MAR in semi-confined lower aquifer unit (LAU)

When the sampled water from two aquifer system were analyzed, results showed that water quality in LAU was better than groundwater in UAU, which has laid the foundation of LAU as an ideal source of potable water supply for the past few decades. Several previous efforts focused on implementing MAR directly in LAU, however, the pilot injection study carried out by Tredoux and Engelbrecht (2009) indicated that direct injection in LAU at the WCDM well field was failed to keep water stored underground as initially expected. Based on the NGA borehole logs, results showed a clay-missing window area located at the west of Hopefield an area which was considered as natural recharge area. Subsequently, the scenario of recharging water at this clay-missing window was simulated by the numerical model, and the result of which showed that the water recharged at this clay-missing window would flow and recharge the LAU in both Langebaan Road aquifer system and Elandsfontein aquifer system, thereby concluding that the clay-missing window area was a suitable site for implementing MAR for lower semi-confined aquifer unit (LAU). However, implementing MAR in LAU is more complicated than in UAU. According to the borehole logs, the top of the clay layer (the confining layer) around the clay-missing window was about 30 m a.m.s.l (Fig. 5). Conversely, the piezometric head of groundwater in the vicinity of the clay-missing window showed very stable behaviour under the varied rainfall within the scope between 55 m and 80 m a.m.s.l according to the water head monitored by DWS from 2000 to 2017 (Fig. 15). Comparison of the monitoring groundwater head with the elevation of the top of clay layer in the vicinity of the clay-missing window showed that groundwater piezometric surface was much higher than the confining layer. Such observation provided the evidence to argue that implementing MAR

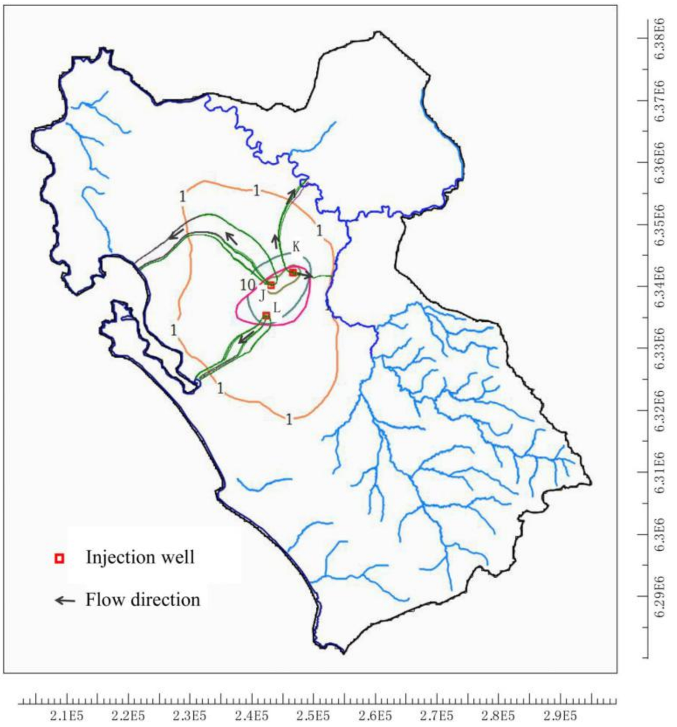

Fig. 10. Simulated rise of water head in LAU and flow path lines of recharged water in scenario two. The water injected in clay-missing window leads to groundwater rise in a large extent of Langebaan Road and Elandsfontein aquifers system. And recharge at different sites within clay-missing window results in divergent discharge directions.

directly to LAU remains impractical because the prevailing results showed that lack of space in LAU to store recharged water at present.

In addition, the result of the simulation in scenario four showed the recharge mechanism of LAU. Normally, LAU gets recharge from percolation of precipitation through the clay-missing window at the west of Hopefield. However, LAU also gets water through leaking recharge from UAU in locations where the clay was observed to be thin and the head difference between the upper and lower aquifer was reported to be large enough to drive vertical recharge (DWAF, 2008). Based on this information, another way to implement MAR for LAU would be to increase the leakage from UAU locally. Fig. 16 shows the idea of artificial recharging LAU through leakage wells.

