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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

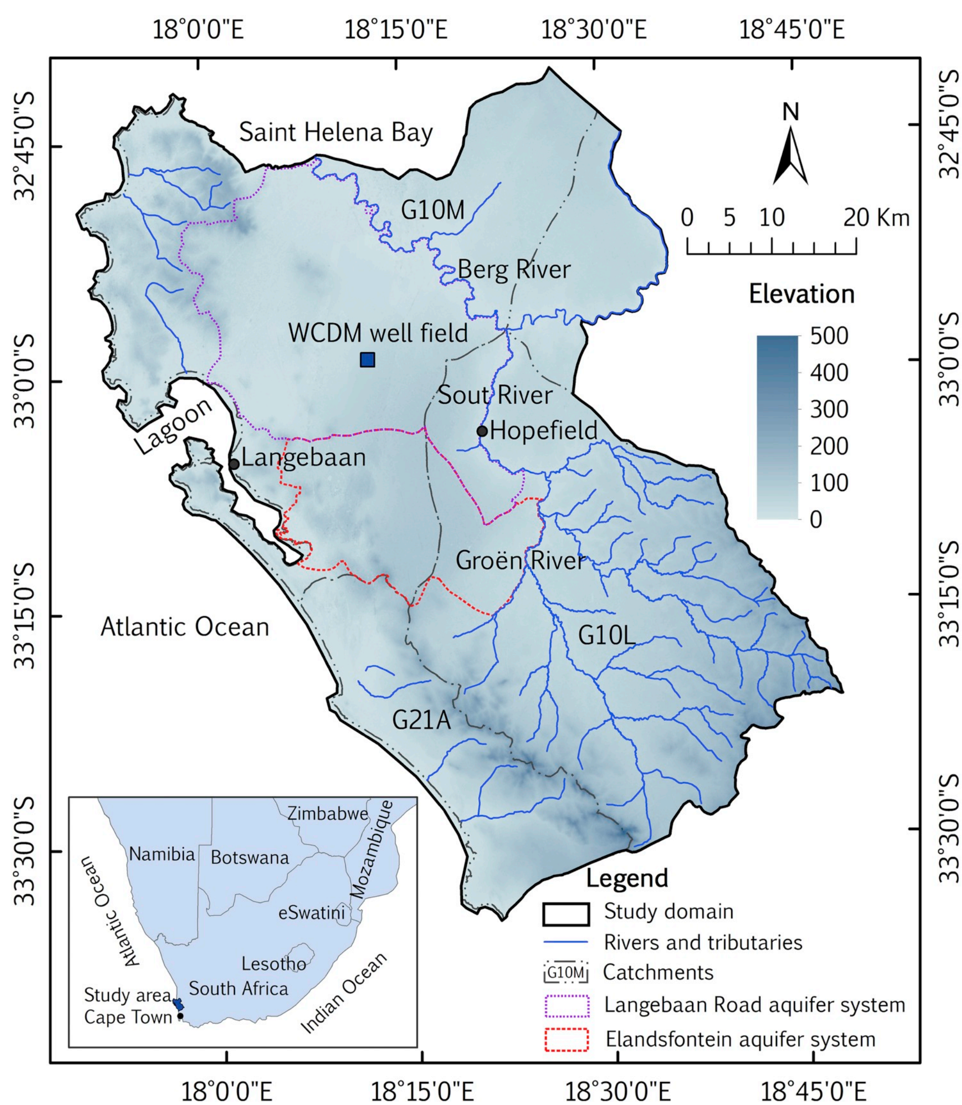

Fig. 1. Topographic elevation and location of the study area.

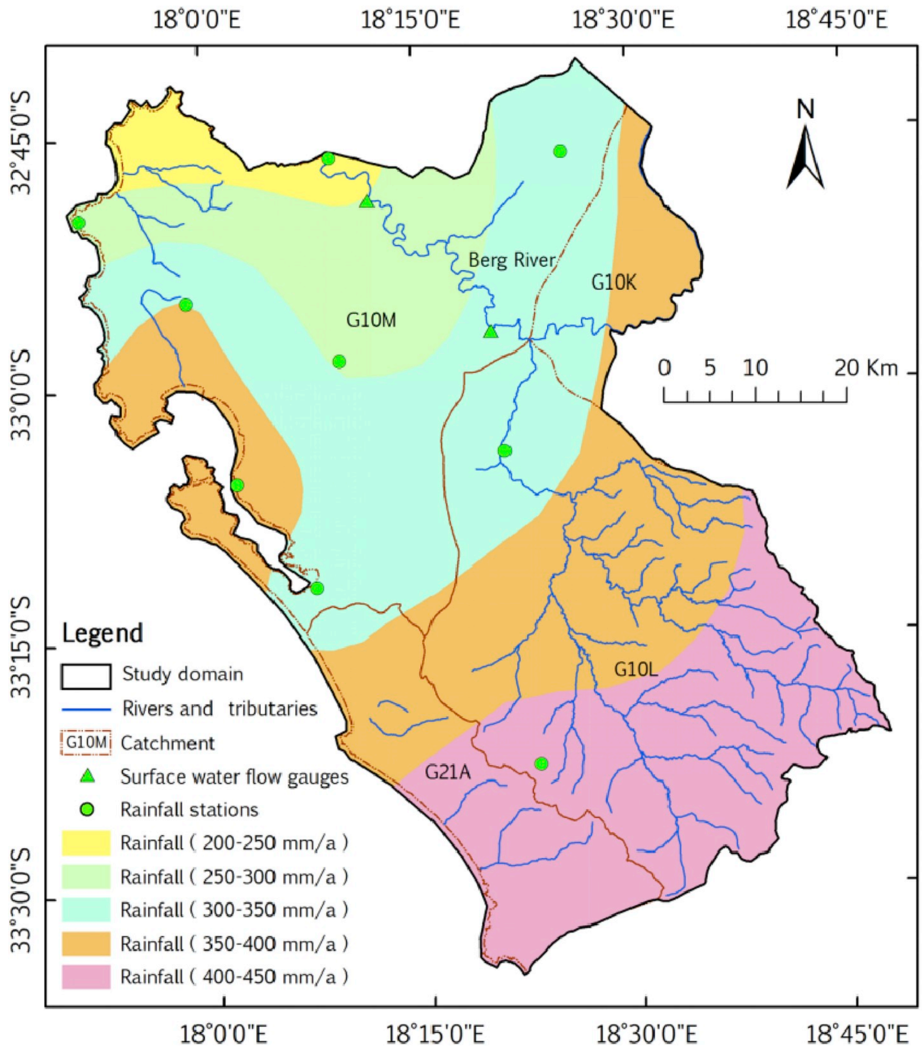

Fig. 2. Average annual rainfall distribution of the study area from 1970 to 2017, showing average annual rainfall ranges from 200 mm/a in the north to 450 mm/a in the south.

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

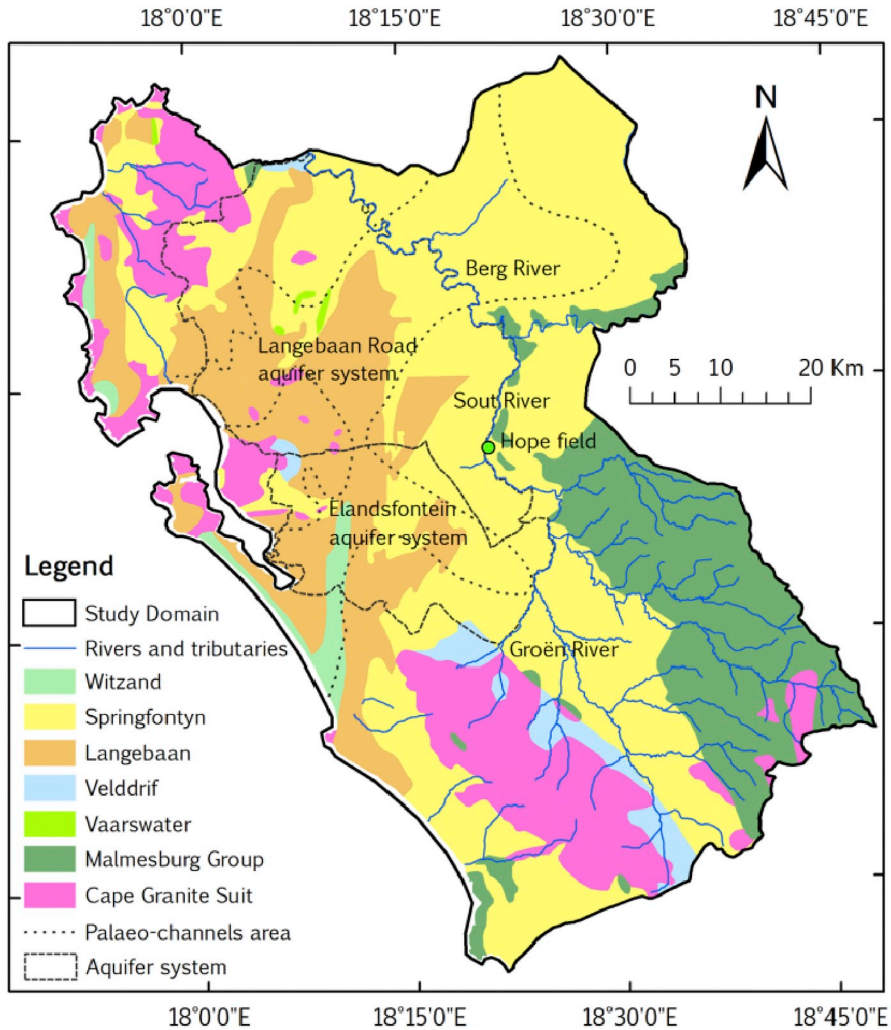

Fig. 3. Geological map of the study area (after DWAF, 2008; Seyler et al., 2016).