Fig. 17 showed a simplified two-dimensional steady-state model, which considered the aquifer system of West Coast as a prototype and included UAU, clay, LAU and bed rock four layers. The model was developed to testify the idea of artificial recharging LAU through leakage wells (Fig. 17a). After data were input to represent initial and boundary condition, three scenarios were assigned to analyze the groundwater flow. In scenario 1, an abstraction well with the pumping rate of 200 m^3/d from LAU was assigned in the model. It can be seen from Fig. 17b that the pumping decreases the piezometric head of the LAU in the vicinity of abstraction well. In scenario 2, the abstraction well was retained, and an infiltration pond with the recharge rate of 100 m^3/d in UAU was placed 300 m east of abstraction well. According to the simulated result (Fig. 17c), the artificial recharge increased the water head of UAU from 50 m to 70 m around the infiltration pond, but it has little impact on the piezometric head of LAU. In scenario 3, the condition of infiltration and abstraction remained the same as scenario 2, and leakage wells were added to enlarge the hydraulic conductivity of clay between the abstraction well and infiltration pond. The simulated result was shown in Fig. 17d. Compared with the result of scenario 2, the leakage wells decreased the water head of the centre of infiltration pond by 10 m, however, they increased the piezometric head of the LAU in the vicinity of abstraction well by 10 m. Therefore, it can be stated that the idea of using leakage wells to increase leaking recharge for LAU from UAU was proved to be functioning. Although results showed that this application was able to increase the quantity of groundwater abstraction from LAU through combining the aquifers of

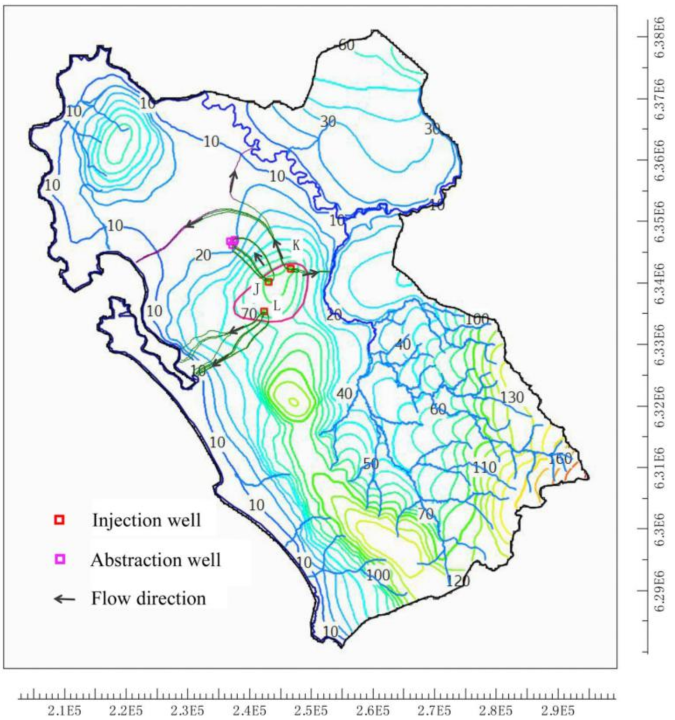

Fig. 11. Simulated piezometric heads in LAU and path lines of recharged water in scenario three. Abstraction at WCDM well field changes the flow path of the water recharged at site J and K which are located in the clay-missing window.

the local UAU and LAU, concerns remain a threat that the quality of recharge water from UAU might contaminate water of LAU (Meng et al., 2015) and that concerns would need to be ruled out through water quality testing which was beyond the scope of the current study for this paper.

5. Conclusions and recommendations

Based on the extensive information available on the West Coast of South Africa, a conceptual model of groundwater flow was designed on the basis of the analysis of hydrogeology of the study area. Thereafter, a numerical model was developed, calibrated and validated on the basis of the conceptual model. Suitable sites for implementing MAR were identified. Appropriate methods for assessing the implementing MAR scheme were established. Models as management tools for decision makers were developed, calibrated and validated to address the research question. The science communication aspect was beyond the scope of the current study to be part of this paper but a recommendation was made to develop a communication path way so that results from the study are shared with stakeholders in the study area beyond publication of such results in scientific media for the science community. The following key findings are critical from the current study: Firstly, implementing MAR in UAU aquifer system can lead to a rise in local groundwater table, thus it is suitable to implement MAR in UAU. Implementing MAR at the west of Hopefield (natural recharge area) can add and store more water in the UAU aquifer and benefit a large area, whereas recharge at other places results in benefiting the local area. The estimation of available space for MAR in Langebaan Road aquifer system and Elandsfontein aquifer system is 366.2 million m^3 and 549.5 million m^3 respectively. Infiltration pond or basin is suggested to be adopted when implementing MAR, but it should be cautious when applied to the Langebaan Formation distribution area for the calcrete and clay embedded in the stratum remain a concern with extremely low permeability. Due to the low permeability of the Langebaan Formation distributed in the vicinity of natural recharge area, the infiltration rate is suggested to be less than 0.003 m/d at the