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

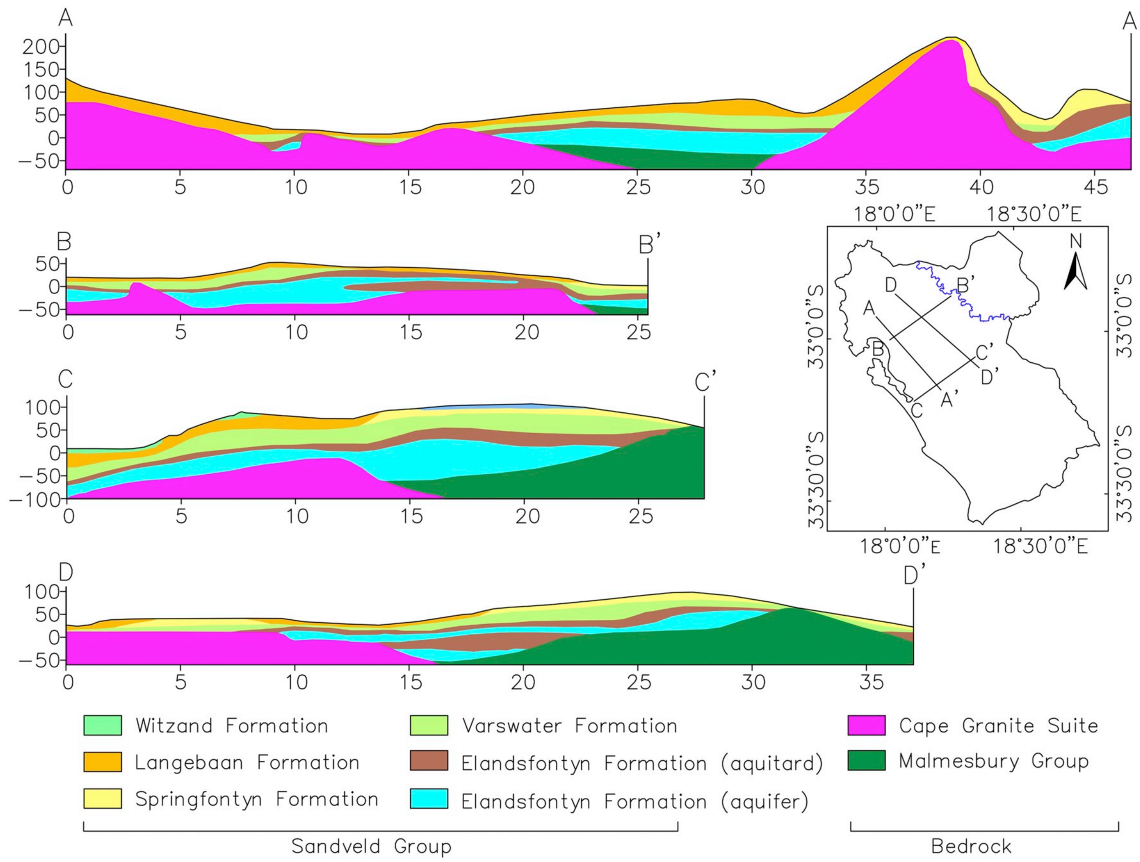

Fig. 4. Geological cross section of Langebaan Road aquifer system and Elandsfontein aquifer system (after DWAF, 2008).

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

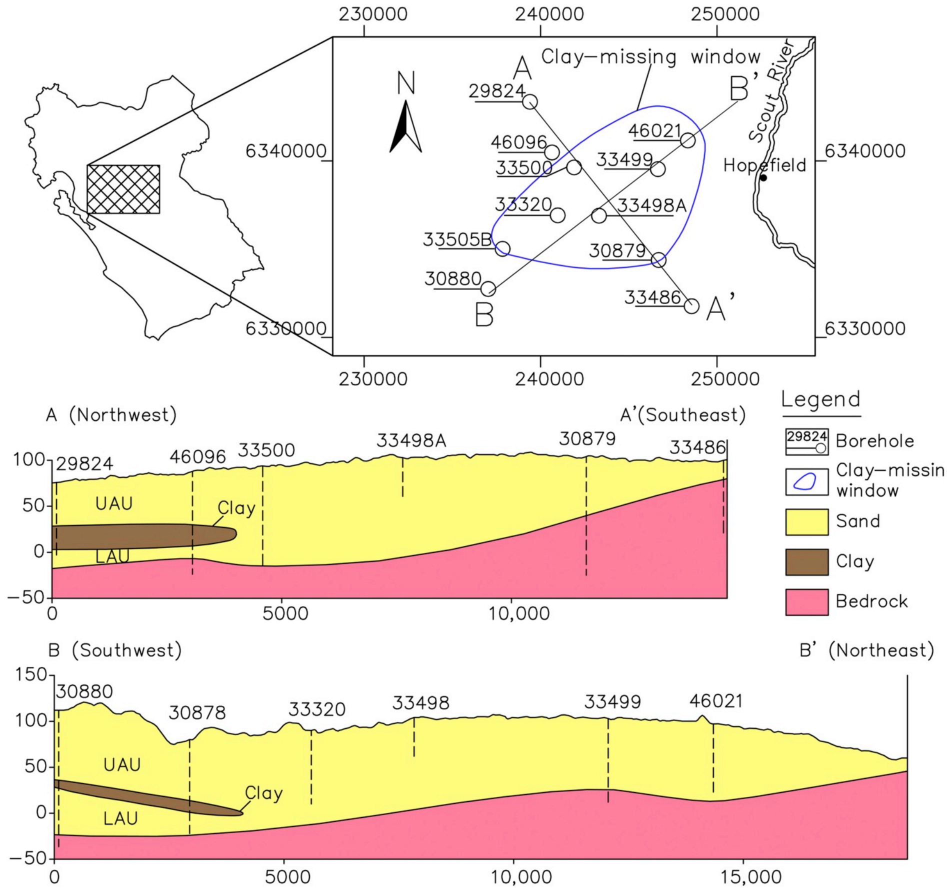

Fig. 5. Geological cross section made by NGA data showing a clay-missing window exited at the west of Hopefield.

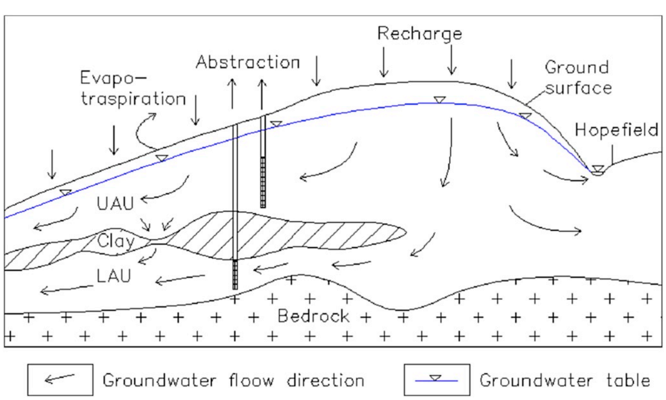

Fig. 6. Conceptual cross-section for groundwater flow mechanisms (after DWA, 2010a).

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.

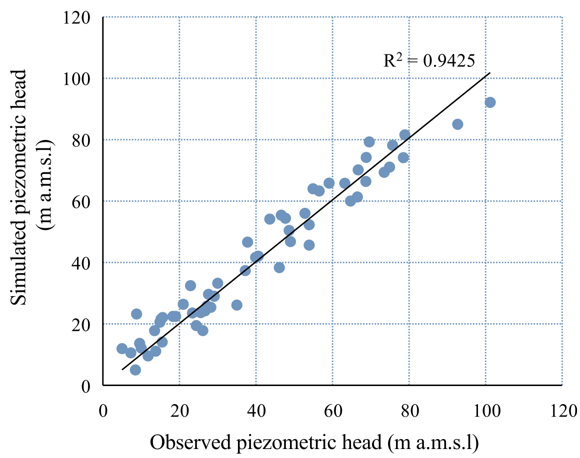

Fig. 7. Simulated and observed piezometric heads of calibration boreholes, showing most of the simulated and observed data distribute close to the 1:1 line with the correlation coefficient value of 0.943.

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

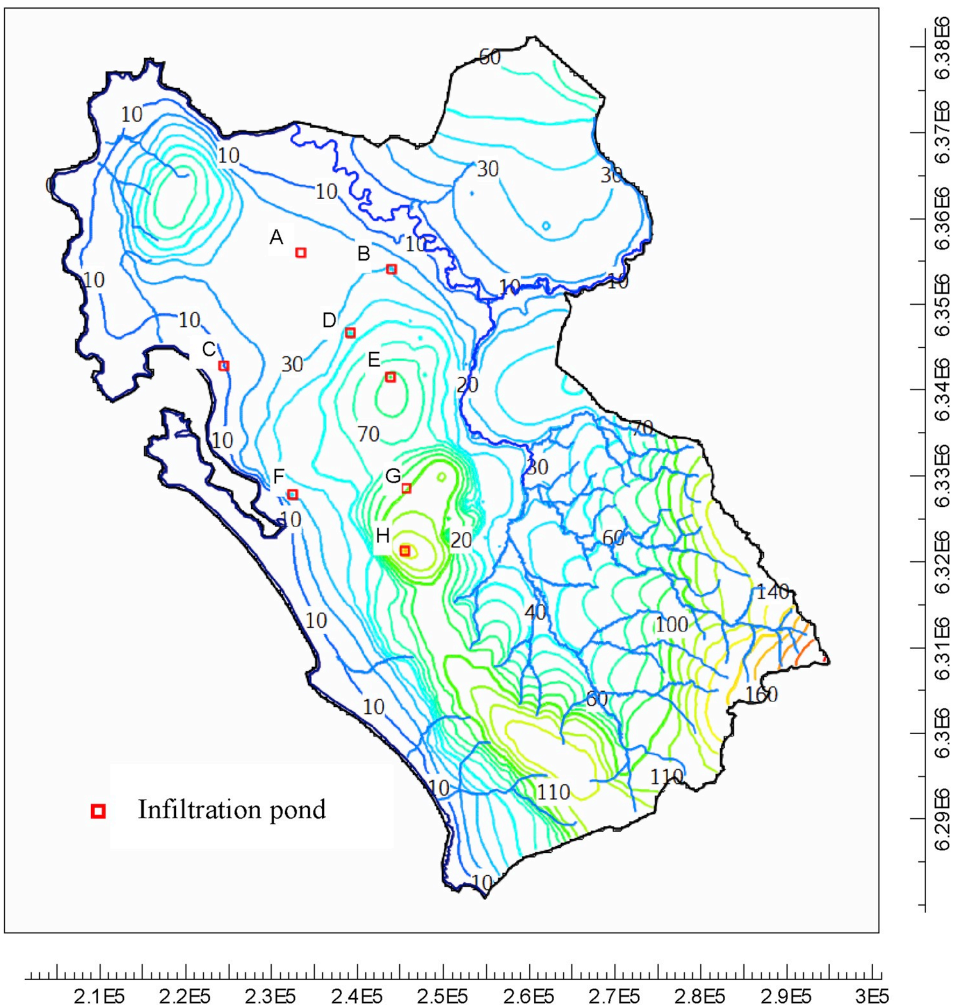

Fig. 8. Simulated groundwater contours of UAU, showing a rise in local groundwater table appeared in the vicinity of the recharge sites.