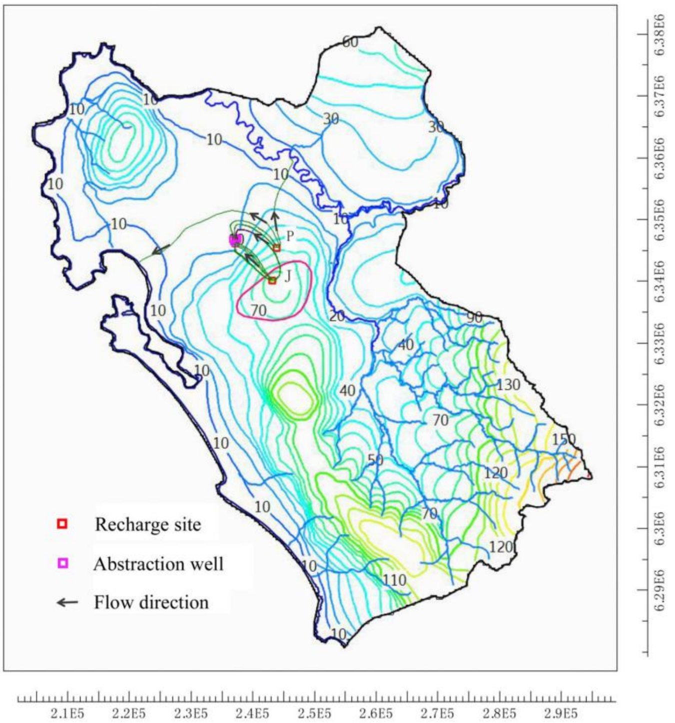

Fig. 12. Simulated piezometric heads in LAU and path lines of recharged water in scenario four, showing water recharged either at site J within the clay-missing window or site P outside the clay-missing window flows to abstraction wells of WCDM well field under the condition of powerful pumping.

west of Hopefield in order to avoid of flooding caused by over recharge. Secondly, the clay-missing window area located in west of Hopefield is a suitable site for implementing MAR in LAU. Recharge within the north of "window" benefits Langebaan Road aquifer system, while recharge within the south of the "window" benefits Elandsfontein aquifer system. However, the elevation of current groundwater piezometric surface is much higher than the top of the clay confining layer in the vicinity of a clay-missing window, thus there is little space in LAU to store recharged water to support the implementation of MAR at present. The result of simulation also shows that LAU gets water through leaking recharge from UAU at a local place under strong abstraction, which indicates the feasibility of increasing water availability of LAU through implementing MAR together with increasing leakage from UAU locally.

Although results of the study seem plausible, conclusions obtained in this study should be considered carefully. Despite the model performing well to improve understanding on implementing MAR scheme, more research should be conducted to increase the knowledge about the complicated aquifers system together with its response to MAR. Further studies including water chemistry, clogging, modelling in transit-state at the local scale and injection trials are suggested to be carried out before implementing MAR. As the clay-missing window area is the natural recharge area of both UAU and LAU, boreholes investigation as well as monitoring work including groundwater head and water chemistry, are suggested to be strengthened in the vicinity of this "window" area. These researches would guide the implementing of MAR in both UAU and LAU by reducing the existing uncertainty in the conceptual model, the numerical model or the parameter values so as to obtain a reliable tool for supporting sound decision-making. The approach presented in this paper is not limited to West Coast but it can be replicated to other areas of similar environments to study feasibility of implementing MAR and possible impacts of MAR for improved water security of drought-prone areas.