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

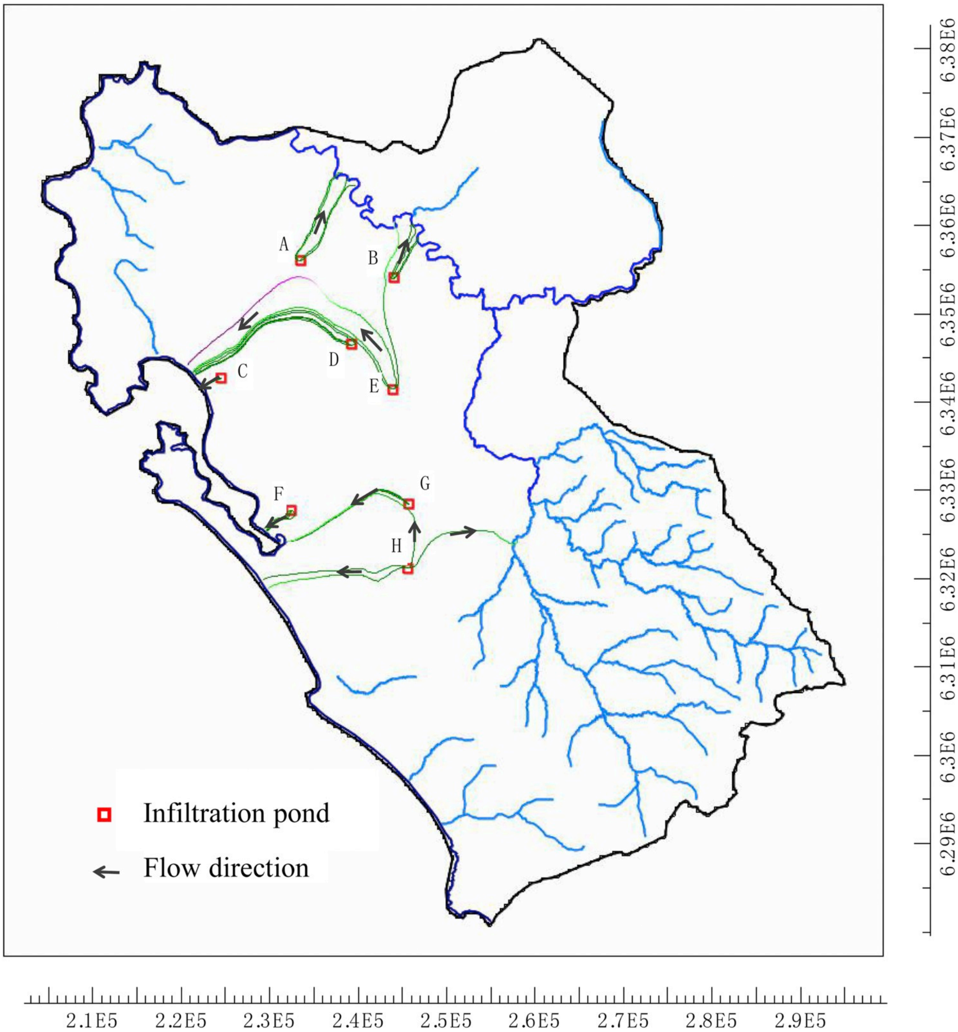

Fig. 9. Simulated flow path lines of recharged water, showing water recharged at different sites varied in discharge directions.

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

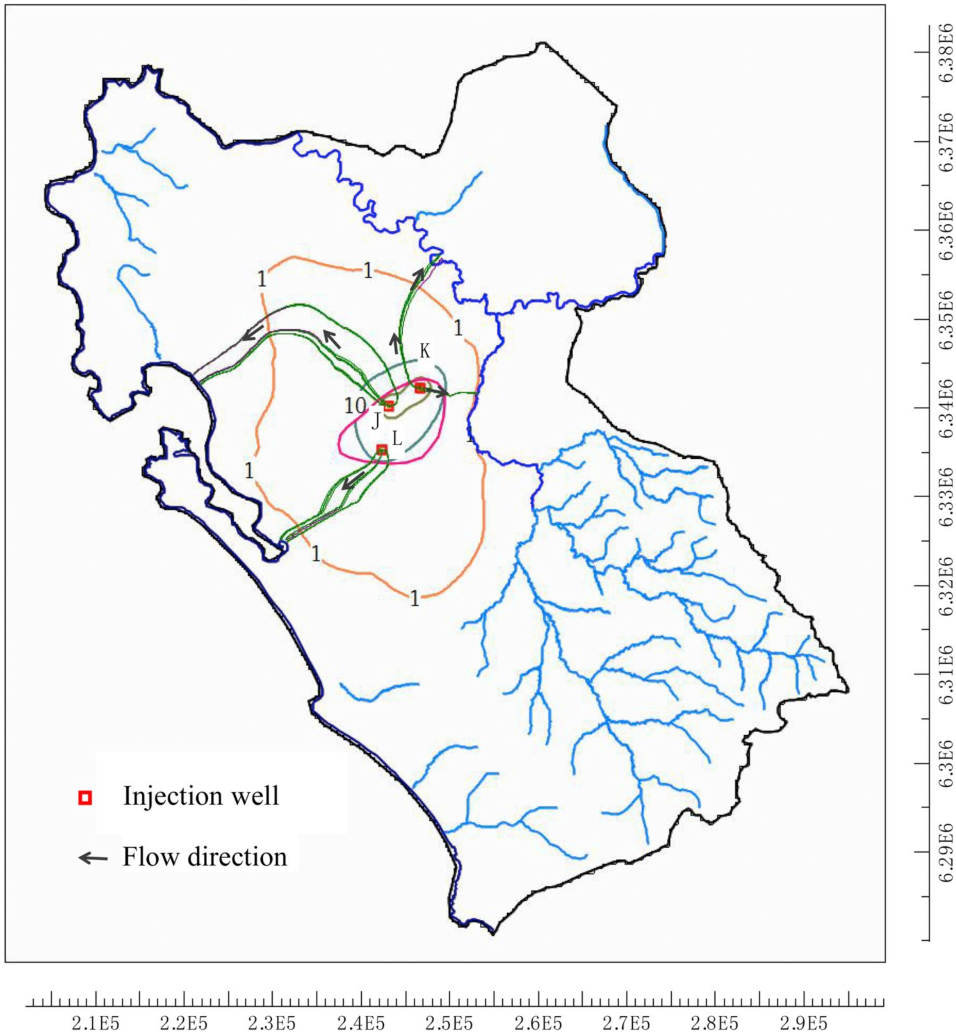

Fig. 10. Simulated rise of water head in LAU and flow path lines of recharged water in scenario two. The water injected in clay-missing window leads to groundwater rise in a large extent of Langebaan Road and Elandsfontein aquifers system. And recharge at different sites within clay-missing window results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