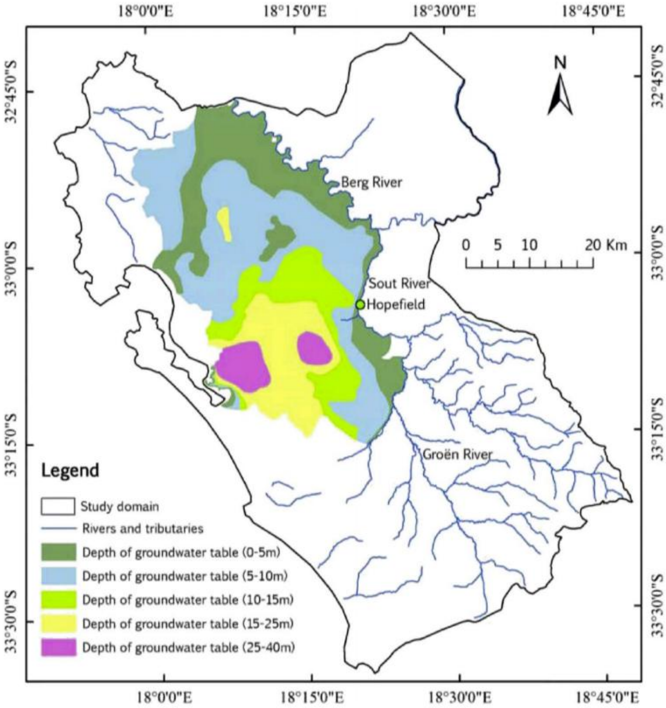

Fig. 13. The depth of groundwater table map of the rainy season in 2018.

Table 7
Estimate of available space for MAR in UAU.

Aquifers	Area of the aquifer (km^2)	Available Space for MAR in UAU (million m^3)
Langebaan Road Aquifer System	907.1	366.2
Elandsfontein Aquifer System	433.6	549.5
Total		915.7

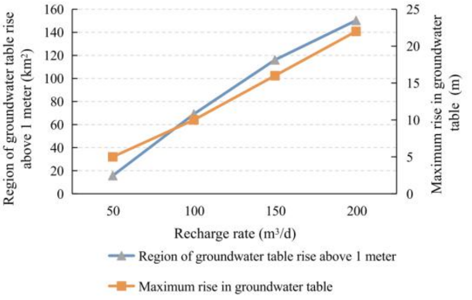

Fig. 14. The relationship between the rise in groundwater table as well as spread region and different recharge rate at location J.

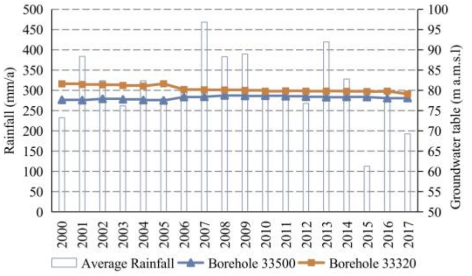

Fig. 15. The relationship between average annual rainfall and groundwater table of boreholes 33500 and 33320, showing the groundwater table in the vicinity of the clay-missing window area hardly change with varied rainfall.

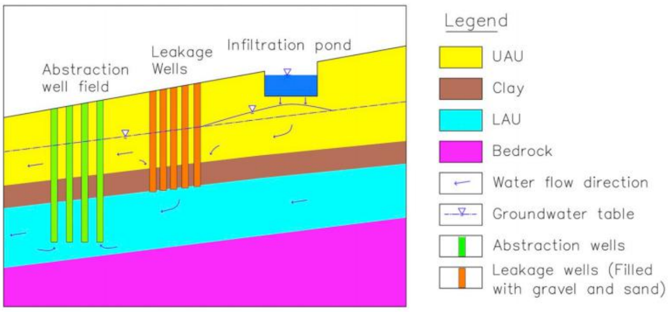

Fig. 16. Sketch map of using leakage wells to increase leaking recharge for LAU from UAU.

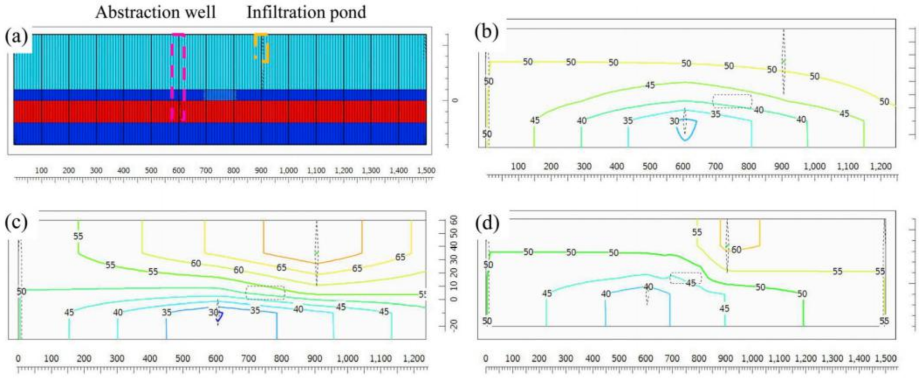

Fig. 17. The finite-difference grid of the 2-D groundwater model and the simulated results. (a) The finite-difference grid of the groundwater model; (b) The simulated groundwater flow of scenario 1; (c) The simulated groundwater flow of scenario 2; (d) The simulated groundwater flow of scenario 3.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.pce.2019.08.005.

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