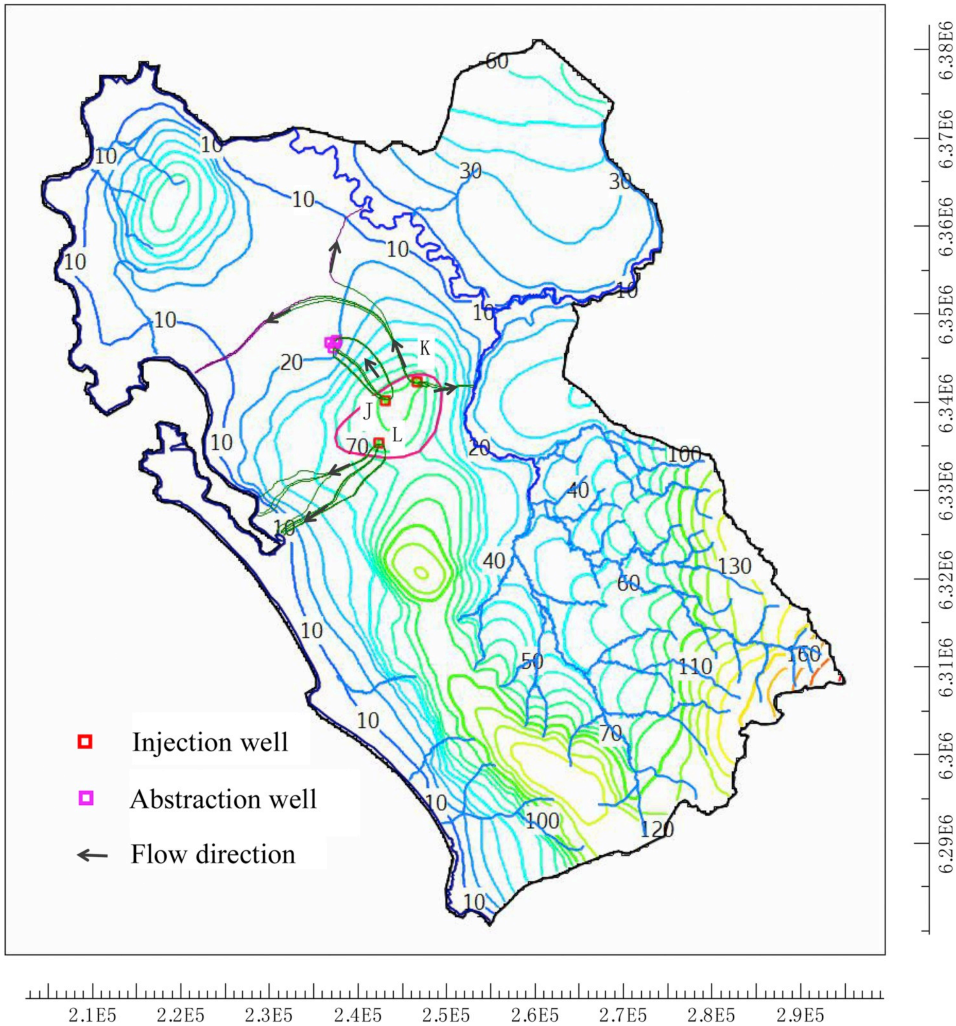

Fig. 11. Simulated piezometric heads in LAU and path lines of recharged water in scenario three. Abstraction at WCDM well field changes the flow path of the water recharged at site J and K which are located in the clay-missing window.

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

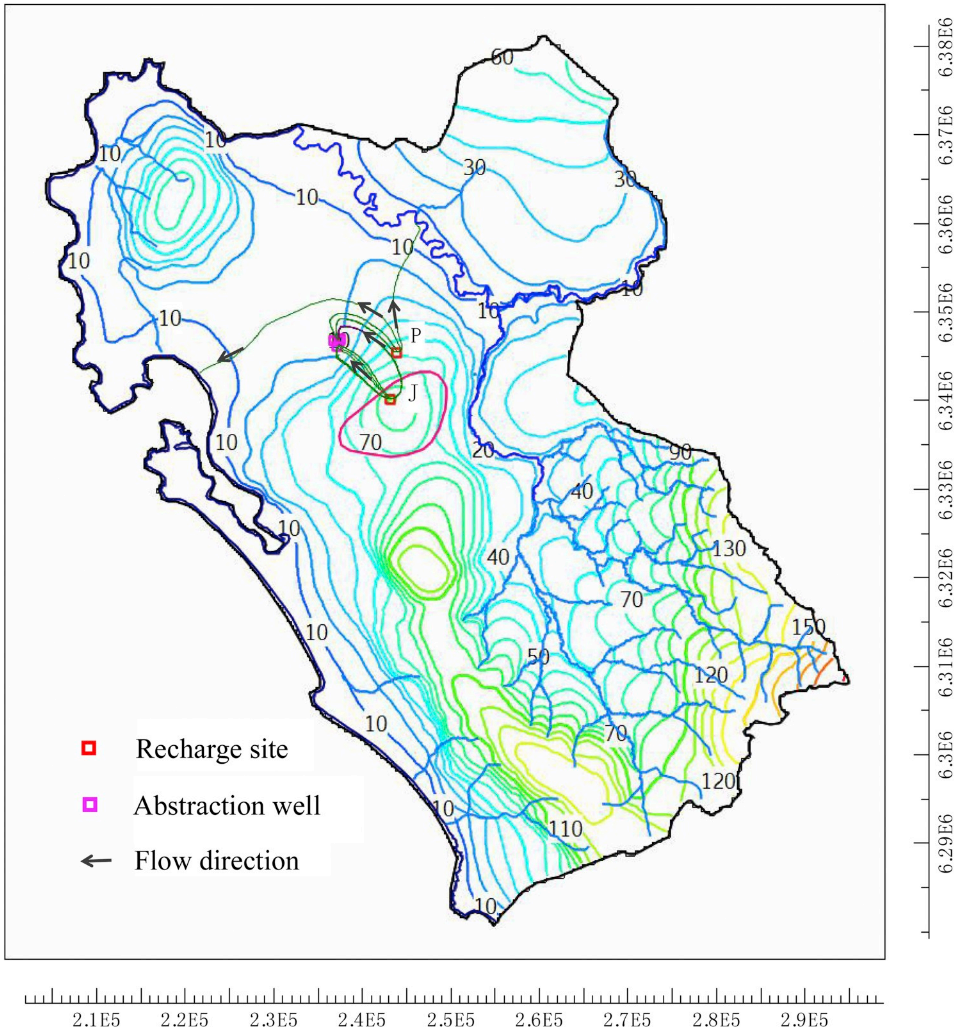

Fig. 12. Simulated piezometric heads in LAU and path lines of recharged water in scenario four, showing water recharged either at site J within the clay-missing window or site P outside the clay-missing window flows to abstraction wells of WCDM well field under the condition of powerful pumping.

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.

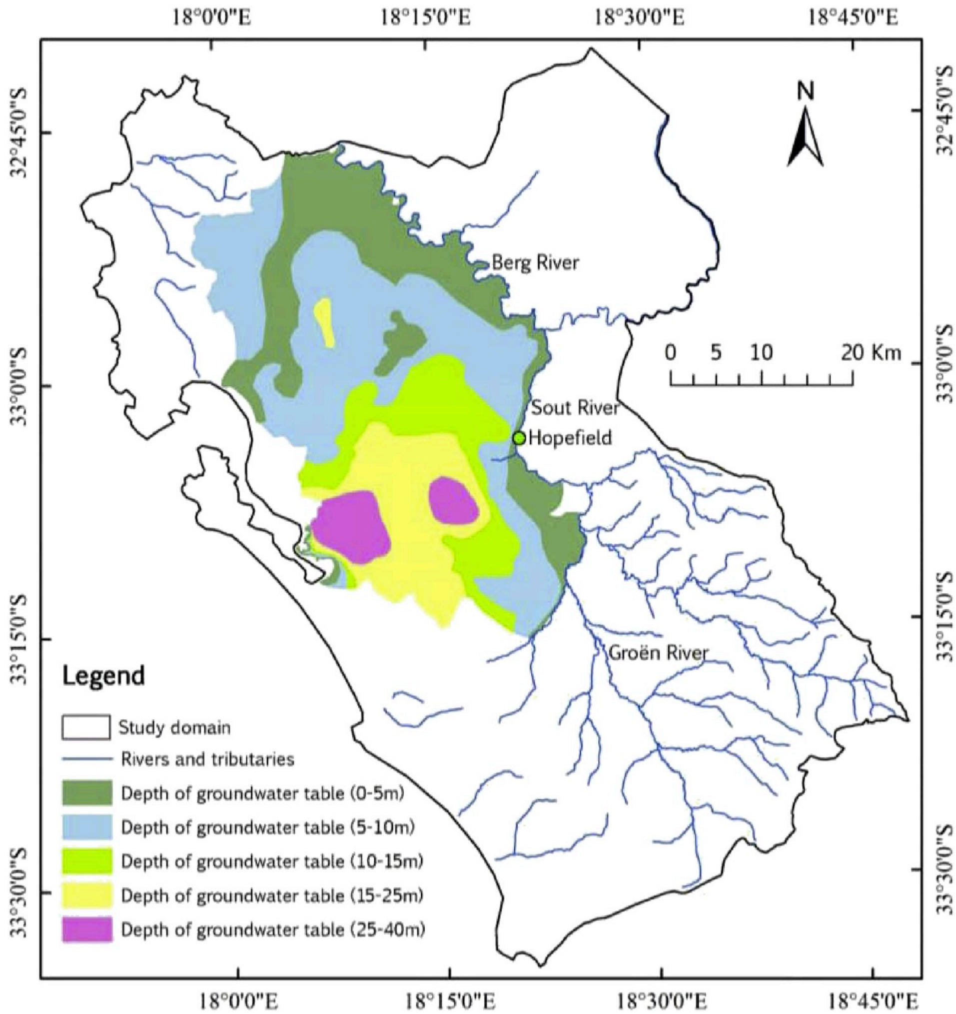

Fig. 13. The depth of groundwater table map of the rainy season in 2018.

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

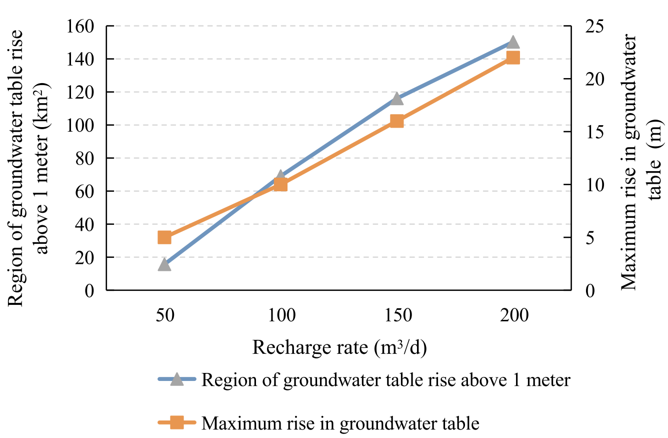

Fig. 14. The relationship between the rise in groundwater table as well as spread region and different recharge rate at location J.

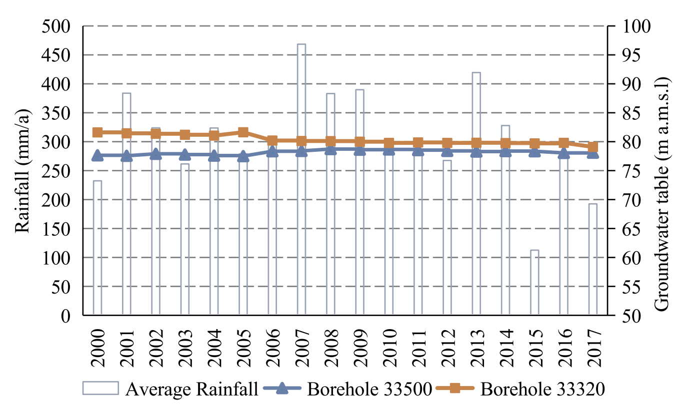

Fig. 15. The relationship between average annual rainfall and groundwater table of boreholes 33500 and 33320, showing the groundwater table in the vicinity of the clay-missing window area hardly change with varied rainfall.

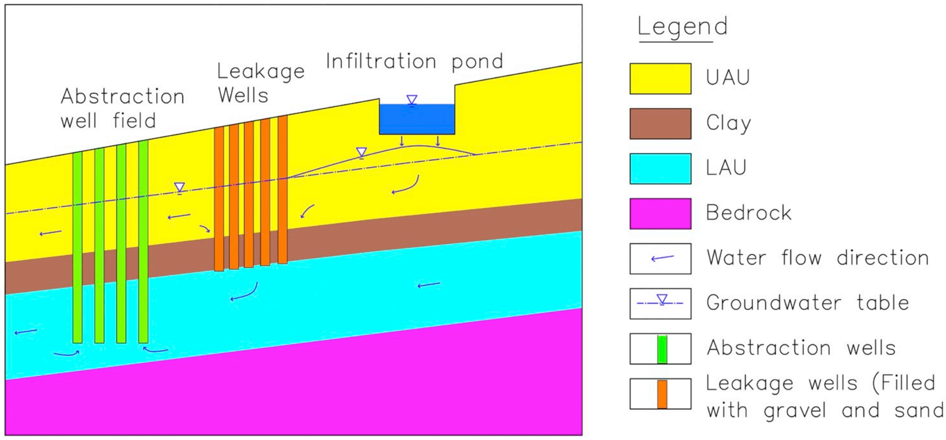

Fig. 16. Sketch map of using leakage wells to increase leaking recharge for LAU from UAU.

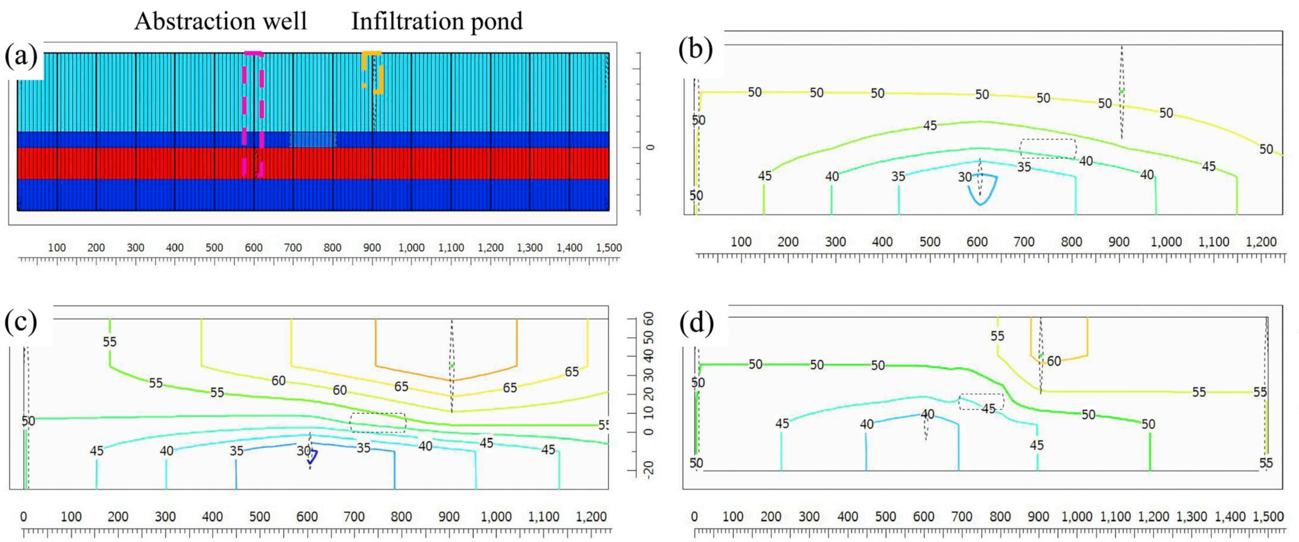

Fig. 17. The finite-difference grid of the 2-D groundwater model and the simulated results. (a) The finite-difference grid of the groundwater model; (b) The simulated groundwater flow of scenario 1; (c) The simulated groundwater flow of scenario 2; (d) The simulated groundwater flow of scenario 3.

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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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